SOLUTIONS MANUAL

TO ACCOMPANY

ENGINEERING THERMODYNAMICS

Fourth Edition

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400 Selected Problems

Solutions Manual, 400 Selected Problems, to Accompany Engineering Thermodynamics, Fourth Edition

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Introduction:

We hope that you find the Solutions Manual helpful in developing your understanding Engineering Thermodynamics. Doing multiple problems will help you develop your engineering modeling abilities, modeling thermodynamic systems. The Solutions Manual follows the same format for problem solution that the text does—each step clearly delineated—stating what is given, what must be found, a sketch with the given data, the assumptions made, and the analysis of the problem.

We hope you find the Solutions Manual and Engineering Thermodynamics 4e, beneficial.

Dave Burghardt
Jim Harbach

CHAPTER I

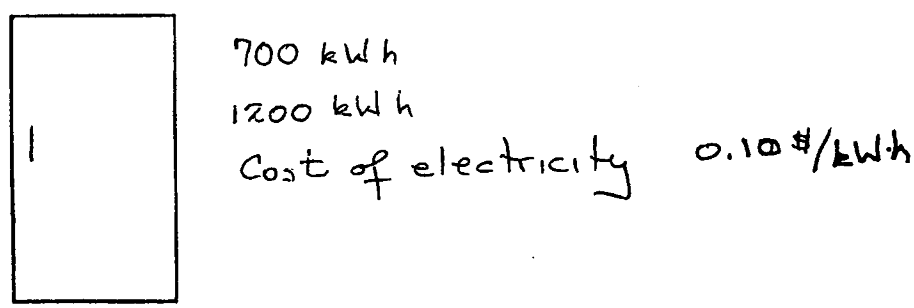
Problem 1.1

Compare the operating costs of a home refrigerator that uses 700 kwh electricity annually to one that uses 1900 kwh. The cost of electricity is $0.10 kwh. If this were enacted nationally, such that 10 million refrigerators were effected, what would be the total savings in kilowatt-hours?

Given: The annual electrical power consumption of refrigerators and the cost of electricity.

Find: The savings in kw-h of electricity by using an energy efficient model.

Sketch & Given Data:



Analysis:

$$\left.\begin{array}{r}1900\ \text{kw-hr}\\ 700\ \text{kw-hr}\end{array}\right\}\ 1200\ \text{kwh savings/unit annually}$$

Cost Savings = (1200 kwh)(0.10 $/kwh) = $12/yr

$$\text{Savings in annual kwh} = \left(1200\frac{\text{kwh}}{\text{unit}}\right)(10\times10^{6}\ \text{units}) = 1.2\times10^{10}\ \text{kwh}$$

Problem 1.5

Consider a subset of the American automotive fleet that comprises one million cars that are driven 10,000 miles annually. The average gasoline consumption for this fleet rises from 26 mpg to 31 mpg over a 5-year period. Calculate the total fuel savings annually and cumulatively over this time.

Given: The estimated rise in an automotive fleet's miles per gallon over a five-year period.

Find: The total fuel savings and the annual fuel savings over the five-year period.

Analysis: 1 millions cars 10,000 mi/yr
26 mpg → 31 mpg over 5 years
Savings per mpg

$$\frac{10{,}000\ \text{mi}}{26\ \text{mi/gal}} = 384.62\ \text{gal/car-year}$$

$$\frac{10{,}000}{27} = 370.37 \qquad \Delta_1 = 14.25$$

$$\frac{10{,}000}{28} = 357.14 \qquad \Delta_2 = 13.23$$

$$\frac{10{,}000}{29} = 344.83 \qquad \Delta_3 = 12.31$$

$$\frac{10{,}000}{30} = 333.33 \qquad \Delta_4 = 11.50$$

$$\frac{10{,}000}{31} = 322.58 \qquad \Delta_5 = 10.75$$

Year	Savings/Million cars	Cumulative Savings (gallons)
1	14,250,000	14,250,000
2	13,230,000	27,480,000
3	12,310,000	39,790,000
4	11,500,000	51,290,000
5	10,750,000	62,040,000

CHAPTER 2

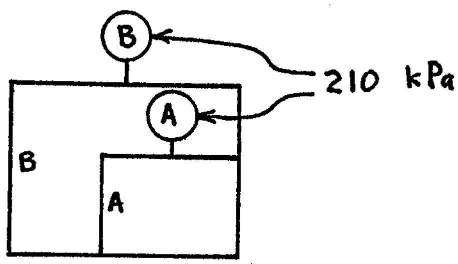
Problem 2.1

Referring to Figure 2.10, the atmospheric pressure is 100 kPa, and the pressure gages A and B read 210 kPa (gage). Determine the absolute pressures in boxes A and B in (a) kPa; (b) mm Hg absolute.

Given: Atmospheric pressure and readings of gages A and B.

Find: The absolute pressures in boxes A and B.

Sketch and Given Data:



$P_{surr} = 100$ kPa

Assumptions: None

Analysis: Determine pressures A and B in kPa, then convert to mmHg absolute.

(a)

$$P_{B_{abs}} = P_{B_{gage}} + P_{surr}$$
$$= 210 \text{ kPa} + 100 \text{ kPa} = 310 \text{ kPa}$$

$$P_{A_{abs}} = P_{A_{gage}} + P_{surr_A} \text{ but } P_{surr_A} = P_{B_{abs}}$$
$$= 210 \text{ kPa} + 310 \text{ kPa} = 520 \text{ kPa}$$

(b) 1mmHg = 0.1333 kPa

$$P_{B_{abs}} = 310 \text{ kPa} \times \frac{1\text{mmHg}}{0.1333 \text{ kPa}} = 2325.6 \text{ mmHg absolute}$$

$$P_{A_{abs}} = 520 \text{ kPa} \times \frac{1\text{mmHg}}{0.1333 \text{ kPa}} = 3901 \text{ mmHg absolute}$$

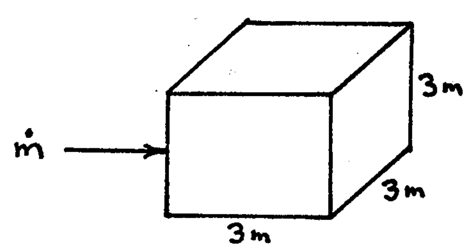
Problem 2.5

A pump discharges into a 3-m-per-side cubical tank. The flow rate is 300 liters per minute and the fluid has a density 1.2 times that of water (density of water = 1000.0 kg/m^3). Determine (a) the flowrate in kilograms per second; (b) the time it takes to fill the tank.

Given: Dimensions of tank, flowrate and fluid density.

Find: Flowrate and time to fill tank.

Sketch and Given Data:



$$\rho = (1.2)(1000\ \text{kg/m}^3) = 1200\ \text{kg/m}^3$$

Assumptions: None

Analysis: (a) Converting volume flowrate to mass flowrate.

$$\frac{(300\ \ell/\text{min})}{(1000\ \ell/\text{m}^3)} \times (1200\ \text{kg/m}^3) \times \left(\frac{1}{60\ \text{s/min}}\right) = 6\ \text{kg/s}$$

(b) Calculating time by dividing volume by volume flowrate.

$$t = \frac{(3\text{m})^3 \times (1000\ \ell/\text{m}^3)}{300\ \ell/\text{min}} = 90\ \text{min}$$

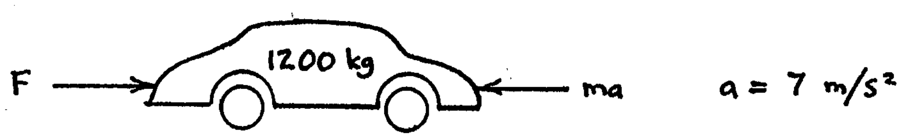
Problem 2.9

An automobile has a 1200-kg mass and is accelerated to 7 m/s^2. Determine the force required to perform this acceleration.

Given: Automobile undergoing acceleration.

Find: Required force.

Sketch and Given Data:



Assumptions:
1) Neglect friction.
2) Horizontal movement.

Analysis: Calculate force to accelerate automobile.

$$F = ma = (1200\ \text{kg})(7\ \text{m/s}^2) = 8400\ \text{N}$$

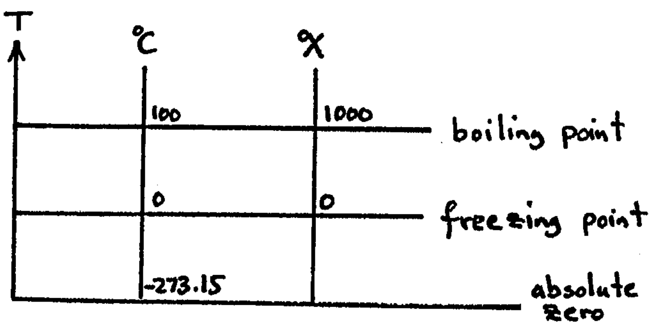
Problem 2.13

A new temperature scale is desired with freezing of water at 0°X and boiling at atmospheric pressure occurring at 1000°X. Derive a conversion between degrees Celsius and degrees X. What is absolute zero in degrees X?

Given: Values in °X at boiling and freezing points of water.

Find: Conversion to °C.

Sketch and Given Data:



Assumptions: None

Analysis: Determine change for each system between boiling point and freezing point.

$$(100°C - 0°C) = (1000°X - 0°X)$$

$$100°C = 1000°X \text{ or } 1°C = 10°X$$

$$\text{absolute zero} = -273.15°C \times 10\frac{°X}{°C} = -2731.5°X$$

Problem 2.17

For the situation sketched below, the following information is known:

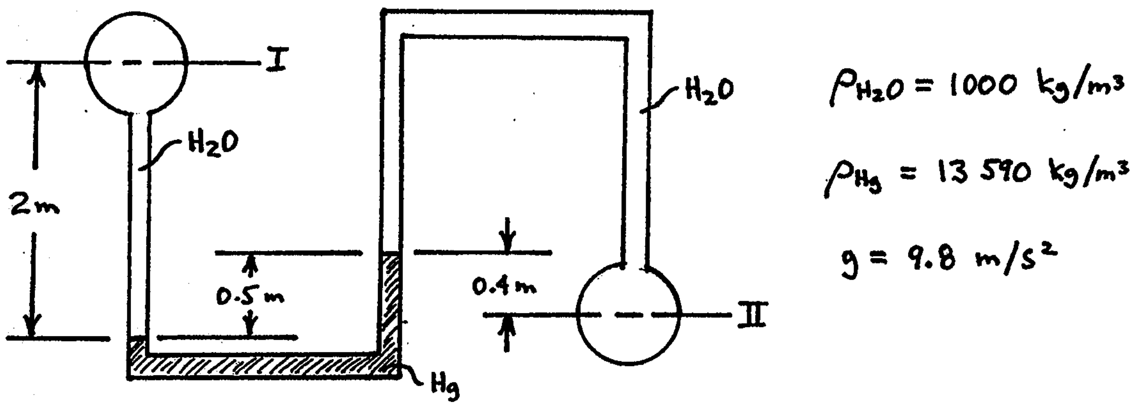
$$P_{H2O} = 1000.0\ kg/m^3$$
$$P_{Hg} = 13590.0\ kg/m^3$$
$$g = 9.8\ m \cdot s^{-2}$$
$$p_I = 500\ kPa$$

Determine pII.

Given: Pressure at I, fluid densities, elevations.

Find: Pressure at II.

Sketch and Given Data:



Assumptions: None

Analysis: Pressure at II is equal to pressure at I plus 2 m column of water minus 0.5 column of Mercury plus 0.4 m column of water.

$$P_{II} = P_I + \rho L g - \rho L g + \rho L g$$

$$= 500\ kPa + \frac{(1000\ kg/m^3)(2m)(9.8\ m/s^2)}{(1000\ Pa/kPa)}$$

$$- \frac{(13590\ kg/m^3)(0.5\ m)(9.8\ m/s^2)}{(1000\ Pa/kPa)}$$

$$+ \frac{(1000\ kg/m^3)(0.4\ m)(9.8\ m/s^2)}{(1000\ Pa/kPa)}$$

$$P_{II} = 456.9\ kPa$$

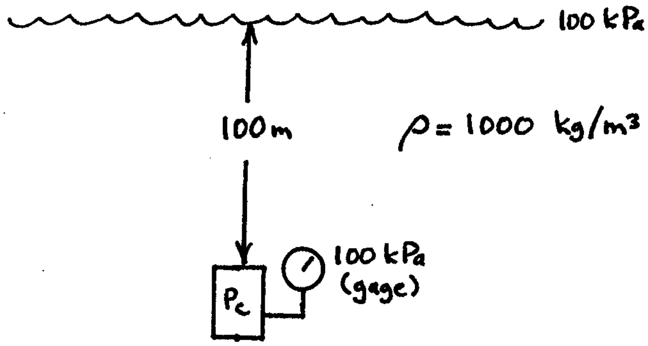
Problem 2.21

A diver descends 100 m to a sunken ship. A container is found with a pressure gage reading 100 kPa (gage). Atmospheric pressure is 100 kPa. What is the absolute pressure of the gas in the container? (The density of water is 1000 kg/m³.)

Given: Gage pressure reading of container at 100 m water depth.

Find: Absolute pressure of gas in container.

Sketch and Given Data:



Assumptions: 1) Acceleration of gravity is 9.8 m/s²

Analysis: Absolute pressure in container is gage reading plus absolute pressure of surroundings.

$$P_c = 100 \text{ kPa} + P_{surr}$$

Surroundings pressure is surface pressure plus pressure of 100 m column of water.

$$P_{surr} = P_{atm} + \rho L g = 100 \text{ kPa} + \frac{(1000 \text{ kg/m}^3)(100 \text{ m})(9.8 \text{ m/s}^2)}{(1000 \text{ Pa/kPa})}$$

$$= 1080 \text{ kPa}$$

$$P_c = 100 \text{ kPa} + 1080 \text{ kPa}$$

$$= 1180 \text{ kPa}$$

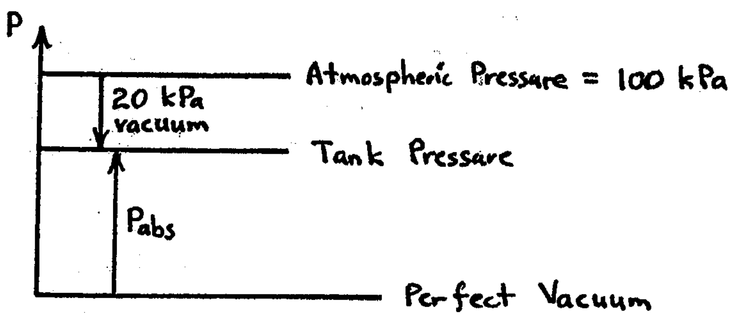
Problem 2.25

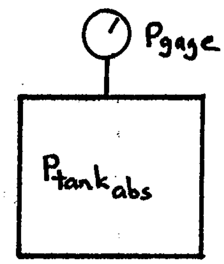
A tank has a vacuum gage attached to ie indicating 20 kPa (vacuum) where the atmospheric pressure is 100 kPa. Determine the absolute pressure in the tank.

Given: Tank vacuum gage reading and atmospheric pressure.

Find: Tank absolute pressure.

Sketch and Given Data:





Assumptions: None

Analysis: The tank absolute pressure is atmospheric pressure minus vacuum gage reading.

$$P_{tank_{abs}} = P_{surr} - P_{gage} = 100 \text{ kPa} - 20 \text{ kPa} = 80 \text{ kPa}$$

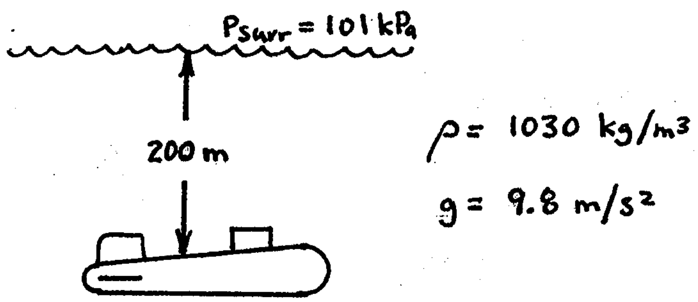
Problem 2.29

A submarine is cruising 200 m below the ocean's surface. Determine the pressure on the submarine's surface if atmospheric pressure is 101 kPa and the density of seawater is 1030 kg/m³. g = 9.8 m/s².

Given: Submarine cruising at given depth.

Find: Pressure on submarine.

Sketch and Given Data:



Assumptions: None

Analysis: Pressure on submarine is surface pressure plus pressure of column of seawater.

$$P_{sub} = P_{surr} + \rho L g = 101\ \text{kPa} + \frac{(1030\ \text{kg/m}^3)(200\ \text{m})(9.8\ \text{m/s})}{(1000\ \text{Pa/kPa})}$$

$$= 2119.8\ \text{kPa}$$

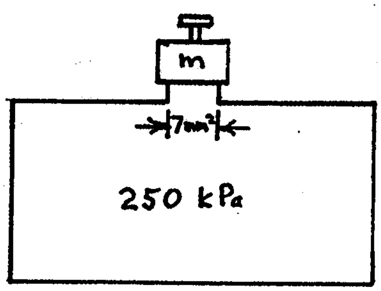
Problem 2.33

A pressure cooker operates by cooking food at a higher pressure and temperature than is possible at atmospheric conditions. Steam is contained in the sealed pot, with a small vent hole in the middle of the cover, allowing steam to escape. The pressure is regulated by covering the vent hole with a small weight, which is displaced slightly by the escaping steam. Atmospheric pressure is 100 kPa, the vent hole area is 7 mm^2, and the pressure inside should be 250 kPa. What is the mass of the weight?

Given: Pressure cooker with weighted vent.

Find: Mass of vent weight.

Sketch and Given Data:



Assumptions: 1) Acceleration of gravity is 9.8 m/s^2.

Analysis: Write balance of vertical forces on vent weight (forces up = forces down).

$$P_{cooker} A_{vent} = A_{surr} A_{vent} + mg$$

$$(250{,}000 \text{ Pa})(7 \times 10^{-6} \text{ m}^2) = (100{,}000 \text{ Pa})(7 \times 10^{-6} \text{ m}^2) + (m)(9.8 \text{ m/s}^2)$$

$$m = 0.107 \text{ kg}$$

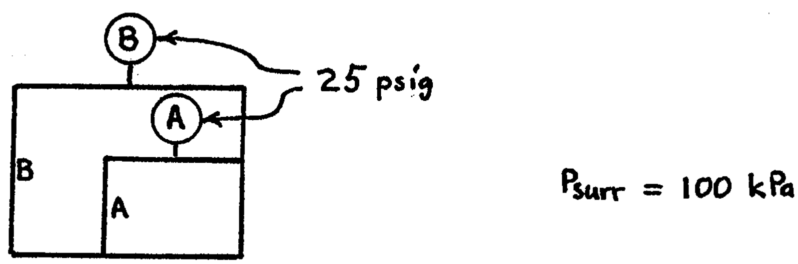
Problem *2.1

Referring to Figure 2.10 in the text, the atmospheric pressure is 100 kPa and the pressure gages A and B read 25 psig. Determine the absolute pressures in boxes A and B in (a) psia; (b) in. Hg absolute.

Given: Atmospheric pressure and readings of gages A and B.

Find: The absolute pressures in boxes A and B.

Sketches and Given Data:



Assumptions: None

Analysis: Convert atmospheric pressure to psia.

$$(100 \text{ kPa}) \left(\frac{1 \text{ psi}}{6.8948 \text{ kPa}} \right) = 14.5 \text{ psia}$$

Determine pressures A and B in psia, then convert to in Hg absolute.

a)
$$P_{B_{abs}} = P_{B_{gage}} + P_{surr}$$

$$= 25 \text{ psia} + 14.5 \text{ psia} = 39.5 \text{ psia}$$

$$P_{A_{abs}} = P_{A_{gage}} + P_{surr_A} \text{ but } P_{surr_A} = P_{B_{abs}}$$

$$= 25 \text{ psia} + 39.5 \text{ psia} = 64.5 \text{ psia}$$

b)
$$P_{B_{abs}} = (39.5 \text{ psia}) \left(\frac{1 \text{ inHg}}{0.4912 \text{ psia}} \right) = 80.42 \text{ in Hg absolute}$$

$$P_{A_{abs}} = (64.5 \text{ psia}) \left(\frac{1 \text{ inHg}}{0.4912 \text{ psia}} \right) = 131.3 \text{ in Hg absolute}$$

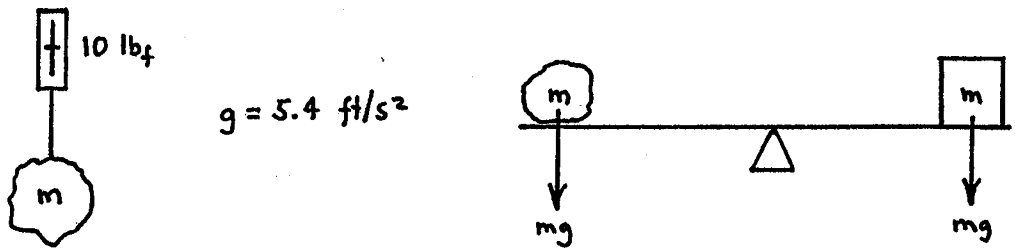
Problem *2.5

A spring scale is used to measure force and to determine the mass of a sample of moon rocks on the moon's surface. The springs were calibrated for g_c. The scale reads 10 lbf and the moon's gravitational attraction is 5.40 ft/sec^2. Determine the sample mass. What would be the reading on a beam balance scale?

Given: Reading of spring scale weighing mass on the moon.

Find: Sample mass.

Sketch and Given Data:



Assumptions: None

Analysis: Determine mass that will exert 10 lb_f under an acceleration of 5.40 ft/sec^2.

$$F = \frac{mg}{g_c} \qquad m = \frac{F\,g_c}{g} = \frac{(10\ lb_f)(32.1739\ lb_m\text{-ft}/lb_f\text{-sec}^2)}{(5.40\ \text{ft/sec}^2)}$$
$$= 59.58\ \text{lbm}$$

With balance scale, reference mass and measured mass are both subjected to the same gravitational acceleration, therefore reading will be:

$$m = 59.58\ \text{lbm}$$

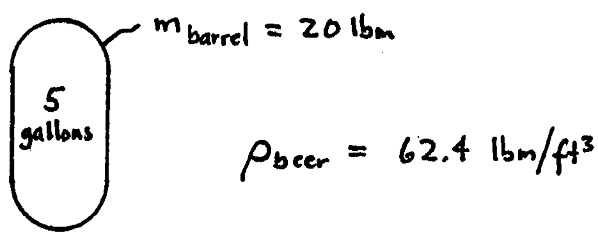
Problem *2.9

A beer barrel has a mass of 20 lbm and a volume of 5 gallons. Beer's density is 62.4 lbm/ft^3. Determine the total mass and weight of the barrel when it is filled with beer.

Given: Mass and volume of beer barrel and density of beer.

Find: Total mass and weight.

Sketch and Given Data:



Assumptions: 1) Acceleration of gravity is 32.1739 ft/sec^2.

Analysis: Total mass is mass of barrel plus mass of beer.

$$m_{total} = m_{barrel} + m_{beer} = 20 \text{ lbm} + (5 \text{ gallons})\left(\frac{1 \text{ ft}^3}{7.481 \text{ gallons}}\right)(62.4 \text{ lbm/ft}^3)$$

$$= 61.7 \text{ lbm}$$

Weight is force exerted by acceleration of gravity on total mass.

$$F = \frac{ma}{g_c} = \frac{(61.7 \text{ lbm})(32.1739 \text{ ft/sec}^2)}{(32.1739 \text{ lbm-ft/lb}_f\text{-sec}^2)} = 61.7 \text{ lb}_f$$

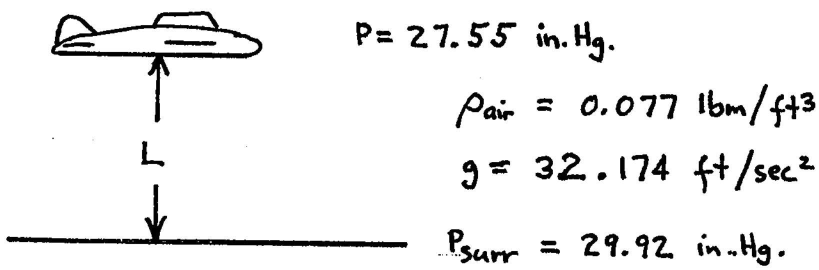
Problem *2.13

A barometer can be used to measure an airplane's altitude by comparing the barometric pressure at a given flying altitude to that on the ground. Determine an airplane's altitude if the pilot measures the barometric pressure at 27.55 in. Hg. absolute while ground reports it to be 29.92 in Hg. absolute. and where the average air density is 0.077 lbm/ft^3. g = 32.174 ft/sec^2.

Given: Pressure at altitude and on ground.

Find: Airplane's altitude.

Sketch and Given Data:



Assumptions: None

Analysis: Pressure change is due to column of air at average density.

$$\Delta P = \rho L g/gc$$

$$L = \frac{\Delta P \; g_c}{pg}$$

$$= \frac{(29.92 \text{ inHg} - 27.55\text{inHg})\left(\frac{.4912 \text{ psi}}{1 \text{ inHg}}\right)\left(\frac{144 \text{ in}^2}{1 \text{ ft}^2}\right)\left(32.174\frac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)}{(0.077 \text{ lbm/ft}^2)(32.174 \text{ ft/sec}^2)}$$

$$= 2177.1 \text{ ft}$$

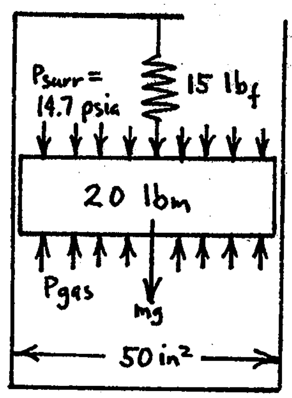
Problem *2.17

A vertical, frictionless piston/cylinder, similar to the one illustrated from Problem 2.31, contains a gas at an unknown pressure. The piston has a mass of 20 lbm and a cross-sectional area of 50 in^2. In addition the spring exerts a downward force of 15 lbf on the piston and atmospheric pressure is 14.7 psia. Determine the pressure of the gas.

Given: Piston with spring force and gas pressure acting on it.

Find: Gas pressure in cylinder.

Sketch and Given Data:



Assumptions: 1) Acceleration of gravity is 32.174 ft/sec^2.

Analysis: Write balance of vertical forces on piston (forces up = forces down).

$$P_{gas}\,A_{piston} = P_{surr}\,A_{piston} + m\frac{g}{g_c} + F_{spring}$$

$$(P_{gas})(50\ \text{in}^2) = (14.7\ \text{psia})(50\ \text{in}^2) + (20\ \text{lbm})\frac{(32.174\ \text{ft/sec}^2)}{\left(32.174\ \dfrac{\text{lbm-ft}}{\text{lbt-sec}^2}\right)} + 15\ \text{lb}_f$$

$$P_{gas} = 15.4\ \text{psia}$$

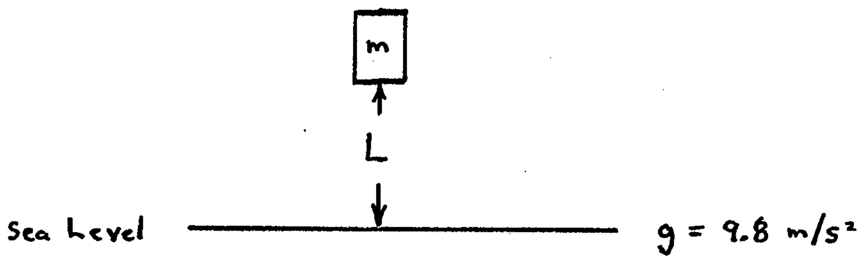
Problem C2.1

Compute the weight of a 50 kg mas at different heights above the earth's surface. At sea level g = 9.8 m/s^2 and decreases by 0.000913 m/s^2 for each 300 m of ascent. Consider a total ascent of 2.5 km with increments of 100 m.

Given: Mass of 50 kg at different heights above earth.

Find: Weight at various heights to 2.5 Km.

Sketch and Given Data:



Assumptions: None

Analysis: The change in acceleration of gravity with height can be calculated as follows:

$$g = 9.8 \frac{-(L)(0.00913)}{300} \text{ m/s}^2$$

Weight at each height is thus

$$F = m\, g$$

Using a spreadsheet program, enter the following.

```
C2.1
     Mass=  50
     g@SL=  9.8

  Height              g                Weight
0              9.8-A6*0.000913/300     +$B$2*B6
+A6+100        9.8-A7*0.000913/300     +$B$2*B7
+A7+100        9.8-A8*0.000913/300     +$B$2*B8

   |                   |                   |
  Copy                Copy                Copy
   ↓                   ↓                   ↓

+A29+100       9.8-A30*0.000913/300    +$B$2*B30
+A30+100       9.8-A31*0.000913/300    +$B$2*B31
```

This yields the following results.

C2.1

Mass= 50

g@SL= 9.8

Height	G	Weight
0	9.8	490
100	9.799695	489.9847
200	9.799391	489.9695
300	9.799087	489.9543
400	9.798782	489.9391
500	9.798478	489.9239
600	9.798174	489.9087
700	9.797869	489.8934
800	9.797565	489.8782
900	9.797261	489.8630
1000	9.796956	489.8478
1100	9.796652	489.8326
1200	9.796348	489.8174
1300	9.796043	489.8021
1400	9.795739	489.7869
1500	9.795435	489.7717
1600	9.795130	489.7565
1700	9.794826	489.7413
1800	9.794522	489.7261
1900	9.794217	489.7108
2000	9.793913	489.6956
2100	9.793609	489.6804
2200	9.793304	489.6652
2300	9.793000	489.6500
2400	9.792696	489.6348
2500	9.792391	489.6195

CHAPTER THREE

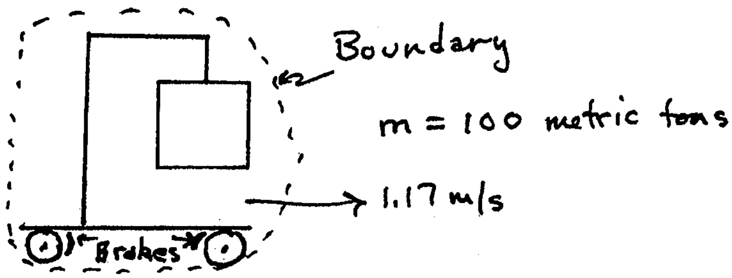
Problem 3.1

The weight of a bridge crane plus its load equals 100 metric tons (1 metric ton = 1000 kg). It is driven by a motor and travels at 1.17 m/s along the crane rails. Determine the energy that must be absorbed by the brakes in stopping the crane.

Given: A moving crane is braked to a stop.

Find: The energy absorbed by the brakes.

Sketch & Given Data:



Assumptions:
1) The crane, load and brakes are considered a closed system.
2) There is no heat transfer or work done.
3) The change in potential energy is zero.

Analysis: The first law for a closed system is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Applying assumptions 2, 3 yields

$$\Delta U = -\Delta KE = KE_1 - KE_2$$

$$V_2 = 0 \quad \therefore \quad KE_2 = 0$$

$$KE_1 = \frac{1}{2}mV_1^2 = \frac{1}{2}\frac{(100000\ \text{kg})(1.17\text{m/s})^2}{(1000\text{J/kJ})}$$

$$KE_1 = 68.4\text{kJ}$$

$$\Delta U = 68.4\text{kJ}$$

Comment: 1) If the brakes are not considered part of the system, frictional heating must be accounted for as the mechanism for transferring heat to the brakes.

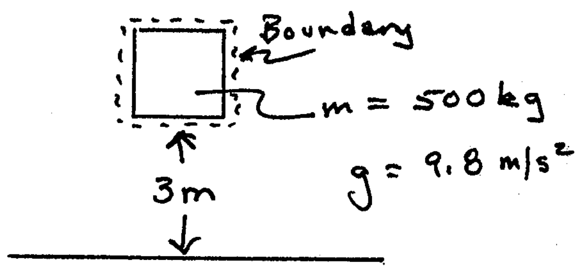
Problem 3.5

A student is watching pilings being driven into the ground. From the size of the pile driver the student calculates the mass to be 500 kg. The distance that the pile driver is raised is measured to be 3 m. Determine the potential energy of the pile drive at its greatest height (the piling is considered the datum). Find the driver velocity just prior to impact with the piling.

Given: The mass of a pile driver and the distance it falls.

Find: The pile driver's velocity just before impact.

Sketch & Given Data:



Assumptions:

1) The pile driver is a closed system.
2) There is no heat or work.
3) The change of internal energy is zero.
4) The gravitational acceleration is constant at 9.8 m/s^2.

Analysis: The first law for a closed system is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions (2) & (3), yielding:

$$\Delta KE = -\Delta PE$$

$$\frac{1}{2}m(v_2^2 - v_1^2) = -mg(z_2 - z_1) = mg(z_1 - z_2)$$

The initial velocity is zero and the final distance z_2, is zero.

$$\frac{1}{2}(v_2^2 \ m^2/s^2) = (9.8 \ m/s^2)(3-0 \ m)$$

$$v_2 = 7.67 \ m/s$$

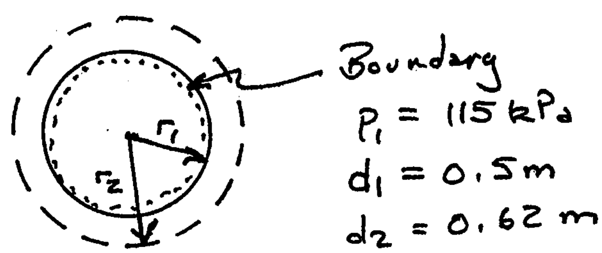
Problem 3.9

An elastic sphere of 0.5 m diameter contains a gas at 115 kPa. Heating of the sphere causes it to increase to 0.62 m and during this process the pressure is proportional to the sphere diameter. Determine the work done by the gas.

Given: The gas in a sphere is heated. During the heating process the pressure is proportional to the expanding diameter.

Find: The work done by the gas in the expansion process.

Sketch & Given Data:



Assumptions:

1) The gas in the sphere is a closed system.
2) The changes in kinetic and potential energies are zero.
3) The expansion process is a quasi-equilibrium one.

Analysis: The mechanical work for a closed system is:

$$W = \int p dV$$

Change variables from volume to radius.

$$V = \frac{4}{3}\pi r^3$$

$$dV = 4\pi r^2 dr$$

The pressure is p = 2ar; at state 1:

$$p_1 = 2ar_1$$

$$(115 \text{ kPa}) = (2)\left(a\frac{\text{kPa}}{\text{m}}\right)(0.25 \text{ m})$$

$$a = 230 \frac{\text{kPa}}{\text{m}}$$

$$W_{1-2} = \int_{0.25}^{0.31}(2ar)(4\pi r^2)dr = 8\pi a\int_{0.25}^{0.31} r^3 dr$$

$$W_{1-2} = (8\pi)\left(230\frac{\text{kPa}}{\text{m}}\right)\left[\frac{r_2^4-r_1^4}{4}\text{m}^4\right]$$

$$W_{1-2} = (2\pi)(230)\left[0.31^4-0.25^4\right] = \underline{7.7 \text{ kJ}}$$

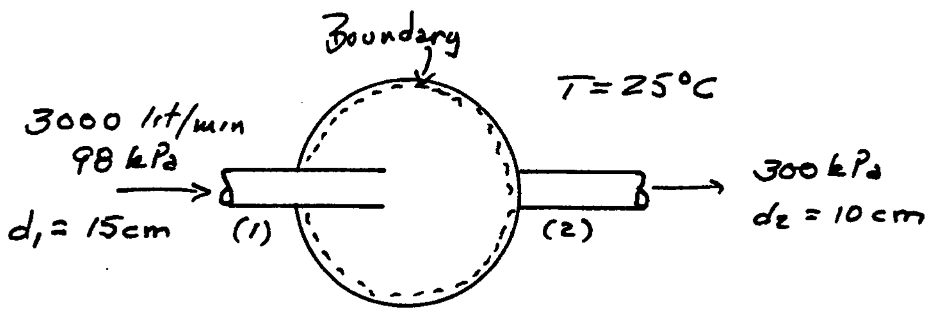
Problem 3.13

A centrifugal pump compresses 3000 liters/min of water from 98 kPa to 300 kPa. The inlet and outlet temperatures are 25°C. The inlet and discharge piping are on the same level, but the diameter of the inlet piping is 15 cm, whereas that of the discharge piping is 10 cm. Determine the pump power in kilowatts.

Given: A pump raises the pressure of a known volume flowrate. The piping diameters into and out of the pump are known.

Find: The power required for the pump.

Sketch & Given Data:



Assumptions:

1) The pump is an open, steady state system.

2) Neglect changes in potential energy.

3) Neglect changes in internal energy as the water's temperature does not change.

4) The heat transfer is zero.

5) Water is incompressible and has a density of 1000 kg/m³.

Analysis: The first law for a steady-state open system is:

$$\dot{Q} + \dot{m}[u+p/\rho+ke+pe]_1 = \dot{W} + \dot{m}[u+p/\rho+ke+pe]_2$$

It is necessary to convert from liter/min to kg/sec. There are 1000 liters per cubic meter and the density of water at 25°C is essentially 1000 kg/m³. hence, the mass flowrate is 3000 kg/min which by dividing by 60 sec/min, yields:

$$\dot{m} = 50 \text{ kg/s}$$

Apply assumptions 2, 3, and 4 to the first law, yielding:

$$\dot{m}(P_1/\rho_1+\frac{v_1^2}{2}) = \dot{W}+\dot{m}(P_2/\rho_2+\frac{v_2^2}{2})$$

Since the mass flowrate is known, as well as the diameter (hence area) and the water's density, the velocity may be calculated from the conservation of mass.

$$\dot{m} = \rho_1 A_1 v_1 = \rho_2 A_2 v_2$$

$$(50\ \mathrm{kg/s}) = (1000\ \mathrm{kg/m^3})(\frac{\pi}{A}(0.15)^2\mathrm{m^2})(v_1\ \mathrm{m/s})$$

$$v_1 = 2.83\ \mathrm{m/s}$$

$$(50\ \mathrm{kg/s}) = (1000\ \mathrm{kg/m^3})(\frac{\pi}{A}(0.10)^2\ \mathrm{m^2})(v_2\ \mathrm{m/s})$$

$$v_2 = 6.37\ \mathrm{m/s}$$

Substitute in the first law, yielding:

$$(50\ \mathrm{kg/s})\left[\left(98\frac{\mathrm{kN}}{\mathrm{m^2}}\right)\left(\frac{1}{1000}\frac{\mathrm{m^3}}{\mathrm{kg}}\right) + \frac{(2.83\ \mathrm{m/s})^2}{(2)(1000\ \mathrm{J/kJ})}\right] = \dot{W} +$$

$$(50\ \mathrm{kg/s})\left[\left(300\frac{\mathrm{kN}}{\mathrm{m^2}}\right)\left(\frac{1}{1000}\frac{\mathrm{m^3}}{\mathrm{kg}}\right) + \frac{(6.37\ \mathrm{m/s})^2}{(2)(1000\ \mathrm{J/kJ})}\right]$$

$$\dot{W} = -10.9\ \mathrm{kW}$$

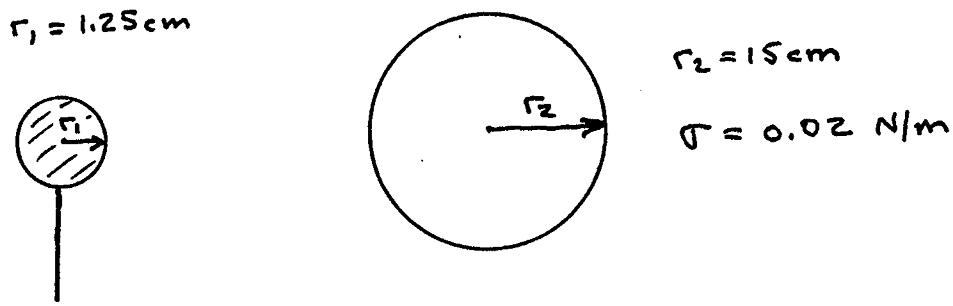
Problem 3.17

A soap bubble with a 15 cm radius is formed by blowing through a 2.5-cm-diam wire loop. Assume that all the soap film goes into making the bubble. The surface tension of the film is 0.02 N/m, find the total surface work required to make the bubble.

Given: A soap bubble is created by blowing through a wire loop. The initial wire loop and final bubble diameters are known.

Find: The surface work required.

Sketch & Given Data:



Assumptions:
1) The soap film is a closed system.
2) The surface tension is constant.

Analysis: From equation 3.20, the surface work is:

$$W = -\int_1^2 \sigma dA$$

$$A_1 = \frac{\pi}{4}d^2 = \left(\frac{\pi}{4}\right)(0.025\ \text{m})^2 = 0.0004909\ \text{m}^2$$

$$A_2 = 4\pi r^2 = 4\pi(0.15\ \text{m})^2 = 0.28274\ \text{m}^2$$

$$W = -\sigma(A_2 - A_1) = -(0.02\frac{\text{N}}{\text{m}})(0.28274 - 0.00049\ \text{m}^2)$$

$$W = -0.0056\ \text{J}$$

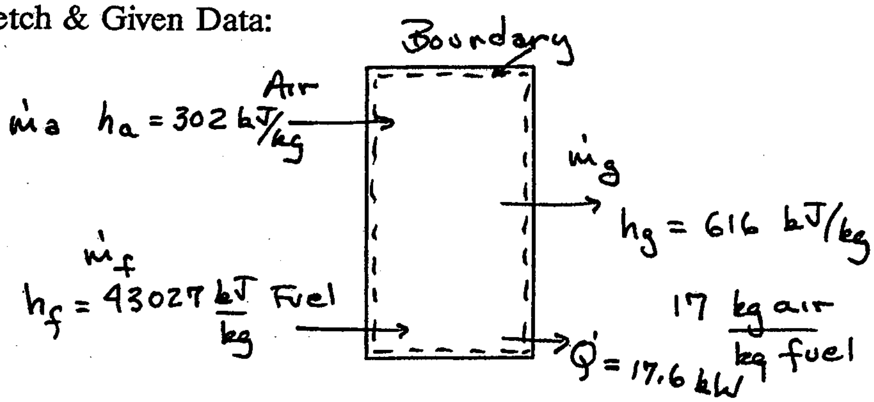
Problem 3.23

Air and fuel enter a furnace used for home heating. The air has an enthalpy of 302 kJ/kg and the fuel an enthalpy of 43 027 kJ/kg. The gases leaving the furnace have an enthalpy of 616 kJ/kg. There are 17 kg air/kg fuel. Water circulates through the furnace wall receiving heat. The house requires 17.6 kW of heat. What is the fuel consumption per day?

Given: A furnace receives air and fuel, combustion occurs, with heat being used for home heating and combustion gases leave the furnace.

Find: The daily fuel consumption necessary to satisfy the heating requirements.

Sketch & Given Data:



Assumptions:

1) The furnace is steady-state open system.

2) Neglect changes in kinetic and potential energies.

3) The work is zero.

Analysis: The first law for the furnace with two fluids entering and one leaving is

$$\dot{Q} + \dot{m}_a(h+ke+pe)_a + \dot{m}_f(h+ke+pe)_f = \dot{W} + \dot{m}_g(h+ke+pe)_g$$

Apply assumptions 2 & 3, yielding

$$\dot{Q} + \dot{m}_a h_a + \dot{m}_f h_f = \dot{m}_g h_g$$

From the conservation of mass, $\dot{m}_g = \dot{m}_a + \dot{m}_f$

$$\dot{Q} + \dot{m}_a h_a + \dot{m}_f h_f = (\dot{m}_a + \dot{m}_f) h_g$$

Divide the equation by $\dot{m}_f$

$$\frac{\dot{Q}}{\dot{m}_f} + \frac{\dot{m}_a}{\dot{m}_f}h_a + h_f = \left(\frac{\dot{m}_a}{\dot{m}_f}+1\right)h_g$$

Substitute in known values:

$$\frac{-17.6\text{kJ/s}}{(\dot{m}_f\ \text{kg fuel/s})} + \left(17\frac{\text{kg air}}{\text{kg fuel}}\right)\left(302\frac{\text{kJ}}{\text{kg air}}\right) + \left(43027\frac{\text{kJ}}{\text{kg fuel}}\right)$$

$$= \left(18\frac{\text{kg gas}}{\text{kg fuel}}\right)\left(616\frac{\text{kJ}}{\text{kg gas}}\right)$$

$\dot{m}_f$ = 0.0004747 kg/s = <u>41 kg/day</u>

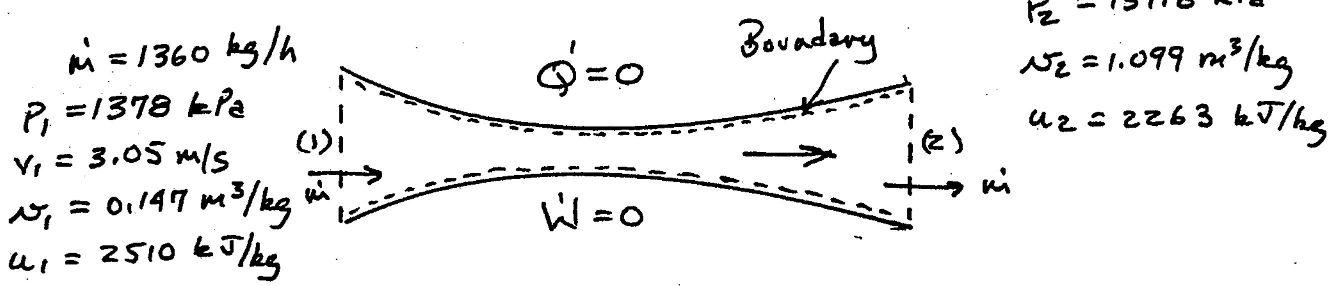
Problem 3.27

Steam with a flowrate of 1360 kg/h enters an adiabatic nozzle at 1378 kPa, 3.05 m/s, with a specific volume of 0.147 m^3/kg, and with a specific internal energy of 2510 kJ/kg. The exit conditions are p = 137.8 kPa, specific volume = 1.099 m^3/kg, and internal energy = 2263 kJ/kg. Determine the exit velocity.

Given; Steam flows steadily through an adiabatic nozzle from a known inlet state to a known exit state.

Find: The exit steam velocity from the nozzle.

Sketch & Given Data:



Assumptions: 1) The nozzle is an open steady state system.

2) Neglect changes in potential energy.

3) Heat and work are zero.

Analysis: The first law for a steady state open system is:

$$\dot{Q} + \dot{m}(u+pv+ke+pe)_1 = \dot{W} + \dot{m}(u+pv+ke+pe)_2$$

Apply assumptions 2 & 3, yielding:

$$\dot{m}(u+pv+ke)_1 = \dot{m}(u+pv+ke)_2$$

Divide by the mass flowrate and substitute in data values:

$$\left(2510\frac{kJ}{kg}\right) + \left(1378\frac{kN}{m^2}\right)\left(0.147\frac{m^3}{kg}\right) + \frac{(3.05\ m/s)^2}{2(1000\ J/kJ)}$$

$$= \left(2263\frac{kJ}{kg}\right) + \left(137.8\frac{kN}{m^2}\right)\left(1.099\frac{m^3}{kg}\right) + \frac{(v_2\ m/s)^2}{2(1000\ J/kJ)}$$

v_2 = <u>772.2 m/s</u>

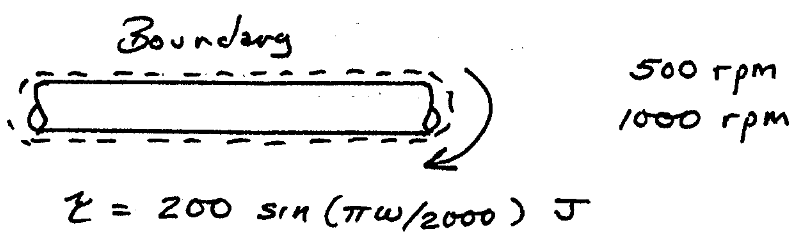
Problem 3.31

The torque of an engine is found to be, $\tau = 200 \sin(\pi\omega/2000)$ J, when ω varies between 500 and 1000 rpm and $\pi\omega/2000$ is expressed in degrees. Determine the power at these two rpm's.

Given: The variation of torque with engine speed.

Find: The power produced at two different engine rpms.

Sketch & Given Data:



Assumptions:
1) The shaft rpm and torque are constant for any given rpm.
2) The engine shaft is a closed system.

Analysis: From the expression for power from a rotating shaft

$$\dot{W} = \tau\omega$$

we can determine the power for the two cases in this problem.

At 500 rpm:

$$\omega = \left(\frac{500}{60}\frac{\text{rev}}{\text{s}}\right)\left(2\pi\frac{\text{rad}}{\text{rev}}\right) = 52.36 \text{ rad/sec}$$

$$\tau = 200 \sin\left(\frac{52.36*\pi*360}{2000}\right) = 98.8 \text{ J}$$

$$\dot{W} = \left(98.8\frac{\text{J}}{\text{rad}}\right)\left(52.36\frac{\text{rad}}{\text{sec}}\right) = \underline{5.17 \text{ kW}}$$

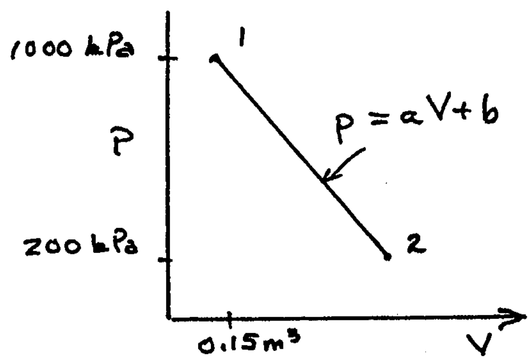
Problem 3.35

A gas expands in a piston from an initial pressure of 1000 kPa and an initial volume of 0.15 m^3 to a final pressure of 200 kPa while following the process described by $p = aV + b$ where $a = 1000$ kPa/m^3 and b is a constant. Calculate the work performed.

Given: Gas in a piston/cylinder expands from an initial state to a final state.

Find: The work done by the gas in the expansion process.

Sketch & Given Data:



a = 1000 kPa/m³

Assumptions:
1) The gas is a closed system.
2) The expansion is a quasi-equilibrium one.

Analysis: The work is found by integrating

$$W = \int_1^2 p dV = \int_1^2 (1000V + b) dV = \left| \frac{1000V^2}{2} + bV \right|_1^2$$

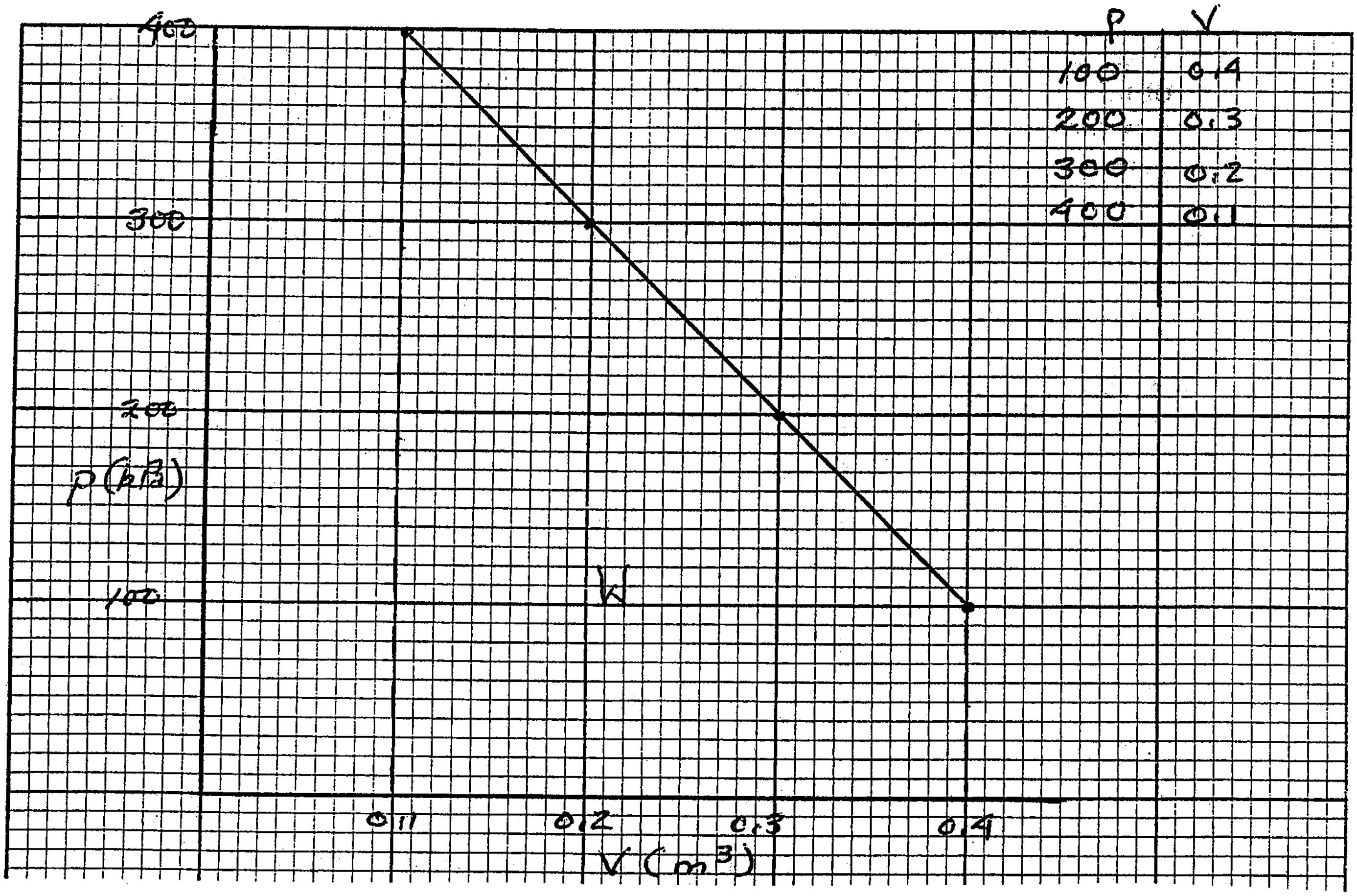
We need to find b. Substitute into the equation for pressure at the initial state.

$$p_1 = aV_1 + b = 1000 \text{ kPa} = \left(1000 \frac{\text{kPa}}{\text{m}^3}\right)(0.15\text{m}^3) + b \text{ kPa}$$

$$b = 850 \text{ kPa}$$

The final volume may be determined:

The curve may be plotted on rectangular graph paper.



The area under the curve is:

$$A = W = -\frac{1}{2}(0.4-0.1\ \text{m}^3)\left(300\frac{\text{kN}}{\text{m}^2}\right) - (0.4-0.1\ \text{m}^3)\left(100\frac{\text{kN}}{\text{m}^2}\right)$$

$$A = W = -75\ \text{kJ}$$

where the minus sign was used because the work is into the gas.

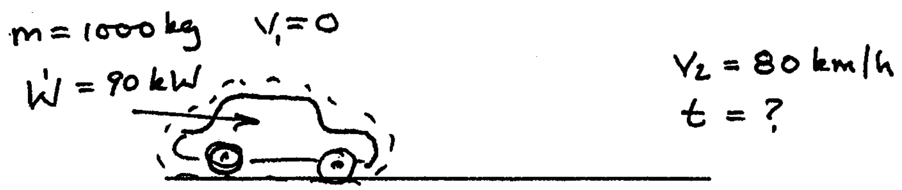
Problem 3.39

Determine the time to accelerate a 1000 kg automobile from rest to 80 km/h if it has an engine rated at 90 kW.

Given: An automobile is accelerated from rest to a final state with an engine of known power.

Find: The time required to accelerate the automobile.

Sketch & Given Data:



Assumptions:

1) The automobile is a closed system.
2) There is no heat transfer or change of internal or potential energies.

Analysis: To determine the time we must first find the work required to move the car from state 1 to state 2 and then use the relationship between work and power to determine the time. For a closed system, the first law is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Applying assumption 2, this reduces to:

$$-W = \Delta KE = \frac{m(v_2^2 - v_1^2)}{2}$$

$$-W = \frac{(1000\text{kg})}{2}\frac{(22.22^2 - 0\ \text{m}^2/\text{s}^2)}{(1000\ \text{J/kJ})} = 246.9\ \text{kJ}$$

$$W = -246.9\ \text{kJ}$$

The relationship between power and work is:

$$\dot{W} = \frac{W}{t}$$

Problem 3.43

Fill in the missing data for a closed system changing from state 1 to state 2 in the table below.

Q(kJ)	W(kJ)	E_1(kJ)	E_2(kJ)	ΔE(kJ)
-20	-5	-25	10	-15
23	-7	7	37	30
36	15	18	39	21
25	10	15	30	15
40	24	19	35	16

Analysis: Apply the first law for a closed system to the values in each row.

$$Q = E_2 - E_1 + W$$

and $\Delta E = E_2 - E_1$

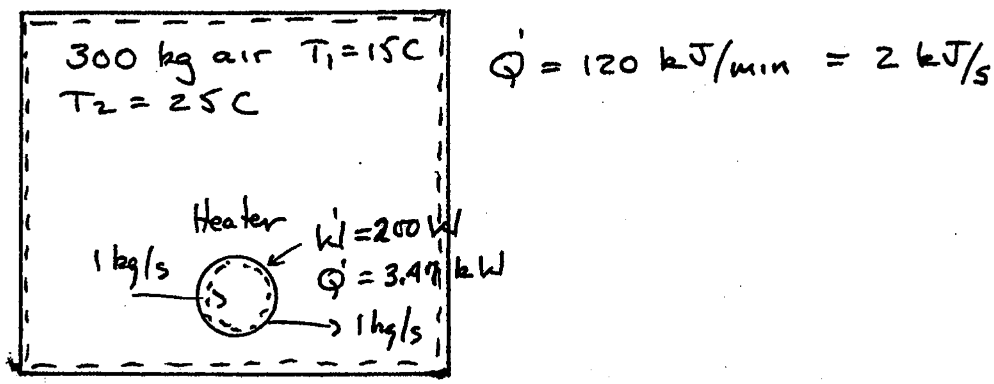
Problem 3.47

The heater in problem 3.46 is now located in a non-adiabatic room of the same size. The heat loss from the room is found to be 120 kJ/min. Determine the time for the room to reach 25 C from the initial 15 C.

Given: The heater in problem 3.46 is located in a non-adiabatic room.

Find: The time required to heat the room to the final temperature.

Sketch & Given Data:



Assumptions:

1) The air in the room is a closed system.
2) Neglect changes in kinetic and potential energies.
3) The fan/heater is an open system.

Analysis: From problem 3.46 we know that the air needs to receive 3300 kJ to reach 25 C. The fan/heater provides 3.67 kW of heat to air and the air loses 2 kW to the surroundings. Thus, the net heat flow to the air is 3.67 - 2.0 = 1.67 kW for the air:

$$\dot{Q}t = Q$$

$$\left(1.67\frac{\text{kJ}}{\text{s}}\right)(t\ \text{s}) = 3300\ \text{kJ}$$

$$t = 1976\ \text{s} = 32.9\ \text{minutes}$$

To achieve the amount of heat entering the air in 15 minutes requires an energy flux of:

$$\dot{Q} = \frac{3300\text{kJ}}{(15\text{min})(60\ \text{s/min})} = 3.67\ \text{kW}$$

The reason energy flux is used is because the fan provides some frictional heating to the air. The first law for the heater, an open system, is (applying assumption 3):

$$\dot{Q} + \dot{m}(h + \cancel{ke} + \cancel{pe})_1 = \dot{W} + \dot{m}(h + \cancel{ke} + \cancel{pe})_2$$

$$\dot{Q} + \dot{m}(h_1) = \dot{W} + \dot{m}(h_2)$$

Also,

$$\dot{Q} - \dot{W} = 3.67\ \text{kW}$$

$$\dot{Q} - (-0.2\ \text{kW}) = 3.67\ \text{kW}$$

$$\dot{Q} = 3.47\ \text{kW}$$

Comments: 1) In the problem we do not know the temperature of the air leaving the heater; however, it is not at 25 C. The problem requires that we convert the rate of heat and work transfer into a total quantity over a given time period.

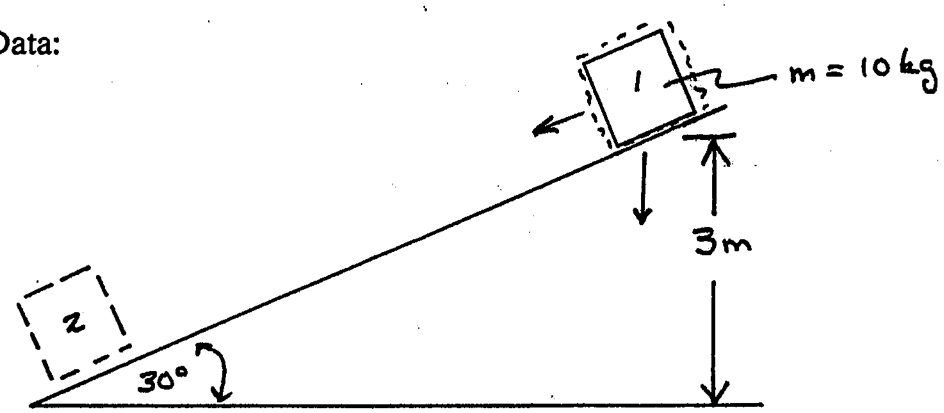
Problem 3.51

A 10 kg mass slides down a ramp inclined at 30 degrees from the horizontal a total vertical distance of 3 m. Determine the velocity of mass when it reaches the bottom, neglecting friction and air resistance.

Given: A block slides down a frictionless inclined ramp.

Find: The velocity of the block when it reaches the bottom.

Sketch & Given Data:



Assumptions:
1) The block is a closed system.
2) The work, heat and change of internal energy are zero.

Analysis: In the first law for the block between states (1) and (2) for a closed system is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$0 = \Delta KE + \Delta PE$$

$$\Delta KE = -\Delta PE$$

$$\frac{m}{2}(v_2^2 - v_1^2) = -mg(z_2 - z_1)$$

The initial velocity is zero.

$$\frac{v_2^2}{2} = +g(z_1 - z_2)$$

$$\left(v_2^2\ m^2/s^2\right) = (2)(9.8m/s^2)(3m)$$

$$v_2 = 7.67\ m/s$$

Problem 3.55

The following table illustrates the variation of pressure and volume in the cylinder of an internal combustion engine during the expansion process.

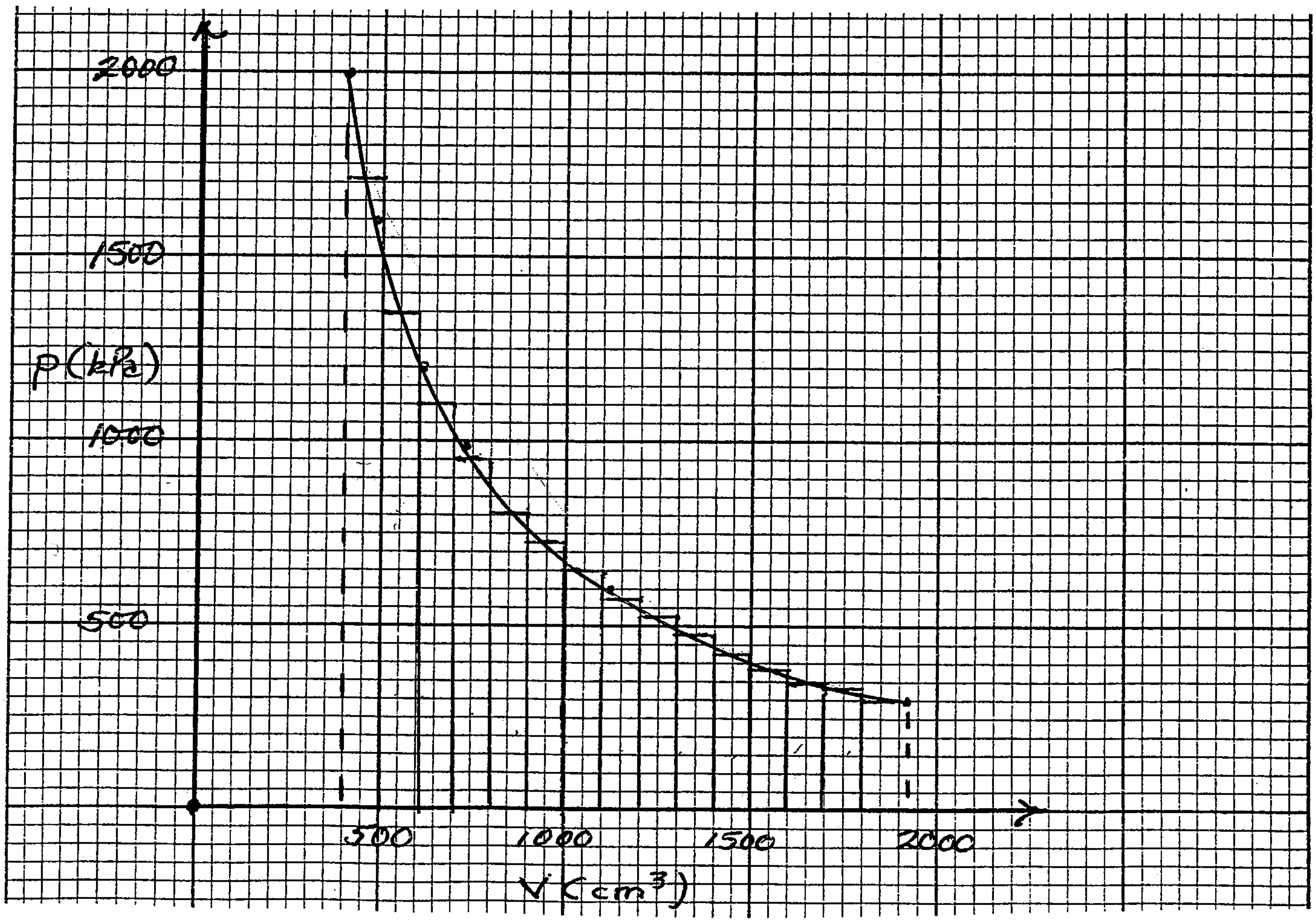
Data Point	Pressure (kPa)	Volume (cm^3)
1	2000	400
2	1600	490
3	1200	620
4	990	730
5	600	1120
6	300	1930

Plot the data on a p-V and determine the work done in kJ. Is this exact or an estimate? Why?

Given: A table of pressure and volume data representing the variation of p vs. V during the expansion stroke of an automotive engine.

Find: A plot of the data and a determination of the work done from the data.

Sketch & Given Data:



Assumptions:

1) The gas in cylinder is a closed system.

2) Neglect kinetic and potential energy changes.

Analysis: The work is estimated by determining the area under the curve connecting the data points. This is an estimate in that we do not have a continuous function describing pressure versus volume, nor do we know if the process is a quasi-equilibrium one.

Finding the area under curve may proceed in several ways: 1) Use rectangles (as illustrated) to determine the area; 2) determine the "best fit" equation connecting the points and integrate that.

The area is found by summing $p\Delta V$ for each rectangle. $\Delta V = 100\ cm^3 = 0.0001\ m^3$.

$W \approx \Sigma p \Delta V$ and for $\Delta V = 0.0001$

$$W = \Delta V \Sigma p_i$$

$$= (0.01)[1710 + 1350 + 1100 + 950 + 800 + 730 + 650 + 575 + 525 + 475 + 425 + 380 + 350 + 330 + 300]$$

$$W = (0.0001\ m^3)(10650\ kN/m^2)$$

$$W = 1.065\ kJ$$

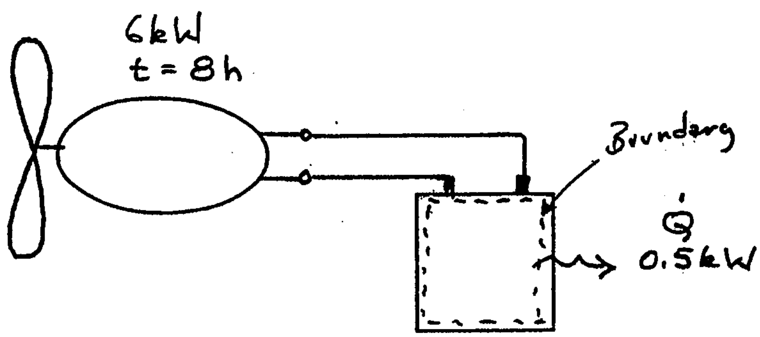
Problem 3.59

A windmill produces on average 6 kW of electrical power over an eight hour period. The electricity is used to charge storage batteries. In the charging process the batteries increase in temperature causing them to lose heat to the surroundings at a rate of 0.5 kW. Determine the total energy stored in the batteries during this 8 hour period.

Given: Batteries are charged at a give rate over an eight hour period. During the charging heat is lost to the surroundings at a known rate.

Find: The total energy stored in the batteries.

Sketch & Given Data:



Assumptions: 1) Rates of charging and heat loss are constant over the eight hour period.

Analysis: An energy balance on the batteries indicates that 6 kW are entering and 0.5 kW are leaving at any moment in time. Thus a net instantaneous energy gain of 5.5 kW occurs.

$$E = \left(5.5\frac{\text{kJ}}{\text{s}}\right)(8\ \text{h})\left(3600\frac{\text{s}}{\text{h}}\right)$$

$$E = 158400 = \underline{158.4\ \text{MJ}}$$

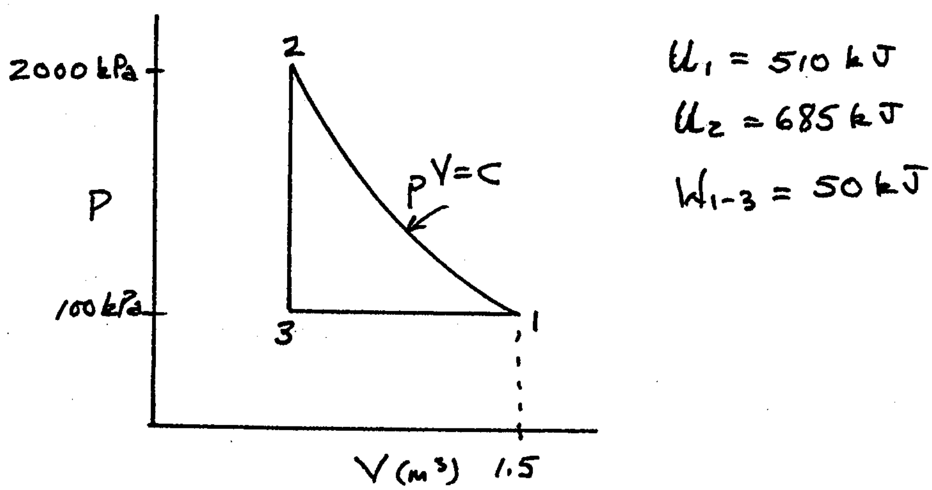
Problem 3.63

A closed system containing a gas undergoes a cycle composed of three processes. The system's initial state is at 100 kPa, 1.5m^3, and an internal energy of 510 kJ. The gas is compressed according to pV = C until the pressure is 2000 kPa and the internal energy is 685 kJ. In the final process returning the system to the initial state the work is 50 kJ. Determine the heat transfer for first and last processes.

Given: A gas undergoes a 3-process cycle. The processes are given as well as information about the heat and work for the processes.

Find: The heat transfer in process 1-2 and process 3-1.

Sketch & Given Data:



Assumptions: 1) The system is closed.

2) Neglect changes in kinetic and potential energies.

Analysis: Calculate the heat transfer for process 1-2. From the first law:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$Q = \Delta U + W$$

$$W_{1\text{-}2} = \int_1^2 p dV = \int_1^2 c\frac{dV}{V} = p_1V_1\ln\left(\frac{V_2}{V_1}\right) = p_1V_1\ln\left(\frac{p_1}{p_2}\right)$$

$$W_{1-2} = \left(100\frac{kN}{m^2}\right)(1.5m^3)\ln\left(\frac{100}{2000}\right) = -449.4\ kJ$$

$\Delta U = (685-510\ kJ) = 175\ kJ$

$Q_{1-2} = 175 - 449.4 = \underline{-274.4\ kJ}$

For the process 2-3, $Q_{2-3} = -150kJ$ and $W_{2-3} = 0$.

For the process 3-1, $W_{3-1} = 50kJ$ and $Q_{3-1} = ?$

For any cycle, $\Sigma Q = \Sigma W$

$$Q_{1-2} + Q_{2-3} + Q_{3-1} = W_{1-2} + W_{2-3} + W_{3-1}$$

$$-274.4 - 150 + Q_{3-1} = -449.4 + 0 + 50$$

$$Q_{3-1} = \underline{+25\ kJ}$$

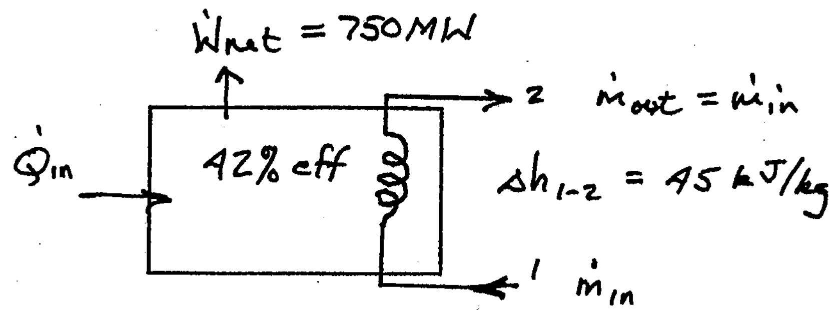
Problem 3.67

A power plant produces 750 MW of electric power while operating with an efficiency of 42%. The heat rejected from the cycle goes into cooling water supplied from an adjacent river. The water's enthalpy increases by 45 kJ/kg as it receives the heat rejected. Determine the mass flowrate of water required.

Given: A power plant produces a given amount of power at a known efficiency. In doing so the heat flow from the plant enters a river.

Find: The flowrate of water required for cooling.

Sketch & Given Data:



Assumptions:

1) The cycle is a closed system.
2) Neglect changes in kinetic and potential energy of the cooling water and there is no work done in the cooling process.

Analysis: For a power producing cycle,

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

$$0.42 = \frac{750}{\dot{Q}_{in}} \qquad \dot{Q}_{in} = 1785.7 \text{ MW}$$

For any cycle:

$$\dot{W}_{net} = \dot{Q}_{in} + \dot{Q}_{out}$$

$$750 \text{ MW} = 1785.7 + \dot{Q}_{out} \text{ MW}$$

$$\dot{Q}_{out} = -1035.7 \text{ MW}$$

From a first law analysis on the cooling water (where the heat is entering the cooling water, hence positive from the water's view)

$$\dot{Q} + \dot{m}(h+ke+pe)_1 = \dot{W} + \dot{m}(h+ke+pe)_2$$

Apply assumption (2)

$$\dot{Q} + \dot{m}h_1 = \dot{m}h_2$$

$$(1035700 \text{ kW}) = (\dot{m} \text{ kg/s})\left(45\frac{\text{kJ}}{\text{kg}}\right)$$

$$\dot{m}_{\frac{\text{cooling}}{\text{water}}} = 23{,}016 \text{ kg/s}$$

Chapter III - CONSERVATION OF MASS AND ENERGY

Problems (English Units)

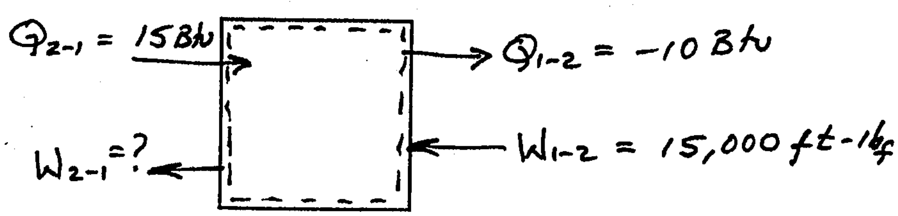
Problem *3.1

A system undergoes a cycle where 10 Btu of heat are removed and 15,000 ft-lbf of work are done by the system during the first process. In the second process 15 Btu of heat are added. What is the work necessary to complete the cycle?

Given: A system undergoes a cycle with heat and some work interactions denoted.

Find: The work necessary to complete the cycle.

Sketch & Given Data:



Assumptions: 1) System is a closed system.

Analysis: For any cycle,

$$\Sigma W = \Sigma Q$$

Convert 15,000 ft-lb_f into Btu:

$$\frac{15000}{778.16} = 19.28 \text{ Btu}$$

$$+19.28 + W_{2\text{-}1} = -10 + 15$$

$$W_{2\text{-}1} = -14.48 \text{ Btu}$$

The negative sign indicates work into the system.

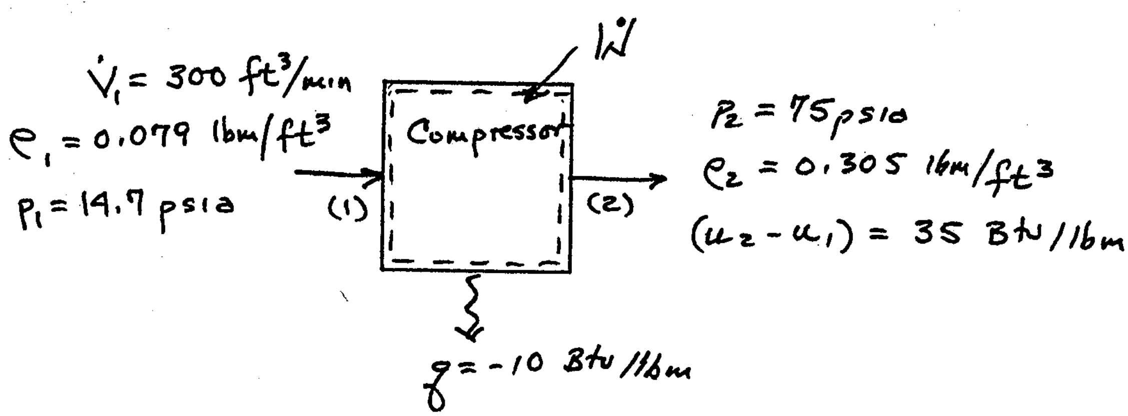
Problem *3.5

An air compressor handles 300 ft^3/min of air with a density of 0.079 lbm/ft^3 and a pressure of 14.7 psia, and it discharges at a pressure of 75 psia with a density of 0.305 lbm/ft^3. The change in specific internal energy across the compressor is 35 Btu/lbm, and the heat loss by cooling is 10 Btu/lbm. Neglecting changes in kinetic and potential energies, find the power in Btu per hour, horsepower, and kilowatts.

Given: A compressor receives a steady flow of air through it. The inlet and discharge are given.

Find: The power required.

Sketch & Given Data:



Assumptions: 1) The compressor is a steady-state open system.

2) Neglect kinetic and potential energies.

Analysis: The first law for a steady-state open system is:

$$\dot{Q} + \dot{m}(u+p/\rho+ke+pe)_1 = \dot{W} + \dot{m}(u+p/\rho+ke+pe)_2$$

Apply assumption (2):

$$\dot{Q} + \dot{m}(u+p/\rho)_1 = \dot{W} + \dot{m}(u+p/\rho)_2$$

$$\dot{Q} + \dot{m}p_1/\rho_1 = \dot{W} + \dot{m}[(u_2-u_1)+p_2/\rho_2]$$

The mass flowrate is not given, so it must be found from volume flowrate.

$$\dot{m} = \rho_1 \dot{V}_1 = \left(0.079\frac{\text{lbm}}{\text{ft}^3}\right)\left(300\frac{\text{ft}^3}{\text{min}}\right) = 23.7\frac{\text{lbm}}{\text{min}}$$

The heat flux, is $\dot{Q} = \dot{m}q$. Substitute data in the first law equation.

$$\left(-10\frac{\text{Btu}}{\text{lbm}}\right)\left(23.7\frac{\text{lbm}}{\text{min}}\right) + \left(23.7\frac{\text{lbm}}{\text{min}}\right)\left(14.7\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(\frac{1\ \ \text{ft}^3}{0.079\,\text{lbm}}\right)\left(\frac{1\ \text{Btu}}{778.16\ \text{ft-lb}_f}\right) =$$

$$\dot{W} + \left(23.7\frac{\text{lbm}}{\text{min}}\right)\left[\left(89.7\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)\left(\frac{1\text{ft}^3}{0.305\ \text{lbm}}\right)\left(\frac{1\text{Btu}}{778.16\ \text{ft-lb}_f}\right) + (35\ \text{Btu/lbm})\right]$$

$$\dot{W} = -1540\frac{\text{Btu}}{\text{min}} = -92{,}415\frac{\text{Btu}}{\text{hr}} = -36.3\ \text{hp} = -27.1\ \text{kW}$$

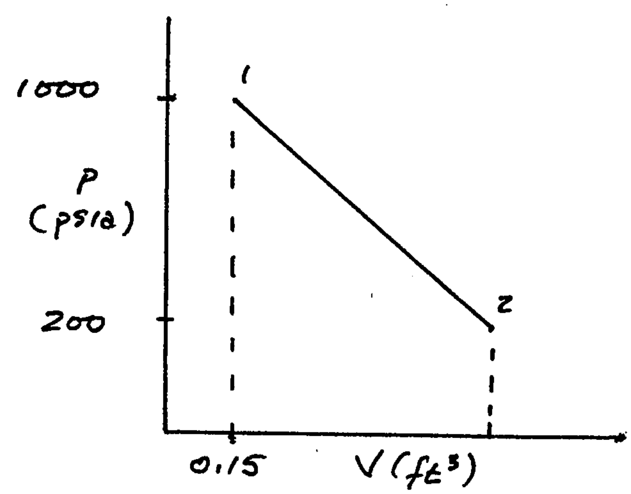
Problem *3.9

A gas expands in a piston from an initial pressure of 1000 psia and an initial volume of 0.15 ft^3 to a final pressure of 200 psia while following the process described by $p = aV + b$ where $a = 1000$ psia/ft^3 and b is a constant. Calculate the work performed.

Given: Gas in a piston/cylinder expands from an initial state to a final state.

Find: The work done by the gas in the expansion process.

Sketch & Given Data:



Assumptions:
1) The gas is a closed system.
2) The expansion is a quasi-equilibrium one.

Analysis: The work is found by integrating:

$$W = \int_1^2 pdV = \int_1^2 (1000V+b)dV = \left|\frac{1000V^2}{2}+bV\right|_1^2$$

We need to find b. Substitute into the equation for pressure at the initial state.

$$p_1 = aV_1 + b = \left(1000\frac{psia}{ft^3}\right)(0.15\ ft^3) + b = 1000psia$$
$$b = 850\ psia$$

The final volume may be determined:

$$p_2 = aV_2 + b = (200 \text{ psia}) = \left(1000\frac{\text{psia}}{\text{ft}^3}\right)(V_2 \text{ ft}^3) + (850 \text{ psia})$$

$$V_2 = 0.65 \text{ ft}^3$$

The integral may now be evaluated.

$$W = \left(500\frac{\text{lb}_f/\text{in}^2}{\text{ft}^3}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)(0.65^2 - 0.15^2 \text{ ft}^6)$$

$$+ \left(850\frac{\text{lb}_f}{\text{in}^2}\right)\left(144\frac{\text{in}^2}{\text{ft}^2}\right)(0.65 - 0.15 \text{ ft}^3)$$

$$W = \underline{90{,}000 \text{ ft-lb}_f}$$

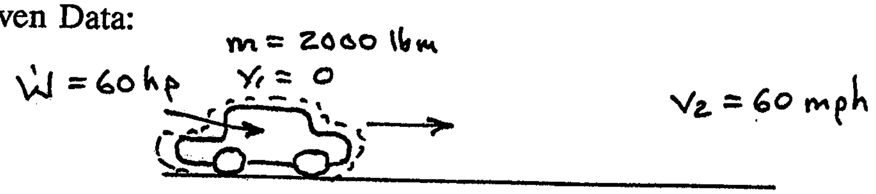
Problem *3.13

Determine the time to accelerate a one ton automobile from rest to 60 mph if it has an engine rated at 60 horsepower.

Given: An automobile is accelerated from rest to a final state with an engine of known power.

Find: The time required to accelerate the automobile.

Sketch & Given Data:



Assumptions:

1) The automobile is a closed system.

2) There is no heat transfer or change of internal or potential energies.

Analysis: To determine the time we must first find the work required to move the car from state 1 to state 2 and then use the relationship between work and power to determine the time. For a closed system, the first law is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Applying assumption 2, yields:

$$-W = \Delta KE = \frac{1}{2}\frac{m}{g_c}(v_2^2 - v_1^2) = \frac{1}{2}\frac{(2000\ \text{lbm})}{\left(32.174\frac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)}(88^2 - 0\ \text{ft}^2/\text{sec}^2) = 240691\ \text{ft-lb}_f$$

The relationship between power and work is $\dot{W} = \frac{W}{t}$

Ignoring the sign on the work and power yields:

$$(60\text{hp})\left(550\frac{\text{ft-lb}_f}{\text{sec-hp}}\right) = \frac{(240691\text{ft-lb}_f)}{(t\ \text{sec})}$$

$$t = \underline{7.29\ \text{seconds}}$$

Problem *3.17

Fill in the missing data for a closed system changing from state 1 to state 2 in the table below.

Q(Btu)	W(Btu)	E_1(Btu)	E_2(Btu)	ΔE(Btu)
5	20	25	10	-15
30	-7	37	74	37
15	-6	18	39	21
25	10	0	15	15
40	24	19	35	16

Analysis: Apply the first law for a closed system to the values in each row.

$$Q = E_2 - E_1 + W$$

and

$$\Delta E = E_2 - E_1$$

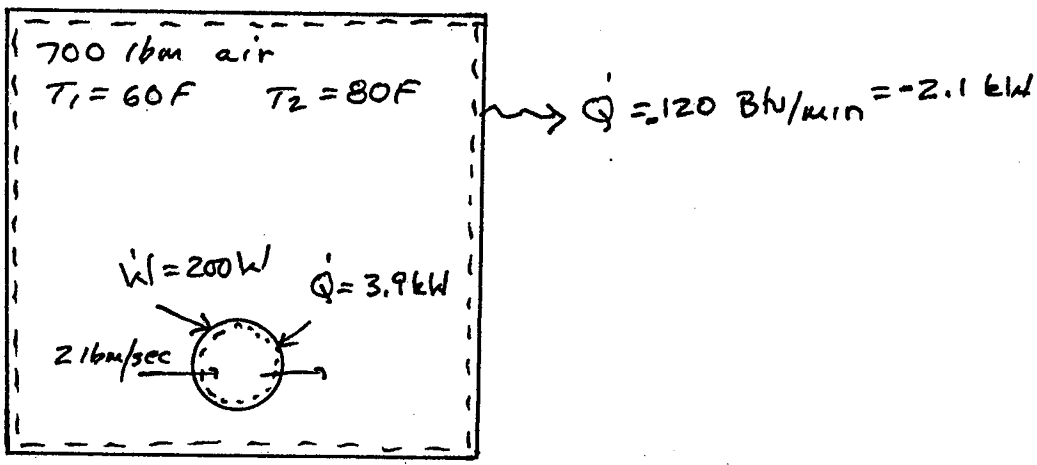
Problem *3.21

The heater in problem 3.20* is now located in a non-adiabatic room of the same size. The heat loss from the room is found to 120 Btu/min. Determine the time for the room to reach 80 F from the initial 60 F.

Given: The heater in problem 3.20* is located in a non-adiabatic room.

Find: The time required to heat room to the final temperature.

Sketch & Given Data:



Assumptions:
1) The air in the room is a closed system.
2) Neglect changes in kinetic and potential energies.
3) The fan/heater is an open system.

Analysis: From problem 3.20* we know that the air needs to receive 3500 Btu to reach 80 F. The fan/heater provides 4.1 kW of heat to air and the air loses 2.1 kW to the surroundings. Thus, the net heat flow to the air is 4.1 - 2.10 = 2.0 kW. For the air

$$\dot{Q}\, t = Q$$

$$\frac{(2.0\text{kW})(t\ \text{sec})}{(1.055\text{kW/Btu/sec})} = (3500\text{Btu})$$

$$t = 1846.2\ \text{sec} = \underline{30.8\ \text{minutes}}$$

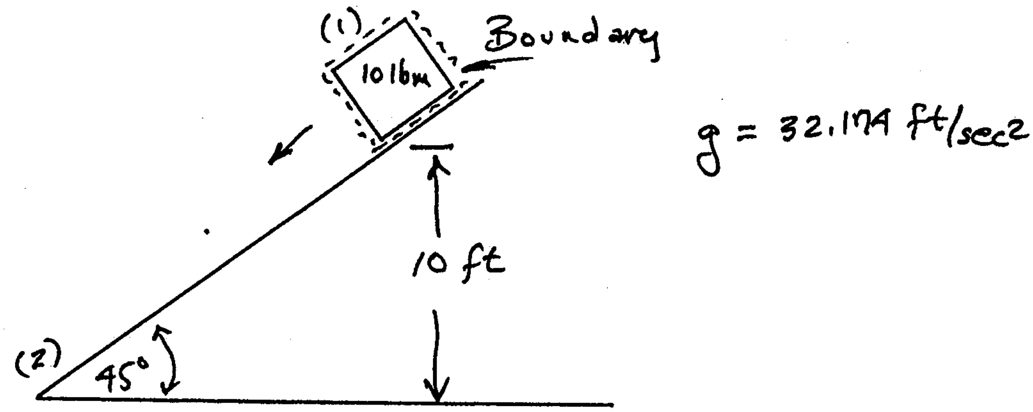
Problem *3.25

A 10 pound mass slides down a ramp inclined at 45 degrees from the horizontal a total vertical distance of 10 feet. Determine the velocity of mass when it reaches the bottom, neglecting friction and air resistance.

Given: A block slides down a frictionless inclined ramp.

Find: The velocity of the block when it reaches the bottom.

Sketch & Given Data:



Assumptions:
1) The block is a closed system.
2) The work, heat and change of internal energy is zero.

Analysis: In the first law for the block between states (1) and (2) for a closed system is:

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$0 = \Delta KE + \Delta PE \therefore \Delta KE = -\Delta PE$$

$$\frac{m}{2g_c}(v_2^2 - v_1^2) = \frac{-mg}{g_c}(z_2 - z_1)$$

The initial velocity is zero.

$$\frac{v_2^2}{2} = g(z_1 - z_2)$$

$$\frac{1}{2}(v_2 \text{ ft/sec})^2 = (32.174 \text{ ft/sec}^2)(10 - 0\text{ft})$$

$$v_2 = 25.4 \text{ ft/sec}$$

Problem *3.29

The following table illustrates the variation of pressure and volume in the cylinder of an internal combustion engine during the expansion process.

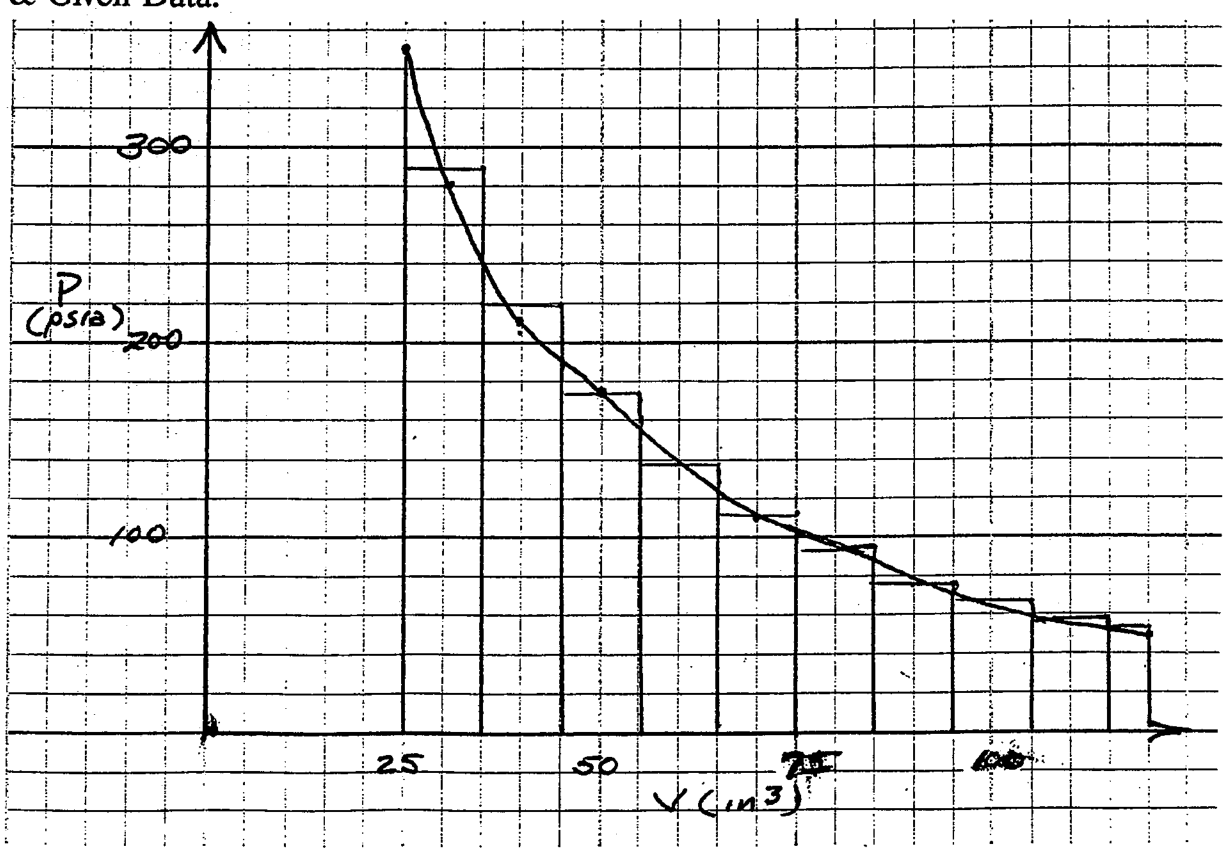
Data Point	Pressure (psia)	Volume (in^3)
1	350	25
2	280	31
3	210	39
4	175	50
5	110	70
6	50	120

Plot the data on a p-V and determine the work done in ft-lbf. Is this exact or an estimate? Why?

Given: A table of pressure and volume data representing the variation of p vs. V during the expansion stroke of an automotive engine.

Find: A plot of the data and a determination of the work done from the data.

Sketch & Given Data:



Assumptions: 1) The gas in cylinder is a closed system.

2) Neglect kinetic and potential energy changes.

Analysis: The work is estimated by determining the area under the curve connecting the data points. This is an estimate in that we do not have a continuous function describing pressure versus volume, nor do we know if the process is a quasi-equilibrium one.

Finding the area under curve may proceed in several ways: 1) Use rectangles (as illustrated) to determine the area; 2)determine the "best fit" equation connecting the points and integrate that.

The area is found by summing p Δ V for each rectangle.

$\Delta V = 10\ in^3 = 0.005787\ ft^3$.

$$W = \Delta V \int p_i = (0.005787\ ft^3)\left[\begin{pmatrix} 290+220+170+140+110 \\ +95+75+68+58+1/2(55) \end{pmatrix} \frac{16_f}{in^2}\right]$$

$$W = (0.005787\ ft^3)\left(1253.5\frac{lb_f}{in^2}\right)\left(144\frac{in^2}{ft^2}\right)$$

$$W = 1044.6\ ft\text{-}lb_f$$

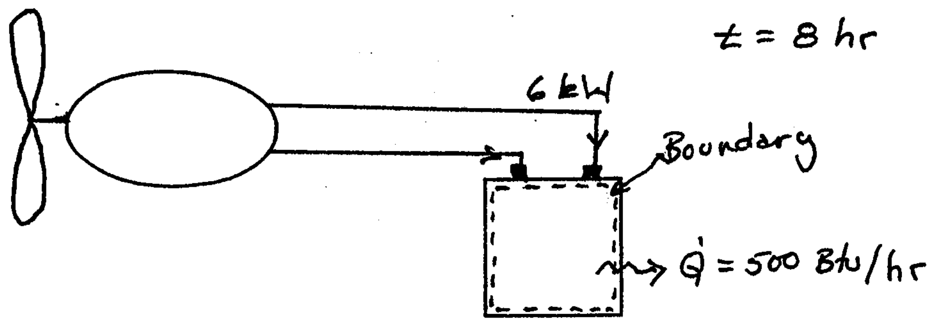
Problem *3.33

A windmill produces on average 6 kW of electrical power over an eight hour period. The electricity is used to charge storage batteries. In the charging process the batteries increase in temperature causing them to lose heat to the surroundings at a rate of 500 Btu/hr. Determine the total energy stored in the batteries during this 8 hour period.

Given: Batteries are charged at a give rate over an tx eight hour period. During the charging heat is lost to the surroundings at a known rate.

Find: The total energy stored in the batteries.

Sketch & Given Data:



Assumptions: 1) Rates of charging and heat loss are constant over the eight hour period.

Analysis: An energy balance on the batteries indicates that 6 kW are entering and 500 Btu/hr are leaving at any moment in time. Thus a net instantaneous energy gain of 5.85 kW occurs.

$$E = \left(5.85\frac{\text{kJ}}{\text{s}}\right)(8\text{h})\left(3600\frac{\text{s}}{\text{h}}\right)$$

E = <u>168480 kJ</u>

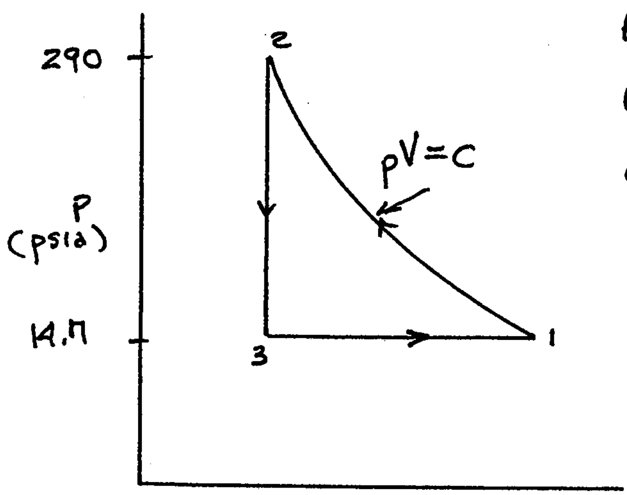
Problem *3.37

A closed system containing a gas undergoes a cycle composed of three processes. The system's initial state is at 14.7 psia, 53.0 ft^3, and an internal energy of 540 Btu. The gas is compressed according to pV = C until the pressure is 290 psia and the internal energy is 723 Btu. The next process is constant volume and the heat loss is 160 Btu. In the final process returning the system to the initial state the work is 41300 ft-lbf. Determine the heat transfer for first and last processes.

Given: A gas undergoes a 3-process cycle. The processes are given as well as information about the heat and work for the processes.

Find: The heat transfer in process 1-2 and process 3-1.

Sketch & Given Data:



$U_1 = 540$ Btu

$U_2 = 723$ Btu

$Q_{2-3} = -160$ Btu

$W_{3-1} = 41300$ ft/lbf

Assumptions:

1) The system is closed.

2) Neglect changes in kinetic and potential energies.

Analysis: Calculate the heat transfer for process 1-2. From the first law

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

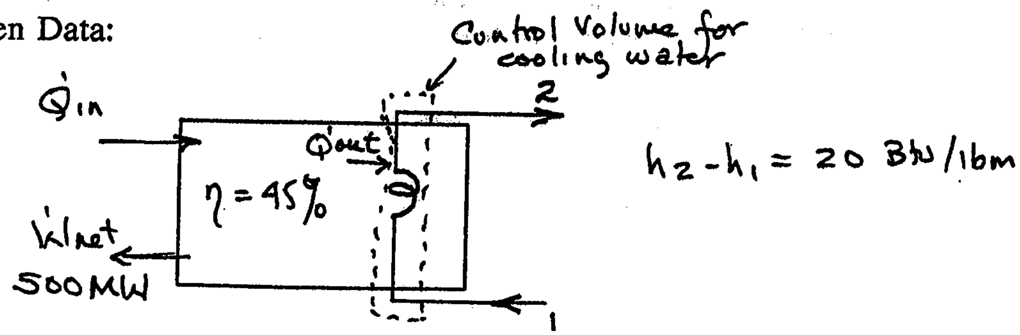
Problem *3.41

A power plant produces 500 MW of electric power while operating with an efficiency of 45%. The heat rejected from the cycle goes into cooling water supplied from an adjacent river. The water's enthalpy increases by 20 Btu/lbm as it receives the heat rejected. Determine the mass flowrate of water required.

Given: A power plant produces a given amount of power at a known efficiency. In doing so the heat flow from the plant enters a river.

Find: The flowrate of water required for cooling.

Sketch & Given Data:



Assumptions:

1) The cycle is a closed system.

2) Neglect changes in kinetic and potential energy of the cooling water and there is no work done in the cooling process.

Analysis: For a power producing cycle,

$$\eta_{Th} = \frac{\dot{W}net}{\dot{Q}in}$$

$$0.45 = \frac{500}{\dot{Q}in}$$

$$\dot{Q}in = 1111.1 \text{ MW}$$

For any cycle:

$$\dot{W}net = \dot{Q}in + \dot{Q}out$$

$$500 = 1111.1 + \dot{Q}out$$

$$\dot{Q}out = -611.1MW$$

$$\dot{Q}out = (-611.1MW)\left(1000\frac{kW}{MW}\right)\left(3412.2\frac{Btu}{hr\text{-}kW}\right) = 2.0852 \times 10^9\frac{Btu}{hr}$$

From a first law analysis on the cooling water (where the heat is entering the cooling water; hence positive from the water's view).

$$\dot{Q} + \dot{m}(h+ke+pe)_1 = \dot{W} + \dot{m}(h+ke+pe)_2$$

Apply assumption (2)

$$\dot{Q} + \dot{m}h_1 = \dot{m}h_2$$

$$\left(2.0852 \times 10^9\frac{Btu}{hr}\right) = \left(\dot{m}\frac{lbm}{hr}\right)\left(20\frac{Btu}{lbm}\right)$$

$$\dot{m} = \underline{1.042 \times 10^8\frac{lbm}{hr}}$$

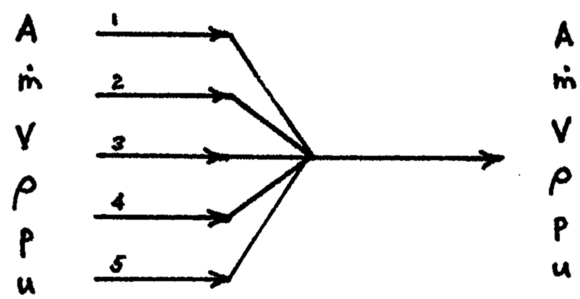
Problem C3.1

Develop a spreadsheet template or computer program that will determine the exit conditions for the adiabatic mixing of up to five inlet streams characterized by area, mass flowrate, velocity, density, pressure, and specific internal energy. The outlet stream should have the same characteristics. Test it using the information from problem 3.14.

Given: Adiabatic mixing of up to five streams.

Find: Exit conditions.

Sketch and Given Data:



Assumptions: 1) Changes in potential and kinetic energies are negligible.

Analysis: Enter the data, continuity equation, and first law equations into the spreadsheet as shown below. In addition to the data from problem 3.14, values for pressure and input enthalpies are entered.

```
  ......................A/.........B/.........C/
 1 Problem C3.1
 2
 3                        Fluid 1     Fluid 2
 4         INPUTS
 5 Density (kg/m3)        1.6         1/0.502
 6 Area (m3)              0.05        0.04
 7 Velocity (m/s)         130         110.9
 8 Pressure (kPa)         100         100
 9 Int. Energy (kJ/kg)    300         500
10        OUTPUTS
11 Mass Flowrate (kg/s)   +B5*B6*B7   +C5*C6*C7
12 Specific Vol.(m3/kg)   1/B5        1/C5
13 Enthalpy (kJ/kg)       +B9+B8*B12  +C9+C8*C12
14
15                        Outlet
16        INPUTS
17 Density (kg/m3)        1/0.437
18 Area (m3)              0.065
19 Pressure (kPa)         100
20        OUTPUTS
21 Velocity (m/s)         +B22/(B17*B18)
22 Mass Flowrate (kg/s)   @SUM(B11..F11)
23 Specific Vol.(m3/kg)   1/B17
24 Int. Energy (kJ/kg)    (B11*B9+C11*C9+D11*D9+E11*E9+F11*F9)/B22
25 Enthalpy (kJ/kg)       (B11*B13+C11*C13+D11*D13+E11*E13+F11*F13)/B22
```

This will yield the following results.

Problem C3.1

	Fluid 1	Fluid 2	Fluid 3	Fluid 4	Fluid 5
INPUTS					
Density (kg/m3)	1.6	1.992031	1	1	1
Area (m3)	0.05	0.04	0	0	0
Velocity (m/s)	130	110.9	0	0	0
Pressure (kPa)	100	100	0	0	0
Int. Energy (kJ/kg)	300	500	0	0	0
OUTPUTS					
Mass Flowrate (kg/s)	10.4	8.836653	0	0	0
Specific Vol.(m3/kg)	0.625	0.502	1	1	1
Enthalpy (kJ/kg)	362.5	550.2	0	0	0

	Outlet
INPUTS	
Density (kg/m3)	2.288329
Area (m3)	0.065
Pressure (kPa)	100
OUTPUTS	
Velocity (m/s)	129.3295
Mass Flowrate (kg/s)	19.23665
Specific Vol.(m3/kg)	0.437
Int. Energy (kJ/kg)	391.8730
Enthalpy (kJ/kg)	448.7228

Comment: The back-solving capabilities of TK Solver would permit the development of a model that would be much more flexible as to which variables are inputs and which are outputs.

CHAPTER FOUR

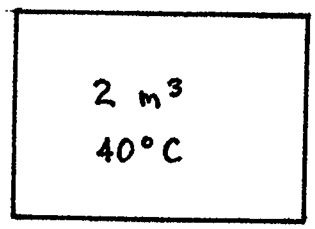
Problem 4.1

A 2-m^3 tank contains a saturated vapor at 40°C. Determine the pressure and mass in the tank if the substance is (a) steam; (b) ammonia; (c) R 12.

Given: Tank containing saturated vapor at 40°C.

Find: Vapor pressure and mass.

Sketch & Given Data:



Assumption: 1) The substances are in equilibrium.

Analysis: (a) From Appendix A.5 at 40°C.

$p = 7.389 \text{ kPa} \quad v_g = 19.511 \text{ m}^3/\text{kg}$

$$m = \frac{V}{v_g} = \frac{2\text{m}^3}{19.511\text{m}^3/\text{kg}} = 0.1025 \text{ kg}$$

(b) From Appendix A.9 at 40°C.

$p = 1554.33 \text{ kPa} \quad v_g = 0.0833 \text{ m}^3/\text{kg}$

$$m = \frac{V}{v_g} = \frac{2\text{m}^3}{0.0833\text{m}^3/\text{kg}} = 24.0 \text{ kg}$$

(c) From Appendix A.11 at 40°C.

$p = 0.9607 \text{ MPa} \quad v_g = 0.018171 \text{ m}^3/\text{kg}$

$$m = \frac{V}{v_g} = \frac{2\text{m}^3}{0.018171\text{m}^3/\text{kg}} = 110.07 \text{ kg}$$

Problem 4.5

Complete the following table for water.

	T(°C)	p(kPa)	x(%)	h(kJ/kg)	u(kJ/kg)	v (m³/kg)
(a)	200			852.4		
(b)		150			1000.0	
(c)	300	1000				
(d)	200	5000				
(e)		250				0.8500
(f)	300		80			
(g)		1000	90			

Indicate for each state whether the state is subcooled liquid, saturated liquid, mixture, saturated vapor or superheated vapor.

Given: Two independent steam properties.

Find: Remaining properties and state of steam.

Assumption: 1) The water is in equilibrium.

Analysis:

(a) Using Saturated Steam Temperature Table (A.5), h_f = 852.59 kJ/kg at 200°C, therefore, water is a very slightly subcooled liquid. Using data for saturated steam at 200°C:

p = 1554.7 kPa

x = 0.0%

$v = v_f$ = 0.0011562 m³/kg

$u = u_f$ = 850.79 kJ/kg

(b) Using Saturated Steam pressure Table (A.6), for 150 kPa steam, u = 1000 kJ/kg is between u_f and u_g. Water is thus a mixture. Interpolating to obtain 150 kPa data:

$T = 111.3°C$

$u_f = 467.2$ kJ/kg

$u_{fg} = 2052.6$ kJ/kg

$h_f = 467.3$ kJ/kg

$h_{fg} = 2226.3$ kJ/kg

$v_f = 0.001053\ m^3/kg$

$v_{fg} = 1.1584\ m^3/kg$

$u = u_f + x\,u_{fg}$

$1000\text{ kJ/kg} = 467.2\text{ kJ/kg} + (x)(2052.6\text{ kJ/kg})$

$x = .2596 = 25.96\%$

$h = h_f + x\,h_{fg}$

$= 467.3\text{ kJ/kg} + (.2596)(2226.3\text{kJ/kg})$

$= 1045.2$ kJ/kg

$v = v_f + x\,v_{fg} = (.001053\ m^3/kg) + (.2596)(1.1584\ m^3/kg) = 0.3018$

(c) Since temperature is greater than saturation temperature at 1000 kPa, steam is superheated. Interpolating data in Appendix A.7.

h = 3051.6 kJ/kg

u = 2793.5 kJ/kg

$v = 0.25806\ m^3/kg$

(d) Since temperature is below saturation temperature at 5000 kPa, water is subcooled. Using Appendix A.8.

h = 853.9 kJ/kg

u = 848.1 kJ/kg

$v = 0.00153\ m^3/kg$

(e) Since specific volume is greater than v_g at 250 kPa, the steam is superheated. Interpolating data in Appendix A.7.

T = 194°F

h = 2855.4 kJ/kg

u = 2642.9 kJ/kg

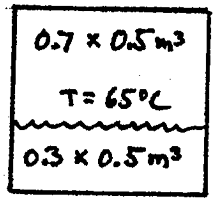
Problem 4.9

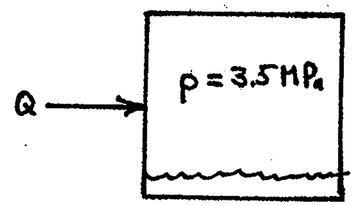
A rigid steel tank contains a mixture of vapor and liquid water at a temperature of 65°C. The tank has a volume of 0.5 m³, the liquid phase occupying 30% of the volume. Determine the amount of heat added to the system to raise the pressure to 3.5 MPa.

Given: Tank with mixture of saturated vapor and liquid.

Find: Heat added to raise pressure to 3.5 MPa.

Sketch & Given Data:





Assumption: 1) Tank is in equilibrium.

Analysis: From Appendix A.5, interpolating to 65°C.

$v_f = 0.0010199\ m^3/kg$ $u_f = 272.71\ kJ/kg$
$v_g = 6.328\ m^3/kg$ $u_{fg} = 2181.7\ kJ/kg$

From Appendix A.6 at 3500 kPa:

$v_f = 0.0012342\ m^3/kg$ $u_f = 1045.8\ kJ/kg$
$v_g = 0.057079\ m^3/kg$ $u_{fg} = 1557.9\ kJ/kg$

Calculate initial quality:

$$x_1 = \frac{m_{v_1}}{m_{v_1}+m_{\ell_1}} = \frac{\dfrac{(0.7)(0.5m^3)}{(6.328m^3/kg)}}{\dfrac{(0.7)(0.5m^3)}{(6.328m^3/kg)} + \dfrac{(0.3)(0.5m^3)}{(0.0010199m^3/kg)}} = 0.000376$$

Initial specific volume equals final specific volume.

$$v_1 = v_2$$
$$v_{f1} + x_1\, v_{fg1} = v_{f2} + x_2\, v_{fg2}$$

v_1 = (0.0010199 m³/kg) + (0.000376)(6.328 - 0.0010199 m³/kg)

v_1 = v_2 = (0.0012342 m³/kg) + (x_2)(0.057079 - 0.0012342 m³/kg)

$$x_2 = 0.03876$$

$$Q = m\,\Delta u + W^{0}$$

$$= (m_{total})(u_2 - u_1)$$

$$= (m_{v1} + m_{f1})[(u_{f2} + x_2\, u_{fg2}) - (u_{f1} + x_1\, u_{fg1})]$$

$$= (147.07\ kg)\ [(1045.8\ kJ/kg + (0.03876)(1557.9\ kJ/kg))$$

$$- (272.71\ kJ/kg + (0.000376)(2181.7\ kJ/kg))]$$

$$Q = 122\ 458\ kJ$$

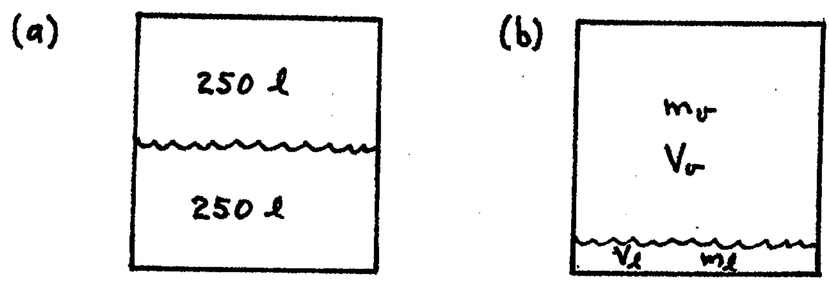
Problem 4.13

A 500-liter tank contains a saturated mixture of steam and water at 300°C. Determine (a) the mass of each phase if their volumes are equal; (b) the volume occupied by each phase if their masses are equal.

Given: Tank with saturated mixture at 300°C.

Find: Mass for equal volumes, and volume for equal masses.

Sketch & Given Data:



Assumption: 1) Mixture is in equilibrium.

Analysis: Using Appendix A.5 at T = 300°C.

$v_f = 0.0014038\ m^3/kg \qquad v_g = 0.021648\ m^3/kg$

(a)

$$m_\ell = \frac{V_\ell}{v_f} = \frac{0.25m^3}{0.0014038m^3/kg} = 178.09\ kg$$

$$m_v = \frac{V_v}{v_g} = \frac{0.25m^2}{0.021648m^3/kg} = 11.55kg$$

(b)

$m_\ell = m_v \qquad V_\ell + V_v = 0.5\ m^3$

$$\frac{V_\ell}{v_f} = \frac{V_v}{v_g} = \frac{0.5-V_\ell}{v_g}$$

$$V_\ell v_g = v_f(0.5-V_\ell)$$

$$(V_\ell)(0.021648m^3/kg) = (0.0014038m^3/kg)(0.5m^3-V_\ell)$$

$V_\ell = 0.03045m^3 \qquad V_v = 0.46955m^3$

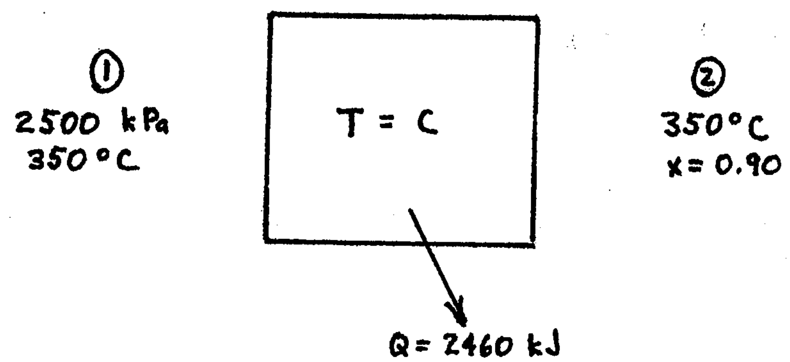
Problem 4.17

Three kilograms of steam initially at 2.5 MPa and a temperature of 350°C have 2460 kJ of heat removed at constant temperature until the quality is 90%. Determine (a) *T-v* and *p-v* diagrams; (b) pressure when dry saturated steam exists; (c) work.

Given: Steam being cooled at constant temperature.

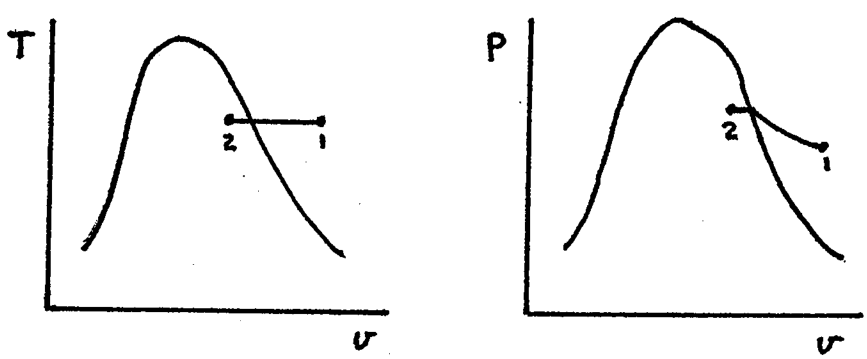
Find: Pressure at saturation and process work.

Sketch & Given Data:



Assumption: 1) Steam is in equilibrium.

Analysis: (a)



(b) Pressure when dry saturation exists is saturation pressure corresponding to 350°C. Using Appendix A.5.

$p = 16\,527$ kPa

(c) Using Appendix A.7 to find initial internal energy.

$u_1 = 2852.9$ kJ/kg

From Appendix A.5.

$u_f = 1641$ kJ/kg $u_{fg} = 777.48$ kJ/kg

$u_2 = u_f + x\,u_{fg} = 1641$ kJ/kg + (0.9)(777.48 kJ/kg)

= 2340.7 kJ/kg

Writing the first law equation for a closed system.

$$q = \Delta u + w = (u_2 - u_1) + w$$

$$-\frac{2460 \text{ kJ}}{3 \text{ kg}} = (2340.7 \text{ kJ/kg} - 2852.9 \text{ kJ/kg}) + w$$

w = -307.8 kJ/kg

Comment: 1. Negative sign for work indicates work is supplied to the system during the process.

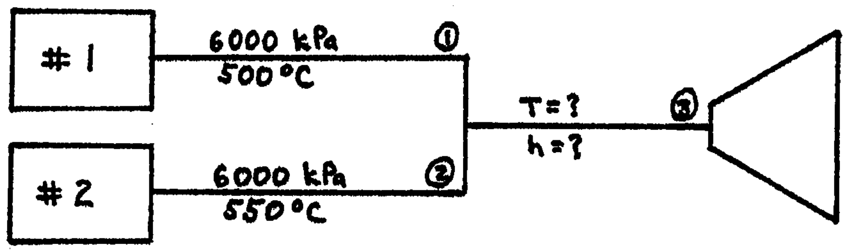
Problem 4.21

The main steam turbine of a ship is supplied by two steam generators. One steam generator delivers steam at 6.0 MPa and 500°C, and the other delivers steam at 6.0 MPa and 550°C. Determine the steam enthalpy and temperature at the entrance to the turbine.

Given: Two steam generators supplying steam to a turbine.

Find: Enthalpy and temperature entering turbine.

Sketch & Given Data:



Assumptions:
1) Steam is in equilibrium.
2) Steam generators are delivering equal flows.

Analysis: Using Appendix A.7, interpolating as necessary.

h_1 = 3423.2 kJ/kg $\qquad$ h_2 = 3540.4 kJ/kg

Writing first law equations.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \qquad \dot{m}_1 + m_2 = \dot{m}_3$$

$$\text{and } \dot{m}_1 = \dot{m}_2$$

$$\dot{m}_1 h_1 + \dot{m}_1 h_2 = (\dot{m}_1 + \dot{m}_1) h_3$$

(a) $$h_3 = \frac{\dot{m}_1 h_1 + \dot{m}_1 h_2}{2\dot{m}_1} = \frac{h_1 + h_2}{2}$$

$$= \frac{3423.2\text{kJ/kg} + 3540.4\text{kJ/kg}}{2} = 3481.8\text{kJ/kg}$$

(b) From Appendix A.7, interpolating as necessary. T = 524.9°C.

Comment: 1. Using SHTSTM.TK will eliminate the need to interpolate.

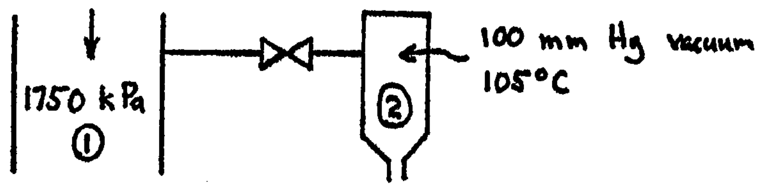
Problem 4.25

A throttling calorimeter is connected to a main steam line where the pressure is 1750 kPa. The calorimeter pressure is 100 mm Hg vacuum and 105°C. Determine the main steam quality.

Given: Throttling calorimeter attached to steam line.

Find: Steam quality.

Sketch & Given Data:



Assumptions:
1) Steam is in equilibrium.
2) Atmospheric pressure is 760 mm Hg.

Analysis: Find calorimeter pressure.

$$P_2 = 760\text{mmHg} - 100\text{mmHg} = (660\text{mmHg})\left(\frac{0.1333\text{kPa}}{1\text{mmHg}}\right) = 88\text{kPa}$$

From Appendix A.7 at 88 kPa and 105°C, interpolating as required.

$h_2 = 2687$ kJ/kg

From Appendix A.6 at 1750 kPa, interpolating as required.

$h_f = 878.4$ kJ/kg $\qquad h_{fg} = 1918.1$ kJ/kg

Steam enthalpy in line equals enthalpy in calorimeter.

$$h_1 = h_2 = h_f + x\,h_{fg}$$

$$2687 \text{ kJ/kg} = 878.4 \text{ kJ/kg} + (x)(1918.1 \text{ kJ/kg})$$

$$x = 0.943$$

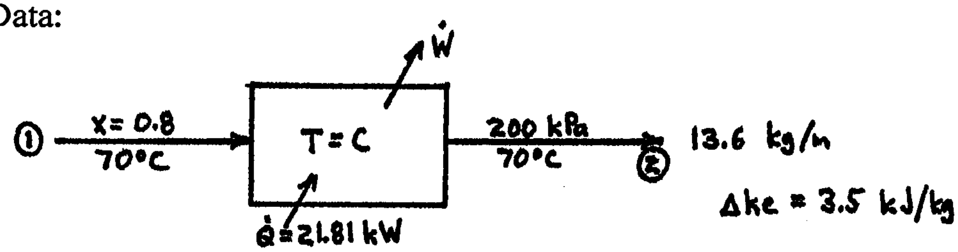
Problem 4.29

Refrigerant 12 is expanded steadily in an isothermal process. The flow rate is 13.6 kg/min with an inlet state of wet saturated vapor with an 80% quality to a final state of 70°C and 200 kPa. The change of kinetic energy across the device is 3.5 kJ/kg and the heat added is 21.81 kW. Determine the system power.

Given: R 12 being expanded isothermally with heat addition and change in kinetic energy.

Find: Power.

Sketch & Given Data:



Assumptions:
1) R 12 is in equilibrium.
2) Change in potential energy is negligible.

Analysis: Using Appendix A.11 to find initial enthalpy.

$h_f = 107.067$ kJ/kg $\qquad h_{fg} = 104.255$ kJ/kg

$$h_1 = h_f + x\,h_{fg} = 107.067\text{ kJ/kg} + (0.8)(104.255\text{ kJ/kg}) = 190.471\text{ kJ/kg}$$

Using Appendix A.12 to find exit enthalpy.

$h_2 = 234.291$ kJ/kg

Writing first law equation for the open system.

$$\dot{Q} + \dot{m}h_1 + \dot{m}ke_1 = \dot{W} + \dot{m}h_2 + \dot{m}ke_2$$

$$\dot{W} = \dot{Q} + \dot{m}(h_1 - h_2) + \dot{m}(ke_1 - ke_2)$$

$$= 21.81\text{kw} + \left(\frac{13.6\text{kg/m}}{60\text{s/m}}\right)(190.471\text{kJ/kg} - 234.291\text{kg/kg})$$

$$+ \left(\frac{13.6\text{kg/m}}{60\text{s/m}}\right)(-3.5\text{kJ/kg})$$

=11.08kw

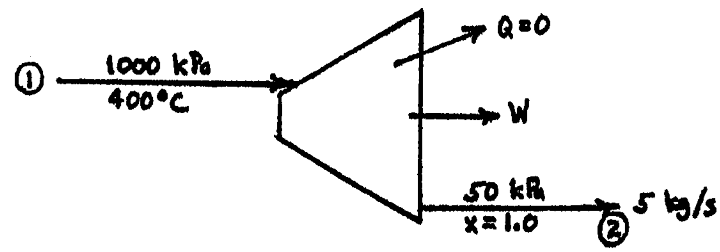
Problem 4.33

An adiabatic steam turbine receives 5 kg/s of steam at 1.0 MPa and 400°C and the steam exits at 50 kPa and 100% quality. Determine: (a) the power produced; (b) the exit area in m^2 if the exit velocity is 250 m/s.

Given: Adiabatic turbine expanding steam with specified inlet and exit conditions.

Find: Power and exit area.

Sketch & Given Data:



Assumptions:
1) Steam is in equilibrium.
2) Changes in kinetic and potential energy are negligible.

Analysis: Find inlet enthalpy using Appendix A.7.

$$h_1 = 3263.9 \text{ kJ/kg}$$

Find exit enthalpy and specific volume using Appendix A.6.

$$h_2 = h_g = 2645.9 \text{ kJ/kg} \qquad v_2 = v_g = 3.2408 \text{ m}^3\text{/kg}$$

(a) Writing first law equation for the open system.

$$\dot{m}h_1 = \dot{m}h_2 + W$$

$$W = \dot{m}(h_1 - h_2) = (5\text{kg/s})(3263.9\text{kJ/kg} - 2645.9\text{kJ/kg})$$

$$= 3090\text{kw}$$

(b) Using continuity equation.

$$A_2 = \frac{\dot{m}v_2}{V} = \frac{(5\text{kg/s})(3.2408\text{m}^3\text{/kg})}{(250\text{m/s})} = 0.0648\text{m}^3$$

Problem 4.37

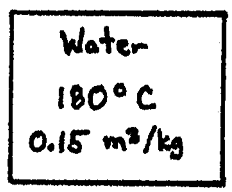
Determine the quality of a two phase mixture of: (a) water at 180°C and a specific volume of 0.15 m^3/kg; (b) R 12 at 745 kPa and a specific volume of 0.020 m^3.

Given: Mixtures of saturated water and R 12.

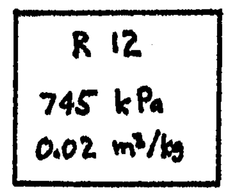
Find: Quality.

Sketch & Given Data:

(a)



(b)



Assumption: 1) Water and R 12 are in equilibrium.

Analysis: (a) Using Appendix A.5 at 180°C.

$$v_f = 0.0011274 m^3/kg \qquad v_g = 0.19391 m^3/kg$$

$$v = v_f + x(v_g - v_f)$$

$$x = \frac{(v - v_f)}{(v_g - v_f)} = \frac{(0.15 m^3/kg - 0.0011274 m^3/kg)}{(0.19391 m^3/kg - 0.0011274 m^3/kg)}$$

$$= 0.7715$$

(b) Using Appendix A.11 at 745 kPa.

$$v_f = 0.000774 m^3/kg \qquad v_{fg} = 0.022734 m^3/kg$$

$$v = v_f + x\, v_{fg}$$

$$x = \frac{v - v_f}{v_{fg}} = \frac{(0.020 m^3/kg - 0.000774 m^3/kg)}{0.022734 m^3/kg}$$

$$x = 0.8457$$

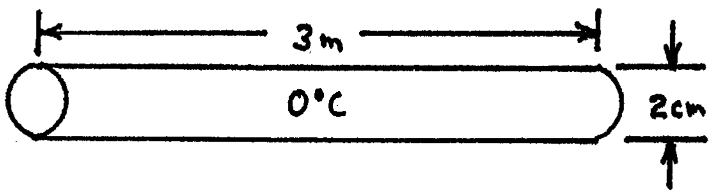
Problem 4.41

Regrigeration tubing is 2 cm in diameter and 3 m long and contains R 12 as a saturated vapor at 0°C. What is the mass of R 12 in the tubing?

Given: Tubing containing saturated R 12 vapor.

Find: Mass of R 12.

Sketch & Given Data:



Assumptions:
1) R 12 is in equilibrium.
2) Tube diameter is inside.

Analysis: Find volume inside tubing.

$$V = \frac{\pi d^2}{4} \cdot L = \left[\frac{(\pi)(0.02m)^2}{4}\right](3m) = 0.0009425m^3$$

Using Appendix A.11 at 0°C.

$$v_g = 0.055389m^3/kg$$

$$m = \frac{V}{v} = \frac{(0.0009425m^3)}{(0.055389m^3/kg)} = 0.017016kg$$

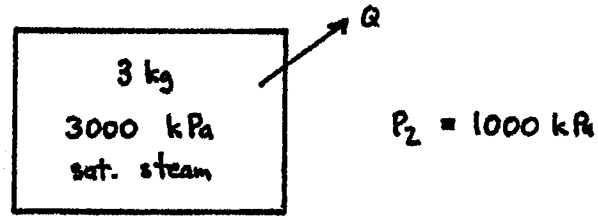
Problem 4.45

A rigid tank contains three kilograms of saturated steam at pressure of 3000 kPa. Because of heat transfer to the surroundings, the pressure decreases to 1000 kPa. Determine the tank's volume and the quality of steam at the final state.

Given: Tank containing saturated steam is cooled.

Find: Tank volume and steam quality.

Sketch & Given Data:



Assumption: 1) Steam is in equilibrium.

Analysis: Initial and final specific volumes will be equal.

From Appendix A.6 at 3000 kPa.

$$v_g = 0.066694 \text{ m}^3/\text{kg}$$

From Appendix A.6 at 1000 kPa.

$$v_f = 0.0011272 \text{ m}^3/\text{kg} \qquad v_g = 0.19444 \text{ m}^3/\text{kg}$$

$$v = v_f + x(v_g - v_f)$$

$$0.066694 \text{ m}^3/\text{kg} = 0.0011272 \text{ m}^3/\text{kg} + (x)(0.19444 \text{ m}^3/\text{kg} - 0.0011272 \text{ m}^3/\text{kg})$$

$$x = 0.3392$$

$$V = mv = (3 \text{ kg})(0.066694 \text{ m}^3/\text{kg}) = 0.2 \text{ m}^3$$

Problem 4.49

Two kilograms of steam is compressed at constant pressure in a piston/cylinder from an initial state of 500 kPa and 300°C to a saturated vapor. Determine the work for the process.

Given: Superheated steam compressed at constant pressure to a saturated vapor.

Find: Work for the process.

Sketch & Given Data:

Assumptions:
1) Steam is in equilibrium.
2) Changes in kinetic and potential energy are neglected.

Analysis: From Appendix A.7 at 500 kPa and 300°C.

$u_1 = 2802.9$ kJ/kg $\qquad h_1 = 3064.2$ kJ/kg

From Appendix A.6 at 500 kPa.

$u_2 = u_g = 2561.5$ kJ/kg $\qquad h_2 = h_g = 2749$ kJ/kg

Writing first law equation for the closed system.

$$Q = \Delta U + W$$

Since $h = u + pv$, for constant pressure closed system process, $q = \Delta h$.

First law equation can thus be rewritten as.

$$W = Q - \Delta U$$

$$= m(h_2 - h_1) - m(u_2 - u_1)$$

$$= (2\text{kg})(2749 \text{ kJ/kg} - 3064.2 \text{ kJ/kg}) - (2\text{kg})(2561.5 \text{ kJ/kg} - 2802.9 \text{ kJ/kg})$$

$$= -147.6 \text{ kJ}$$

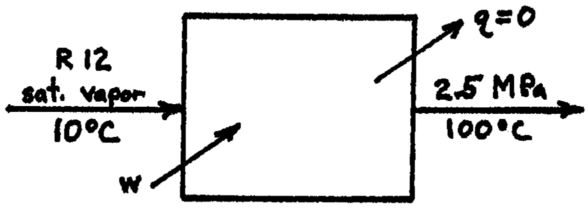
Problem 4.53

R 12 initially a saturated vapor at 10°C is compressed adiabatically to a pressure of 2.5 MPa and 100°C. Determine the work per unit mass, neglecting changes in potential and kinetic energies.

Given: Saturated R 12 vapor being compressed.

Find: Work per unit mass.

Sketch & Given Data:



Assumptions:
1) R 12 is in equilibrium.
2) Compressor is an open system.

Analysis: From Appendix A.11 at 10°C.

$$h_1 = h_g = 191.602 \text{ kJ/kg}$$

From Appendix A.12 at 2.5 MPa and 100°C

$$h_2 = 229.852 \text{ kJ/kg}$$

Writing the first law equation for the open system.

$$h_1 + w = h_2$$

$$w = h_2 - h_1 = 229.582 \text{ kJ/kg} - 191.602 \text{ kJ/kg} \approx 37.98 \text{ kJ/kg}$$

Comment: 1. If a closed system had been assumed, the work would have been equal to the change in internal energy.

Problem *4.1

Fill in the data omitted in the following table for water.

	Pressure (psia)	Temperature (°F)	Specific volume (ft^3/lbm)	Enthalpy (Btu/lbm)	Quality x(%)	State
(a)	500		0.650			
(b)		250		1000		
(c)	600	700				
(d)	800			1399.1		
(e)		300			90	
(f)	1000	200				

Indicate for each state whether the state is subcooled liquid, saturated liquid, mixture, saturated vapor or superheated vapor.

Given: Two independent steam properties.

Find: Remaining properties and state of steam.

Assumption: 1) The water is in equilibrium.

Analysis: (a) Using Appendix A.15 at 500 psia, specific volume is between v_f and v_g, therefore this is a mixture. From Appendix A.15.

$T = 467.02°F$ $\quad$ $h_f = 449.67$ Btu/lbm

$v_f = 0.019739\ ft^3/lbm$ $\quad$ $h_{fg} = 755.64$ Btu/lbm

$v_g = 0.92849\ ft^3/lbm$

$$v = v_f + x(v_g - v_f)$$

$$0.65\ ft^3/lbm = 0.019739\ ft^3/lbm + x(0.92849\ ft^3/lbm - 0.019739\ ft^3/lbm)$$

$$x = 0.694$$

$$h = h_f + x\,h_{fg} = 449.67\ Btu/lbm + (0.694)(755.64\ Btu/lbm)$$

$$= 974.1\ Btu/lbm$$

(b) Using Appendix A.14 at 250°F, enthalpy is between h_f and h_g, therefore, this is a mixture. From Appendix A.15.

$P = 29.864$ psia $\qquad h_f = 218.66$ Btu/lbm

$v_f = 0.017005$ ft³/lbm $\qquad h_{fg} = 945.59$ Btu/lbm

$v_g = 13.808$ ft³/lbm

$$h = h_f + x\, h_{fg}$$

$$1000 \text{ Btu/lb} = 218.66 \text{ Btu/lbm} + (x)(945.59 \text{ Btu/lbm})$$

$$x = 0.826$$

$$v = v_f + x(v_g - v_f) = 0.017005 \text{ ft}^3\text{/lbm}$$

$$+ (0.826)(13.808 \text{ ft}^3\text{/lbm} - 0.017005 \text{ ft}^3\text{/lbm})$$

$$= 11.41 \text{ ft}^3\text{/lbm}$$

(c) From appendix A.16, since temperature is above saturation for 600 psia, this is a superheated vapor.

$v = 1.0732$ m³/kg $\qquad h = 1351.4$ Btu/lbm

(d) From appendix A.16, since enthalpy is above h_g for 800 psia, this is a superheated vapor.

$T = 800$°F $\qquad v = 0.87629$ ft³/lbm

(e) Since quality is given, this is a mixture. From Appendix A.14.

$p = 67.078$ psia $\qquad h_f = 269.64$ Btu/lbm

$v_f = 0.017453$ ft³/lbm $\qquad h_{fg} = 910.64$ Btu/lbm

$v_g = 6.4627$ ft³/lbm

$$v = v_f + x(v_g - v_f) = 0.017453 \text{ ft}^3\text{/lbm} + (0.9)(6.4627 \text{ ft}^3\text{/lbm} - 0.017453 \text{ ft}^3\text{/lbm})$$

$$= 5.818 \text{ ft}^3\text{/lbm}$$

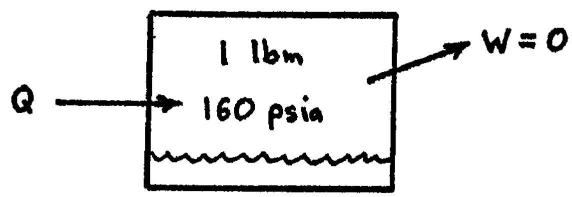
Problem *4.5

One pound mass of a steam-water mixture at 160 psia is contained in an inflexible tank. Heat is added until the pressure rises to 600 psia and the temperature to 600°F. Determine the heat added.

Given: Heat is added to tank containing a mixture, increasing the pressure.

Find: The heat added.

Sketch & Given Data:



Assumption: 1) Steam is in equilibrium.

Analysis: Using Appendix A.15 at 160 psia.

$v_f = 0.01815$ ft³/lbm $\quad$ $u_f = 335.51$ Btu/lbm

$v_g = 2.8359$ ft³/lbm $\quad$ $u_{fg} = 776.52$ Btu/lbm

Using Appendix A.15 at 600 psia and 600°F,

$v = 0.94626$ ft³/lbm $\quad$ u = 1185 Btu/lbm

Since initial and final specific volumes are equal, solving for quality.

$$v_f + (x)(v_g - v_f) = v_2$$

$$0.01815 \text{ ft}^3/\text{lbm} + (x)(2.8359 \text{ ft}^3/\text{lbm} - 0.01815 \text{ ft}^3/\text{lbm}) = 0.94626 \text{ ft}^3/\text{lbm}$$

$$x = 0.329$$

Solving for the initial internal energy.

$$u_1 = u_f + x\, u_{fg}$$

$$= 335.51 \text{ Btu/lbm} + (0.329)(776.52 \text{ Btu/lbm})$$

$$= 591 \text{ Btu/lbm}$$

$$Q = \Delta U + \cancel{W}^{0} = m(u_2 - u_1)$$

$$= (1\ \text{lbm})(1185\ \text{Btu/lbm} - 591\ \text{Btu/lbm})$$

$$= 594\ \text{Btu}$$

Comments: 1. Linear interpolation for v_2 introduces errors. Using SHTSTM.TK will produce more accurate results.

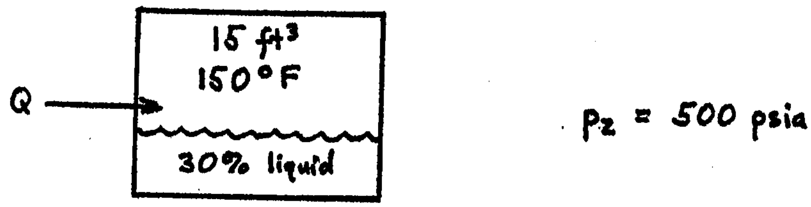
Problem *4.9

A rigid steel tank contains a mixture of vapor and liquid water at a temperature of 150°F. The tank has a volume of 15 ft^3, the liquid phase occupying 30% of the volume. Determine the amount of heat added to the system to raise the pressure to 500 psia.

Given:. Tank with mixture of saturated vapor and liquid.

Find: Heat added to raise pressure to 500 psia.

Sketch & Given Data:



Assumption: 1) Tank is in equilibrium.

Analysis: From Appendix A.14, interpolating to 150°F

$v_f = 0.016341$ ft^3/lbm $\quad u_f = 118.28$ Btu/lbm

$v_g = 96.901$ ft^3/lbm $\quad u_{fg} = 940.97$ Btu/lbm

From Appendix A.15 at 500 psia

$v_f = 0.019739$ ft^3/lbm $\quad u_f = 447.85$ Btu/lbm

$v_g = 0.92849$ ft^3/lbm $\quad u_{fg} = 671.56$ Btu/lbm

Calculate initial quality.

$$x_1 = \frac{m_{v_1}}{m_{v_1}+m_{\ell_1}} = \frac{\dfrac{(0.7)(15\text{ft}^3)}{96.901\text{ft}^3/\text{lbm}}}{\dfrac{(0.7)(15\text{ft}^3)}{96.901\text{ft}^3/\text{lbm}} + \dfrac{(0.3)(15\text{ft}^3)}{0.016341\text{ft}^3/\text{lbm}}} = 0.000393$$

Initial specific volume equals final specific volume.

$$v_1 = v_2$$

$$v_{f1} + x_1 v_{fg1} = v_{f2} + x_2 v_{fg2}$$

$(0.016341\ \text{ft}^3/\text{lbm}) + (0.000393)(96.901\ \text{ft}^3/\text{lbm} - 0.016341\ \text{ft}^3/\text{lbm}) =$

$(0.019739\ \text{ft}^3/\text{lbm}) + (x_2)(0.92849\ \text{ft}^3/\text{lbm} - 0.019739\ \text{ft}^3/\text{lbm})$

$x_2 = 0.03816$

$$Q = m\,\Delta u + \cancel{W}^{0}$$

$$= (m_{total})(u_2 - u_1)$$

$$= (m_{f_1} + m_{v_1})\left[(u_{f_2} + x_2 u_{fg_2}) - (u_{f_1} + x_1 u_{fg_1})\right]$$

$$= (275.5\text{lbm})\left[(447.85\text{Btu/lbm} + (0.03816)(671.56\text{Btu/lbm}))\right.$$

$$\left. - (118.28\text{Btu/lbm} + (0.000393)(940.97\text{Btu/lbm}))\right]$$

$Q = 97{,}755$ Btu

Problem *4.13

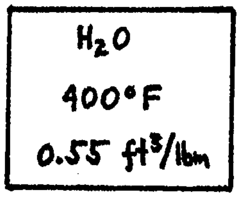
Determine the quality of a two phase mixture of : (a) water at 400°F and a specific volume of 0.55 ft³/lbm; (b) R 12 at 350 psia and a specific volume of 0.025 ft³/lbm.

Given: Mixtures of saturated water and R 12.

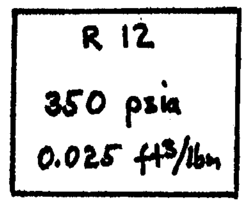
Find: Quality.

Sketch & Given Data:

(a)



(b)



Assumption: 1) Water and R 12 are in equilibrium.

Analysis: (a) Using Appendix A.14 at 400°F.

$v_f = 0.018633 \text{ ft}^3/\text{lbm} \qquad v_g = 1.8645 \text{ ft}^3/\text{lbm}$

$v = v_f + x(v_g - v_f)$

$$x = \frac{(v - v_f)}{(v_g - v_f)} = \frac{(0.55\text{ft}^3/\text{lbm} - 0.018633\text{ft}^3/\text{lbm})}{(1.8645\text{ft}^3/\text{lbm} - 0.018633\text{ft}^3/\text{lbm})}$$

$$= 0.288$$

(b) Using Appendix A.11 at 350 psia.

$v_f = 0.01536 \text{ ft}^3/\text{lbm} \qquad v_{fg} = 0.08794 \text{ ft}^3/\text{lbm}$

$v = v_f + x\, v_{fg}$

$$x = \frac{v - v_f}{v_{fg}} = \frac{(0.025\text{ft}^3/\text{lbm} - 0.01536\text{ft}^3/\text{lbm})}{0.08794\text{ft}^3/\text{lbm}}$$

$x = 0.1096$

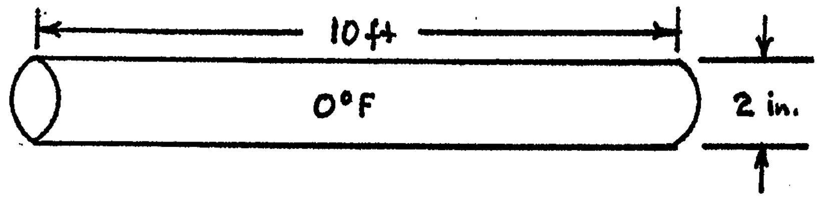
Problem *4.17

Refrigeration tubing is 2 inches in diameter and 10 ft. long and contains R 12 as a saturated vapor at 0°F. What is the mass of R 12 in the tubing?

Given: Tubing containing saturated R 12 vapor.

Find: Mass of R 12.

Sketch & Given Data:



Assumptions:
1) R 12 is in equilibrium.
2) Tube diameter is inside.

Analysis: Find volume inside tubing.

$$V = \frac{\pi d^2}{4} \cdot L = \left[\frac{(\pi)(2\text{in})^2}{(4)(144^{\text{in}^2}/\text{ft}^2)}\right](10\text{ft}) = 0.2182\text{ft}^3$$

Using Appendix A.20 at 0°F.

$$v_g = 1.6089 \text{ ft}^3/\text{lbm}$$

$$m = \frac{V}{v} = \frac{(0.2182\text{ft}^3)}{(1.6089\text{ft}^3/\text{lbm})} = 0.1356\text{lbm}$$

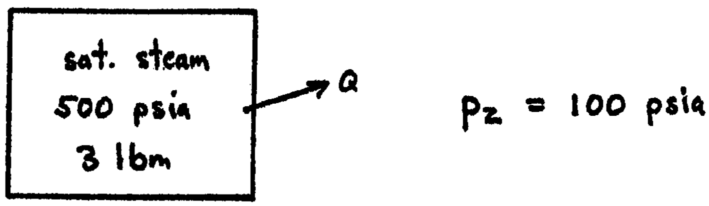
Problem *4.21

A rigid tank contains three pounds of saturated steam at pressure of 500 psia. Heat transfer to the surroundings occurs and as a result the pressure decreases to 100 psia. Determine the tank's volume and the quality of steam at the final state.

Given: Tank containing saturated steam is cooled.

Find: Tank volume and steam quality.

Sketch & Given Data:



Assumption: 1) Steam is in equilibrium.

Analysis: Initial and final specific volumes will be equal.

From Appendix A.15 at 500 psia.

$$v_g = 0.92849 \text{ ft}^3/\text{lbm}$$

From Appendix A.15 at 100 psia.

$$v_f = 0.017738 \text{ ft}^3/\text{lbm} \qquad v_g = 4.4339 \text{ ft}^3/\text{lbm}$$

$$v = v_f + x(v_g - v_f)$$

$$0.92849 \text{ ft}^3/\text{lbm} = 0.017738 \text{ ft}^3/\text{lbm} + (x)(4.4339 \text{ ft}^3/\text{lbm} - 0.017738 \text{ ft}^3/\text{lbm})$$

$$x = 0.2062$$

$$V = mv = (3 \text{ lbm})(0.92849 \text{ ft}^3/\text{lbm}) = 2.7855 \text{ ft}^3$$

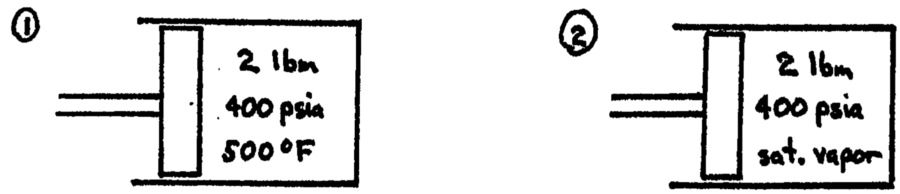
Problem *4.25

Two lbm of steam are compressed at constant pressure in a piston/cylinder from an initial state of 400 psia and 500°F to a saturated vapor. Determine the work for the process.

Given: Superheated steam compressed at constant pressure to a saturated vapor.

Find: Work for the process

Sketch & Given Data:



Assumptions:
1) Steam is in equilibrium.
2) Changes in kinetic and potential energy are neglected.

Analysis: From Appendix A.16 at 400 psia and 500°F.

$u_1 = 1150$ Btu/lbm $h_1 = 1245.1$ Btu/lbm

From Appendix A.15 at 400 psia.

$u_2 = u_g = 1119.4$ Btu/lbm $h_2 = h_g = 1205.4$ Btu/lbm

Writing first law equation for the closed system.

$$Q = \Delta U + W$$

Since $h = u + v$, for constant pressure closed system process, $q = \Delta h$.

First law equation can thus be rewritten as:

$$W = Q - \Delta U$$

$$= m(h_2\text{-}h_1) - m(u_2\text{-}u_1)$$

$$= (2\text{ lbm})(1205.4\text{ Btu/lbm} - 1245.1\text{ Btu/lbm}) - (2\text{ lbm})(1119.4\text{ Btu/lbm} - 1150\text{ Btu/lbm})$$

$$= -18.2\text{ Btu}$$

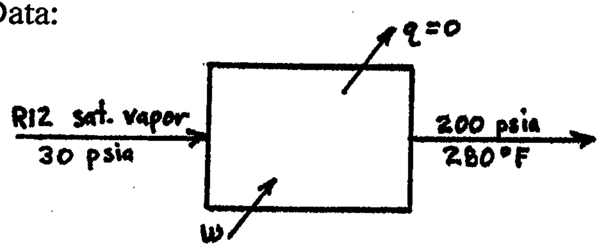
Problem *4.29

Ammonia initially a saturated vapor at 30 psia is compressed adiabatically to a pressure of 200 psia and 280°F. Determine the work per unit mass, neglecting changes in potential and kinetic energies.

Given: Saturated R 12 vapor being compressed.

Find: Work per unit mass.

Sketch & Given Data:



Assumptions: 1) R 12 is in equilibrium.

2) Compressor is an open system.

Analysis: From Appendix A.18 at 30 psia.

$$h_1 = h_g = 611.6 \text{ Btu/lbm}$$

From Appendix A.19 at 200 psia and 280°F.

$$h_2 = 752.5 \text{ Btu/lbm}$$

Writing the first law equation for the open system.

$$h_1 + w = h_2$$

$$w = h_2 - h_1 = 752.5 \text{ Btu/lbm} - 611.6 \text{ Btu/lbm} = 140.9 \text{ Btu/lbm}$$

Comment: 1. If a closed system had been assumed, the work would have been equal to the change in internal energy.

Problem C4.3

Using the TK Solver model R 12SAT.TK, determine the pressure of a mixture of R 12 with a quality of 50 percent and an enthalpy of 125 kJ/kg.

Given: R 12 mixture with given quality and enthalpy.

Find: Pressure.

Assumption: 1) R 12 is in equilibrium.

Analysis: Enter the equation for the enthalpy of a mixture in the Rule Sheet of R 12SAT.TK.

$$h = h_f + x(h_g - h_f)$$

Enter the values of quality and enthalpy into the Variable Sheet, and solve.

```
==================== VARIABLE SHEET ====================
St Input---- Name---- Output---- Unit------ Comment--------------------
                                             ***Saturated R12 Properties***
                                            ENGINEERING THERMODYNAMICS 4/E
                                            M. David Burghardt & James A. Harbach

             Psat     561.78     kPa        Pressure (kPa,MPa,psia)
             Tsat     19.654     degC       Temperature (degK,degC,degR,degF)

             vf       .00075135  m3/kg      Liquid Specific Volume (m3/kg,ft3/lbm)
             vg       .031076    m3/kg      Vapor Specific Volume (m3/kg,ft3/lbm)

             hf       54.496     kJ/kg      Liquid Enthalpy (kJ/kg,BTU/lbm)
             hg       195.5      kJ/kg      Vapor Enthalpy (kJ/kg,BTU/lbm)

             sf       .20648     kJ/kg-K    Liquid Entropy (kJ/kg-K,B/lbm-R)
             sg       .68802     kJ/kg-K    Vapor Entropy (kJ/kg-K,B/lbm-R)
   125       h
   .5        x
```

Problem C4.7

Use the model developed for problem C4.6 to determine the maximum moisture that can be measured by a throttling calorimeter exhausting to atmosphere for line pressures of 200 kPa, 2000 kPa, 10000 kPa and 20000 kPa. Assume a minimum superheat of 3°C in the calorimeter.

Given: Throttling calorimeter exhausting to atmosphere.

Find: Maximum moisture for various line pressures.

Sketch & Given Data: See Problem C4.6.

Assumptions:
1) Steam is in equilibrium.
2) Process is adiabatic.

Analysis: Entering the data into the Rule Sheet of the model developed for C4.6 produces the following results.

200 kPa	x = 0.98833 (moisture = 1.167%)
2000 kPa	x = 0.93731 (moisture = 6.269%)
10000 kPa	x = 0.9665 (moisture = 3.35%)
20000 kPa	x = 1.4619 (not possible!)

Comments: 1. For line pressures above 12000 kPa, a throttling calorimeter cannot be used to determine the moisture. A quick look at the Mollier chart (Appendix B.1a) will indicate why.

CHAPTER FIVE

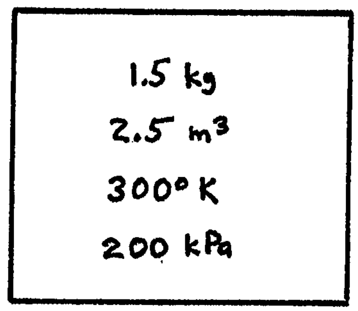
Problem 5.1

An unknown gas has a mass of 1.5 kg and occupies 2.5 m³ while at a temperature of 300°K and a pressure of 200 kPa. Determine the ideal gas constant for the gas.

Given: Mass, volume, temperature and pressure of unknown gas.

Find: Ideal gas constant.

Sketch and Given Data:



Assumptions: 1) The gas is in equilibrium.

Analysis: Solving the ideal gas equation for R.

$$R = \frac{pV}{mT} = \frac{(200\ \text{kPa})(2.5\ \text{m}^3)}{(1.5\ \text{kg})(300°\text{K})} = 1.111\ \text{kJ/kg-K}$$

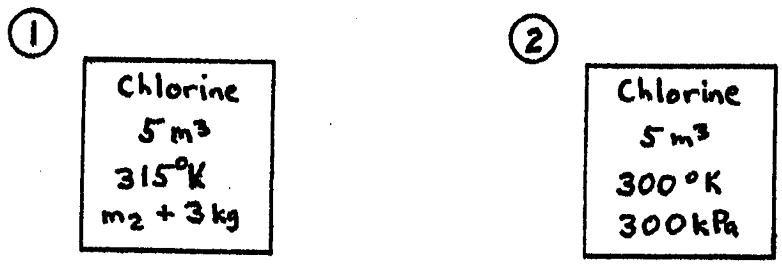
Problem 5.5

A 5-m³ tank contains chlorine at 300 kPa after 3 kg of chlorine has been used. Determine the original mass and pressure if the original temperature was 315°K.

Given: 3 kg removed from tank containing chlorine at known pressure and temperature.

Find: Original mass and pressure.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: From Appendix A.1, R = 0.1172 kJ/kg-K.

Using ideal-gas equation.

$$m_2 = \frac{P_2V_2}{RT_2} = \frac{(300\ \text{kPa})(5\ \text{m}^3)}{(0.1172\ \text{kJ/kg-K})(300°\text{K})} = 42.66\ \text{kg}$$

$$m_1 = m_2 + 3\ \text{kg} = 42.66\ \text{kg} + 3\ \text{kg} = 45.66\ \text{kg}$$

$$P_1 = \frac{m_1RT_1}{V_1} = \frac{(45.66\ \text{kg})(0.1172\ \text{kJkg-K})(315°\text{K})}{(5\ \text{m}^3)} = 337.1\ \text{kPa}$$

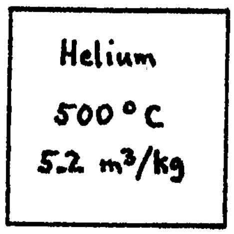
Problem 5.9

Helium is assumed to obey the Beattie-Bridgeman equation of state. Determine the pressure for a temperature of 500°C and a specific volume of 5.2 m^3/kg. Compare with the ideal-gas equation of state.

Given: Temperature and specific volume of helium.

Find: Pressure using Beattie-Bridgeman and ideal-gas equations.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: From Table 5.2, Beattie-Bridgeman constants are.

$A_o = 2.1886$ $\quad B_o = 0.014$ $\quad c = 0.0040 \times 10^4$

$a = 0.05984$ $\quad b = 0.0$

Substituting into Beattie-Bridgeman equation.

$$p = \frac{\bar{R}T\,(1-E)}{\bar{v}^2}(\bar{v} + B) - \frac{A}{\bar{v}^2}$$

Where: $A = A_o(1 - a/\bar{v})$

$B = B_o(1 - b/\bar{v})$ $\quad \bar{v} = Mv$

$$E = \frac{c}{\bar{v}\,T^3}$$

$p = 309.0$ kPa

Substituting into the ideal-gas equation, with gas constant from Appendix A.1.

$$p = \frac{RT}{v} = \frac{(2.077 \text{ kJ/kg-K})(773.15°\text{K})}{(5.2 \text{ m}^3/\text{kg})} = 308.8 \text{ kPa}$$

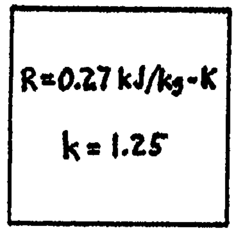
Problem 5.13

For a certain ideal gas, R = 0.270 kJ/kg-K and k = 1.25. Determine (a) c_p; (b) c_v; (c) M.

Given: Gas constant and specific heat ratio.

Find: Specific heats and molecular mass.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: Using equations 5.22 and 5.19.

$$c_p - c_v = R = 0.270 \text{ kJ/kg-K} \qquad \frac{c_p}{c_v} = k = 1.25$$

$$c_p = 1.25\, c_v$$

(b) $1.25\, c_v - c_v = 0.270$ kJ/kg-K

$$c_v = 1.08 \text{ kJ/kg-K}$$

(a) $c_p = 1.25\, c_v = 1.35$ kJ/kg-K

(c) $$M = \frac{\bar{R}}{R} = \frac{8.3143 \text{ kJ/kgmol-K}}{0.270 \text{kJ/kg-K}} = 30.79 \text{ kg/kgmol}$$

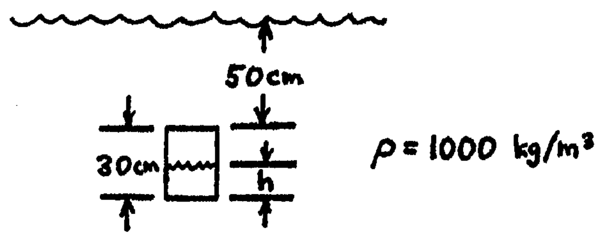
Problem 5.17

An empty, opened can is 30 cm high with a 10-cm diameter. The can, with the open end down, is pushed under water with a density of 1000 kg/m³. Find the water level in the can when the top of the can is 50 cm below the surface. Thermal equilibrium exists at all times.

Given: Empty can forced underwater.

Find: Amount water level rises into can.

Sketch and Given Data:



Assumptions:
1) Air is in equilibrium.
2) Atmospheric pressure is 101.325 kPa.
3) Acceleration of gravity is 9.8 m/s².

Analysis: For constant temperature process, $p_1V_1 = p_2V_2$

$$p_1 = 101.325 \text{ kPa}$$

$$V_1 = \frac{\pi}{4} d^2 L = \left(\frac{\pi}{4}\right)(0.1 \text{ m})^2 (0.3 \text{ m})$$

$$V_2 = \left(\frac{\pi}{4}\right) (0.1 \text{ m})^2 (0.3 \text{ m} - h \text{ m})$$

$$p_2 = p_1 + \rho L g = 101.325 \text{ kPa} + \frac{(1000 \text{ kg/m}^3)(0.8 \text{ m} - h \text{ m})(9.8 \text{ m/s}^2)}{(1000 \text{ Pa/kPa})}$$

$$= 101.325 \text{ kPa} + (0.8 \text{ m-h m})(9.8 \text{ k/s}^2)$$

$$p_1V_1 = p_2V_2$$

Substituting and solving resulting quadratic equation.

$$h = 0.021 \text{ m or } 11.4 \text{ m}$$

$h = 2.1$ cm is only physically possible solution.

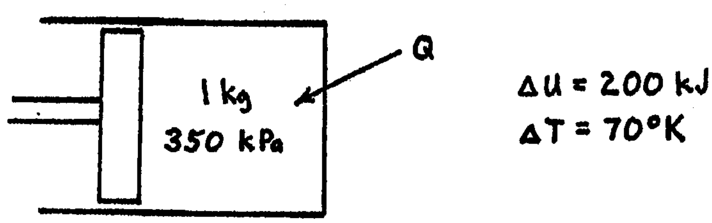
Problem 5.21

A 1-kg gaseous system is in a piston-cylinder and receives heat at a constant pressure of 350 kPa. The internal energy increases 200 kJ, and the temperature increases 70°K. If the work done is 100 kJ, determine (a) c_p; (b) the change in volume.

Given: Closed system receiving heat at constant pressure. Internal energy increase, temperature increase and work is given.

Find: Specific heat and volume change.

Sketch and Given Data:



Assumptions:
1) Gas is in equilibrium.
2) Change in potential and kinetic energy is negligible.

Analysis: For a constant pressure process, $Q = \Delta H$. Writing first law equation for a closed system.

$$Q = \Delta U + W = \Delta H = m\, C_p\, \Delta T$$

(a)
$$200\text{ kJ} + 100\text{ kJ} = (1\text{ kg})(C_p)(70°\text{K})$$

$$C_p = 4.286\text{ kJ/kg-K}$$

Using definition of work for a closed system.

$$W = \int p dV = p\Delta V \text{ for } p = c$$

(b)
$$\Delta V = \frac{W}{p} = \frac{100\text{ kJ}}{350\text{ kPa}} = 0.286\text{ m}^3$$

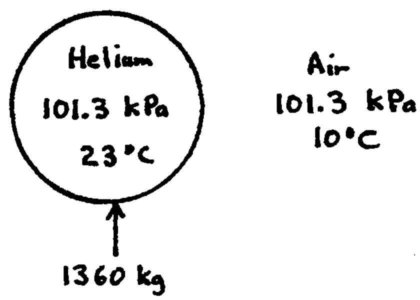
Problem 5.25

Determine the size of a spherical balloon required to lift a payload of 1360 kg. The gas to be used is helium at 101.3 kPa and 23°C. The surrounding air is 101.3 kPa and 10°C.

Given: Helium-filled spherical balloon is to lift a 1360 kg payload.

Find: Diameter.

Sketch and Given Data:



Assumptions: 1) Gasses are in equilibrium.

Analysis: Difference between mass of air displaced and mass of helium is equal to 1360 kg payload.

From Appendix A.1, for air $R = 0.287$ kJ/kg-K
for helium $R = 2.077$ kJ/kg-K

$$v_{air} = \frac{RT}{p} = \frac{(0.287\ \text{kJ/kg-K})(283.15°\text{K})}{(101.3\ \text{kPa})} = 0.8022\ \text{m}^3/\text{kg}$$

$$v_{helium} = \frac{RT}{p} = \frac{(2.077\ \text{kJ/kg-K})(296.15°\text{K})}{(101.3\ \text{kPa})} = 6.072\ \text{m}^3/\text{kg}$$

$$1360\ \text{kg} = m_{air} - m_{helium} = \frac{V}{v_{air}} - \frac{V}{v_{helium}} = V\left(\frac{1}{v_{air}} - \frac{1}{v_{helium}}\right)$$

$V = 1257.1\ \text{m}^3$ $\quad V = \frac{4}{3}\pi r^3 = 1257.1\ \text{m}^3$

$r = 6.695$ m $\quad d = 13.39$ m

Problem 5.29

Given the equation $pv = RT$, show that the following equations may be derived from it:

(a) $pV = mRT$ (b) $pV = n\bar{R}T$ (c) $p\bar{v} = \bar{R}T$ (d) $pv = \bar{R}T/M$

Given: The ideal gas equation, $pv = RT$.

Find: Four other forms.

Assumptions: None

Analysis:

(a) $pv = RT$

Multiply both sides by m, with $vm = V$.

$$pvm = mRT$$

$$pV = mRT$$

(b) $pV = mRT$

From Section 5.1: $R = \dfrac{\bar{R}}{M}$ and $m = nM$

$$pV = (nM)\left(\frac{\bar{R}}{M}\right)T = n\bar{R}T$$

(c) $pv = RT$

Since $v = \dfrac{\bar{v}}{M}$ and $R = \dfrac{\bar{R}}{M}$

$$p\left(\frac{\bar{v}}{M}\right) = \left(\frac{\bar{R}}{M}\right)T$$

$$p\bar{v} = \bar{R}T$$

(d) $pv = RT$

Since $R = \frac{\overline{R}}{M}$

$$pv = \left(\frac{\overline{R}}{M}\right)T = \frac{\overline{R}T}{M}$$

Problem 5.33

A typical adult breathes 0.5 liters of air with each breath and has 25 breaths per minute. At 101.3 kPa and 22°C, determine the mass of air per hour entering a person's lungs. This person now is skiing on a mountain where the air is -10°C and the pressure is 89 kPa. How many breaths per minute are required if the mass of air per hour entering the lungs is to be constant?

Given: Adult breathing at sea level.

Find: Breaths per minute on a mountain for same mass flow.

Sketch and Given Data:

Assumptions: 1) Air is in equilibrium.

Analysis: Use ideal gas law and determine mass flowrate.
From Appendix A.1, R = 0.287 kJ/kg-K.

$$\dot{m} = \frac{p\dot{V}}{RT} = \frac{(101.3\ \text{kPa})(12.5\ \ell/\text{m})}{(0.287\ \text{kJ/kg-K})(295.15°\text{K})(1000\ \ell/\text{m}^3)} = 0.01495\ \text{kg/m}$$

Calculate mass per breath on the mountain.

$$m = \frac{pV}{RT} = \frac{(89\ \text{kPa})(0.5\ \ell)}{(0.287\ \text{kJ/kg-K})(263.15°\text{K})(1000\ \ell/\text{m}^3)} = 5.892 \times 10^{-4}\ \text{kg}$$

$$\text{Breaths/m} = \frac{0.01495\ \text{kg/m}}{5.892 \times 10^{-4}\ \text{kg}} = 25.37$$

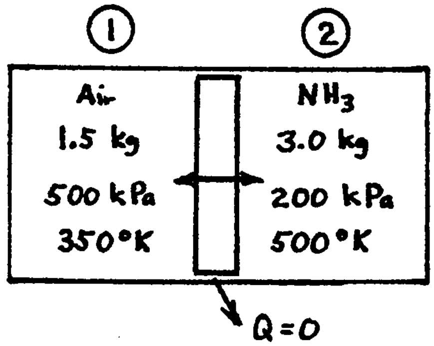
Problem 5.37

An adiabatic tank has an internal partition that separates two gases. On one side of the partition is air—1.5 kg at 500 kPa and 350°K; on the other side is ammonia--3.0 kg at 200 kPa and 500°K. Imagine now that the partition is free to move and allows the conduction of heat from one side to the other. Determine the final temperature and pressure of each gas, assuming that the ideal gas laws, constant specific heats, may be used.

Given: Adiabatic tank with air on one side of movable partition and ammonia on the other. The partition allows heat conduction.

Find: Final temperature and pressure.

Sketch and Given Data:



Assumptions: 1) Gases are in equilibrium.

Analysis: Use ideal gas law to calculate initial volumes.
From Appendix A.1, R_1 = 0.287 kJ/kg-K and R_2 = 0.4882 kJ/kg-K.

$$V_1 = \frac{m_1R_1T_1}{p_1} = \frac{(1.5\ \text{kg})(.0287\ \text{kJ/kg-K})(350°\text{K})}{(500\ \text{kPa})} = 0.30135\ \text{m}^3$$

$$V_2 = \frac{m_2R_2T_2}{p_2} = \frac{(3.0\ \text{kg})(0.4882\ \text{kJ/kg-K})(500°\text{K})}{(200\ \text{kPa})} = 3.6115\ \text{m}^3$$

Final temperature and pressure of the air and ammonia will be equal. The ideal gas equation for the air and the ammonia, and the first law equation can be written.

$$p(V_1 + \Delta V) = m_1R_1T$$

$$p(V_2 - \Delta V) = m_2R_2T$$

$$m_1\, c_{v1}(t - 350) = m_2\, c_{v2}(500 - T)$$

This is three equations with three unknowns (p, T and ΔV). The first law equation can be solved for T.

$$T = 472.5°K$$

Substituting T into the first two equations and solving simultaneously yields.

$$\Delta V = 0.599\ m^3$$

$$p = 225.96\ kPa$$

Comment: 1) The three simultaneous equations can be easily solved using TK solver.

Problem *5.1

Determine the change of enthalpy for air and carbon dioxide when the temperature changes form 70°F to 1000°F. Use equations from Table 5.4.

Given: Air and CO_2 changing temperature from 70° to 1000°F.

Find: Change of enthalpy using equations for variable specific heat.

Assumptions: 1) Gases are in equilibrium.

Analysis: Calculate change in enthalpy using the following equation.

$$h_2 - h_1 = \int_1^2 cp(T)\, dT \qquad T_1 = 294.3°K \quad T_2 = 810.7°K$$

Integrating the equation for air from Table 5.4.

$$h_2 - h_1 = 0.9167\left[T_2 - T_1\right] + \frac{2.577 \times 10^{-4}}{2}\left[T_2^2 - T_1^2\right] - \frac{3.974 \times 10^{-8}}{3}\left[T_2^3 - T_1^3\right]$$

Substituting values of T_1 and T_2 in the above.

$$h_2 - h_1 = 540.19 \text{ kJ/kg} = 232.23 \text{ Btu/lbm}$$

Integrating the equation for CO_2 from Table 5.4.

$$h_2 - h_1 = 1.540\left[T_2 - T_1\right] - 345.1 \ln\left(\frac{T_2}{T_1}\right) - 4.13 \times 10^4 \left[\frac{1}{T_2} - \frac{1}{T_1}\right]$$

Substituting the values of T_1 and T_2 in the above.

$$h_2 - h_1 = 534.96 \text{ kJ/kg-K} = 229.98 \text{ Btu/lbm}$$

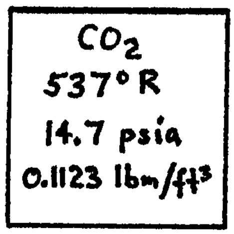
Problem *5.5

Carbon dioxide at 537°R and 14.7 psia has a density of 0.1123 lbm/ft³. Determine (a) the gas constant; (b) the molecular weight based on the gas constant.

Given: Temperature, pressure and density of carbon dioxide.

Find: Gas constant and molecular weight.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: Using ideal-gas equation.

$$pv = RT \qquad v = \frac{1}{\rho} \qquad p = \rho RT$$

(a) $$R = \frac{p}{\rho T} = \frac{(14.7\ \text{psia})(144\ \text{in}^2/\text{ft}^2)}{(0.1123\text{lbm/ft}^3)(537°\text{R})} = 35.1\ \text{ft-lbf/lbm-R}$$

(b) $$\bar{R} = MR \qquad M = \frac{\bar{R}}{R} = \frac{(1545.32\ \text{ft-lbf/pmol-R})}{(35.1\ \text{ft-lbf/lbm-R})} = 44.03\ \text{lbm/pmol}$$

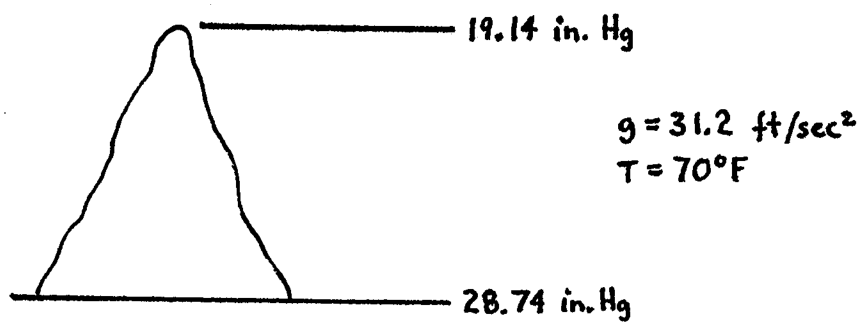
Problem *5.9

A mountain is measured by finding the change in pressure at constant temperature. A barometer at the base of the mountain reads 28.74 in. Hg, while at the top it reads 19.14 in. Hg. The average local gravitational acceleration is 31.2 ft/sec². Determine the height if the temperature may be assumed constant at 70°F.

Given: Barometer readings at base and top of mountain.

Find: Height of mountain.

Sketch and Given Data:



Assumptions: 1) Air is in equilibrium.

Analysis: Calculate average air density based on average air pressure and ideal-gas equation. From Appendix A.1, R = 53.34 ft-lbf/lbm-R.

$$p_{ave} = \frac{(28.74 \text{ inHg} + 19.14 \text{ inHg})}{2}(0.4912 \text{ psi/inHg})(144 \text{ in}^2/\text{ft}^2) = 1693.3 \text{ lbf/ft}^2$$

$$\rho_{ave} = \frac{P_{ave}}{RT} = \frac{(1693.3 \text{ lbf/ft}^2)}{(53.34 \text{ ft-lbf/lbm-R})(529.67°\text{R})} = 0.05993 \text{ lbm/ft}^3$$

$$\Delta p = \rho L g/g_c$$

$$L = \frac{\Delta p g_c}{\rho g} = \frac{(28.74 \text{ inHg} - 19.14 \text{ inHg})(0.4912 \text{ psi/inHg})(144 \text{ in}^2/\text{ft}^2)\left(32.1739 \ \frac{\text{lbm-ft}}{\text{lbf-s}^2}\right)}{(0.05993 \text{ lbm/ft}^3)(31.2 \text{ ft/sec}^2)}$$

$$= 11{,}703 \text{ ft}$$

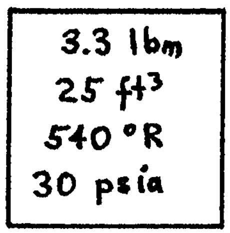
Problem *5.13

An unknown gas has a mass of 3.3 lbm and occupies 25 ft^3 while at 540°R and 30 psia. Determine the gas constant.

Given: Unknown gas, with mass, volume, temperature and pressure given.

Find: Gas constant.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: Using ideal-gas equation.

$$pV = mRT$$

$$R = \frac{pV}{mT} = \frac{(30\ \text{psia})(144\ \text{in}^2/\text{ft}^2)(25\ \text{ft}^3)}{(3.3\ \text{lbm})(540°\text{R})}$$

$$= 60.61\ \text{ft-lbf/lbm-R}$$

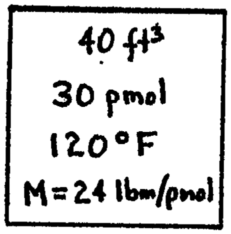
Problem *5.17

A rigid 40 ft^3 tank contains 30 pmol of an ideal gas at 120°F with a molecular weight of 24 lbm/pmol. (a) Determine the gas pressure; (b) Heat transfer occurs, and the temperature decreases to 60°F. What is the pressure?

Given: Rigid tank contains an ideal gas.

Find: Pressure before and after heat transfer.

Sketch and Given Data:



Assumptions: 1) Gas is in equilibrium.

Analysis: Using the ideal gas equation, equation 5.5.

(a) $pV = n\bar{R}T$

$$p = \frac{n\bar{R}T}{V} = \frac{(30\text{ pmol})(1545.32\text{ ft-lbf/lbm-R})(579.67°\text{R})}{(40\text{ ft}^3)}$$

$$= 671{,}832\text{ lbf/ft}^2$$

$$= 4665.5\text{ psia}$$

Recalculating for T = 60°F.

(b) $$p = \frac{(30\text{ pmol})(1545.32\text{ ft-lbf/lbm-R})(519.67°\text{R})}{(40\text{ ft}^3)} = 602{,}292\text{ lbf/ft}^2$$

$$= 4182.6\text{ psia}$$

Problem *5.21

Determine the pressure range for air in psia for $0.95 < Z < 1.05$ at temperatures of $2T_c$, $3T_c$ and $4T_c$, where T_c is the critical temperature.

Given: Air at two, three, and four times critical temperature.

Find: Pressure range for z between 0.95 and 1.05.

Assumptions: 1) Air is in equilibrium.

Analysis: Using Figure 5.4 for T_r = 2, 3, and 4, for $0.95 < Z < 1.05$.

$2T_c$ (T_r = 2) p_r ranges from 0 to 7.25

$3T_c$ (T_r = 3) p_r ranges from 0 to 4.25

$4T_c$ (T_r = 4) p_r ranges from 0 to 3.25

From Table 5.3, p_c = 3.76 MPa = 545.34 psia, therefore, pressure ranges for $0.95 < Z < 1.05$ are.

$2T_c$ - p from 0 to 3954 psia

$3T_c$ - p from 0 to 2318 psia

$4T_c$ - p from 0 to 1772 psia

Comment: 1) For T = > $2T_c$, Z is always above 0.95. The upper limit on pressure is limited by $Z > 1.05$.

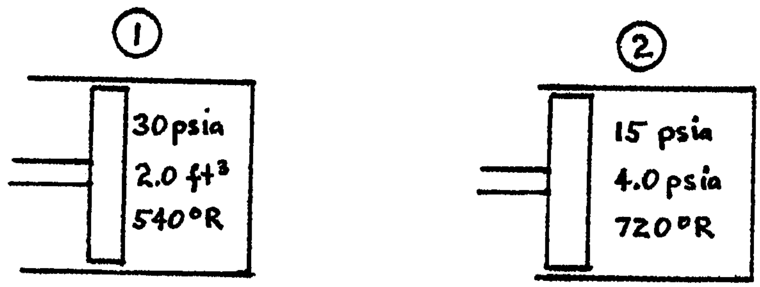
Problem *5.25

Air expands in a piston/cylinder from 30 psia, 2.0 ft³ and 540°R to a final state of 4.0 ft³ and 720°R. The pressure varies linearly with volume during the process. Determine the work and the heat transfer.

Given: Air expanding in piston-cylinder, with pressure varying linearly with volume.

Find: Work and heat transfer.

Sketch and Given Data:



Assumptions: 1) Air is in equilibrium.

Analysis: Calculating mass using ideal gas law. From Appendix A.1, R = 53.34 ft-lbf/lbm-R.

$$m = \frac{pV}{RT} = \frac{(30\ \text{psia})(144\ \text{in}^2/\text{ft}^2)(2.0\ \text{ft}^3)}{(53.34\ \text{ft/lbf/lbm-R})(540°\text{R})} = 0.30\ \text{lbm}$$

Calculate work using $W = \int pdV$. Since pressure varies linearly with volume, pV = constant.

$$W = \int_1^2 pdV = \int_1^2 p_1V_1 \frac{dV}{V} = p_1V_1 \ln\left(\frac{V_2}{V_1}\right)$$

$$= (30\ \text{psia})(144\ \text{in}^2/\text{ft}^2)(2.0\ \text{ft}^3)\left[\ln\left(\frac{4.0\ \text{ft}^3}{2.0\ \text{ft}^3}\right)\right] = 5989\ \text{ft-lbf}$$

From Appendix A.1, c_v = 0.1714 Btu/lbm-R.

$$\Delta U = mc_v \, \Delta T = (0.30 \text{ lbm})(0.1714 \text{ Btu/lbm-R})(720°R - 540°R)$$

$$= 9.2556 \text{ Btu} = 7202 \text{ ft-lbf}$$

First law equation for closed system.

$$Q = \Delta U + W$$

$$Q = 7202 \text{ ft-lbf} + 5989 \text{ ft-lbf}$$

$$= 13{,}191 \text{ ft-lbf}$$

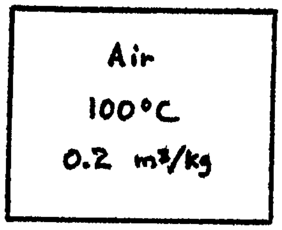
Problem C5.1

Compute the pressure of air at a temperature 100°C and a specific volume of 0.2 m^3/kg using (a) the ideal-gas law, (b) the van der Waals equation, (c) the Beattie-Bridgeman equation, (d) the Redlich-Kwong equation.

Given: Air at 100°C and 0.2 m^3/kg.

Find: Pressure using four equations of state.

Sketch and Given Data:



Assumptions: 1) Air is in equilibrium.

Analysis: Using TK Solver, enter the ideal-gas, van der Waals, Beattie-Bridgeman, and Redlich-Kwong equations into the Rule Sheet. Enter the input data into the Rule Sheet and solve.

RULE SHEET

```
S Rule
  p1*vbar1=8.31434*T1        "Perfect Gas Law
  M*v1=vbar1

  p2=8.31434*T2/(vbar2-b2)-a2/vbar2^2    "van der Walls Equation
  M*v2=vbar2
  a2=27/64*(8.31434)^2*(Tc)^2/pc
  b2=(8.31434)*Tc/(8*pc)

  p3=8.31434*T3*(1-E)/vbar3^2*(vbar3+B)-A/vbar3^2  "Beattie-Bridgeman Equation
  M*v3=vbar3
  A=Ao*(1-a3/vbar3)
  B=Bo*(1-b3/vbar3)
  E=c3/(vbar3*T3^3)

  p4=8.31434*T4/(vbar4-b4)-a4/(T4^.5*vbar4*(vbar4+b4)) "Redlich-Kwong Equation
  M*v4=vbar4
  a4=29.551*Tc^2.5/pc
  b4=.720354*Tc/pc
```

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					Problem C5.1
	28.97	M		kg/mole	Molecular Mass
	3760	pc		kPa	Critical Pressure
	133	Tc		degK	Critical Temperature
					Perfect Gas Law
		p1	535.47	kPa	
	100	T1		degC	
	.2	v1		m3/kg	
		vbar1	5.794	m3/kgmole	
					van der Walls Equation
		p2	534.8	kPa	
	100	T2		degC	
	.2	v2		m3/kg	
		vbar2	5.794	m3/kgmole	
		b2	.036762		
		a2	137.2		
					Beattie-Bridgeman Equation
		p3	535.74	kPa	
	100	T3		degC	
	.2	v3		m3/kg	
		vbar3	5.794	m3/kgmole	
		E	.00014417		
		B	.046119		
		A	131.4		
	131.84	Ao			
	.01931	a3			
	.04611	Bo			
	-.001101	b3			
	43400	c3			
					Redlich-Kwong Equation
		p4	535.37	kPa	
	100	T4		degC	
	.2	v4		m3/kg	
		vbar4	5.794	m3/kgmole	
		b4	.025481		
		a4	1603.3		

Comment: This problem can also be easily solved using a spreadsheet problem.

Problem C5.5

Compute the compressibility factor for nitrogen using the Redlich-Kwong equation for temperatures of 300°K and 150°K and a range of pressures between 100 kPa and 30 MPa. Plot the results and compare them to Figure 5.5.

Given: Nitrogen at temperatures of 300°K and 150°K, and pressures between 100 kPa and 30 MPa.

Find: Compressibility factor using Redlich-Kwong equation. Plot.

Assumptions: 1) Gas is in equilibrium.

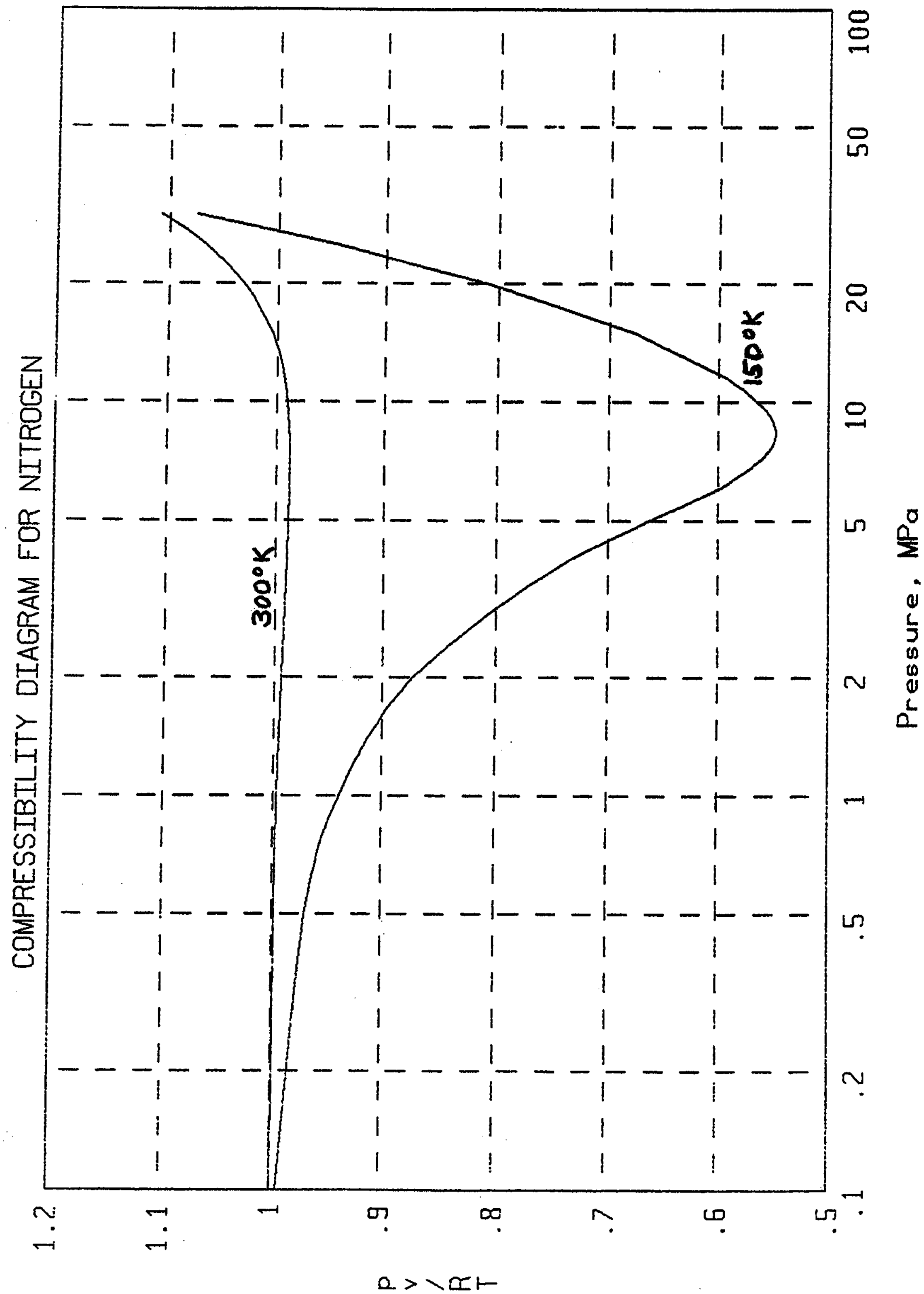
Analysis: Enter the Redlich-Kwong equation and definition of compressibility factor in the Rule Sheet of TK Solver. Enter the constants for Nitrogen, and input pressure and temperature into the Rule Sheet. Use the List Solver to calculate the compressibility factor for the combinations of pressure and temperature. Plot the results using the Plot Sheet.

```
============================ VARIABLE SHEET ============================
St Input---- Name---- Output---- Unit------ Comment-----------------------
                                            Problem C5.5

   28.013    M                    kg/mole   Molecular Mass
   3390      pc                   kPa       Critical Pressure
   126.2     Tc                   degK      Critical Temperature

                                            Redlich-Kwong Equation
L  20        p4                   MPa
L  150       T4                   degK
             v4       .0018041    m3/kg
L            vbar4    .050539     m3/kgmole
             b4       .026817
             a4       1559.6
L            Z4       .81047                Compressibility Factor

============================ RULE SHEET ============================
S Rule-------------------------------------------------------------------
  p4=8.31434*T4/(vbar4-b4)-a4/(T4^.5*vbar4*(vbar4+b4)) "Redlich-Kwong Equation
  M*v4=vbar4
  a4=29.551*Tc^2.5/pc
  b4=.720354*Tc/pc
  Z4=p4*v4/((8.31434/M)*T4)
```


COMPRESSIBILITY DIAGRAM FOR NITROGEN
300°K
150°K
P V / R T
1.2
1.1
1
.9
.8
.7
.6
.5
.1
.2
.5
1
2
5
10
20
50
100
Pressure, MPa

Problem C5.9

Using the equation in Table 5.4, compute and plot curves of specific heat ratio (k) versus temperature in the range of 300°K to 1500°K for (a) methane; (b) ethane; (c) propane.

Given: Methane, ethane, and propane at temperatures from 300°K to 1500°K.

Find: Specific heat ratio. Plot data.

Assumptions: 1) Gases are in equilibrium.

Analysis: Specific heat at constant pressure (cp) is calculated at each temperature using the equations in Table 5.4. The specific heat ratio is calculated as follows.

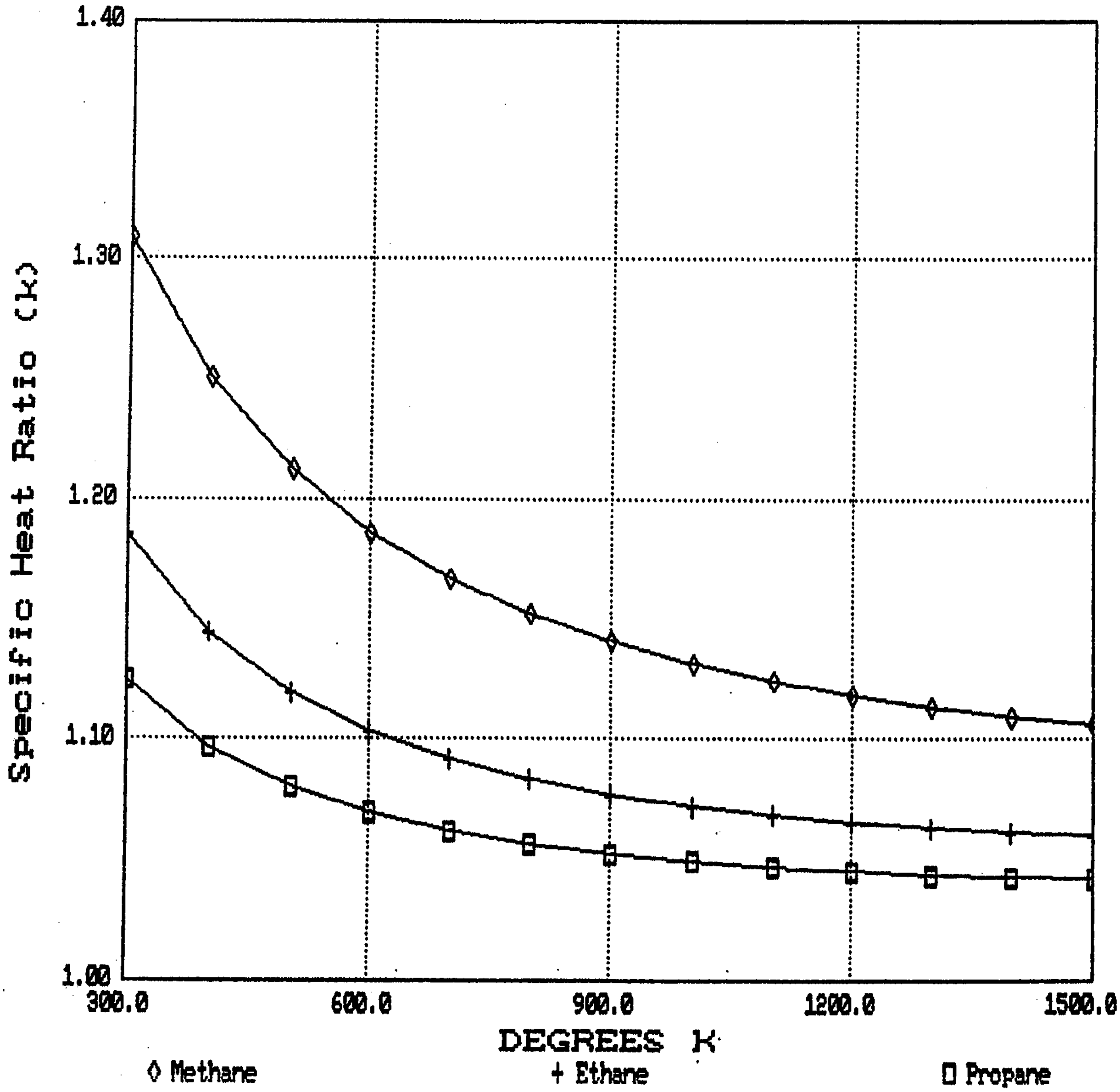
$$c_v = c_p - R$$

$$k = \frac{c_p}{c_v} = \frac{c_p(T)}{c_p(T) - R}$$

Enter the equations into the cells of a spreadsheet or the Rule Sheet of TK Solver. The results calculated using a spreadsheet program are shown below.

Problem C5.9

	Cp			k		
deg C	methane	ethane	propane	methane	ethane	propane
300.0000	2.1951	1.7703	1.7077	1.3091	1.1851	1.1242
400.0000	2.5875	2.1972	2.1388	1.2505	1.1440	1.0967
500.0000	2.9574	2.5935	2.5365	1.2125	1.1193	1.0803
600.0000	3.3049	2.9592	2.9008	1.1860	1.1031	1.0695
700.0000	3.6299	3.2943	3.2317	1.1666	1.0916	1.0620
800.0000	3.9325	3.5988	3.5292	1.1518	1.0832	1.0565
900.0000	4.2126	3.8727	3.7933	1.1403	1.0769	1.0523
1000.0000	4.4702	4.1160	4.0240	1.1312	1.0720	1.0492
1100.0000	4.7054	4.3287	4.2213	1.1238	1.0682	1.0468
1200.0000	4.9181	4.5108	4.3852	1.1178	1.0653	1.0449
1300.0000	5.1083	4.6623	4.5157	1.1129	1.0630	1.0436
1400.0000	5.2761	4.7832	4.6128	1.1089	1.0614	1.0426
1500.0000	5.4214	4.8735	4.6765	1.1057	1.0601	1.0420


1.40
1.30
1.20
1.10
1.00
Specific Heat Ratio (k)
300.0
600.0
900.0
1200.0
1500.0
DEGREES K
◊ Methane
+ Ethane
□ Propane

CHAPTER 6

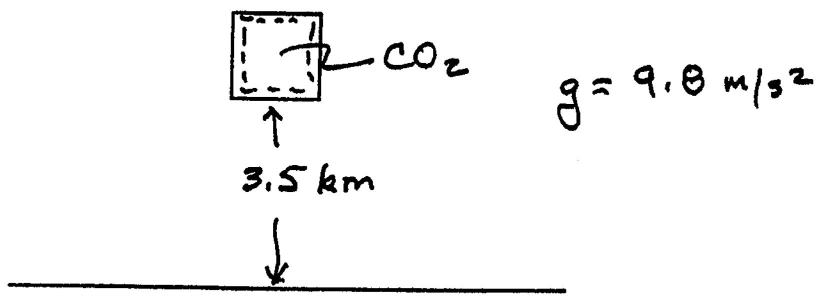
Problem 6.1

An insulated box containing carbon dioxide gas falls from a balloon 3.5 km above the earth's surface. Determine the temperature rise of the carbon dioxide when the box hits the ground.

Given: An insulated box containing a gas falls to the ground.

Find: The temperature of the gas after hitting the ground.

Sketch and Given Data:



Assumptions:
1) The gas in the container is a closed system.
2) The heat and work are zero.
3) The charge of kinetic energy is zero.
4) Carbon dioxide is an ideal gas.

Analysis: The first law for a closed system is.

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 & 3, yielding

$$\Delta U = \Delta PE$$

$$m(u_2 - u_1) = -mg(Z_2 - Z_1) = mg(Z_1 - Z_2)$$

$$u_2 - u_1 = g(Z_1 - Z_2)$$

The equation of state for internal energy of an ideal gas is

$$\Delta u = c_v \Delta T$$

$$c_v(\Delta T) = g(Z_1 - Z_2)$$

$$\left(0.6552 \ \frac{kJ}{kg.K}\right)(\Delta T \ K) = (9.8 \ m/s^2)(3.5 - 0 \ km)$$

$$\Delta T = \underline{52.4°K}$$

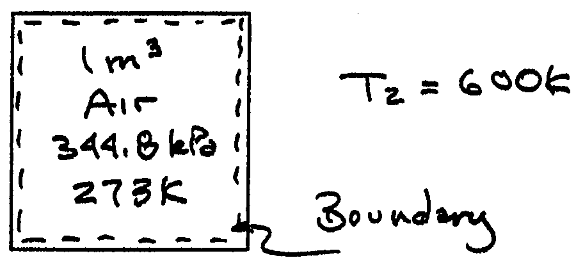
Problem 6.5

A closed rigid container has a volume of 1 m^3 and holds air at 344.8 kPa and 273 K. Heat is added until the temperature is 600 K. Determine the heat added and the final pressure.

Given: Air is contained in a tank and heat is added, raising its temperature. The initial and Final states are known.

Find: The heat added and the final pressure.

Sketch and Given Data:



Assumptions:
1) The air in the tank is a constant volume closed system.
2) The system work is zero.
3) The changes in kinetic and potential energies are zero.
4) Air is and ideal gas.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = \Delta U$$

The ideal gas equation of state for internal energy is

$$\Delta U = mc_v(T_2 - T_1)$$

In this equation, the mass needs to be determined from the ideal gas law.

$$m = \frac{pV}{RT} = \frac{\left(344.8\ \frac{kN}{m^2}\right)(1\ m^3)}{\left(0.287\ \frac{kJ}{kg.K}\right)(273\ K)} = 4.4\ kg$$

The internal energy change is

$$\Delta U = (4.4 \text{ kg})\left(0.7176 \frac{\text{kJ}}{\text{kg.K}}\right)(600 - 273\text{K}) = 1032.5 \text{ kJ}$$

and the heat is

a) $Q = \Delta U = \underline{1032.5 \text{ kJ}}$

The final pressure may be found from the ideal gas law.

$$p_2 = \frac{mRT_2}{V_2} = \frac{(4.4 \text{ kg})\left(0.287 \frac{\text{kJ}}{\text{kg.K}}\right)(600 \text{ K})}{(1 \text{ m}^3)}$$

$p_2 = \underline{758 \text{ kPa}}$

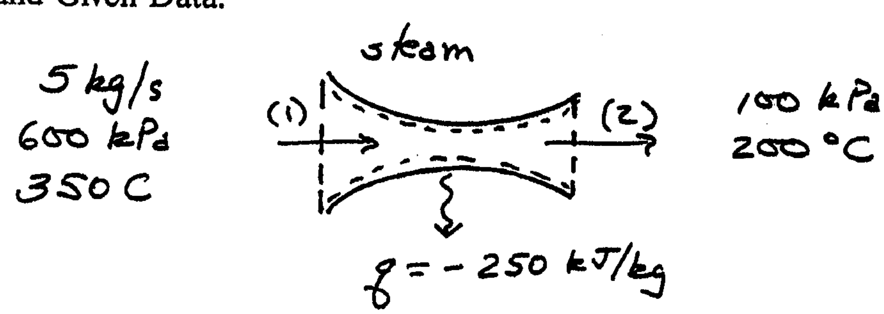
Problem 6.9

A nozzle receives 5 kg/s of steam at 0.6 MPa and 350°C and discharges it at 100 kPa and 200°C. The inlet velocity is negligible, the heat loss is 250 kJ/kg. Determine the exit velocity.

Given: Steam flows steadily through a nozzle which is an open system.

Find: The exit steam velocity.

Sketch and Given Data:



Assumptions:
1) The nozzle is a steady-state open system.
2) The work is zero.
3) The change of potential energy is zero.
4) The inlet kinetic energy is zero.
5) Steam is a pure substance.

Analysis: The first law for an open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions (2), (3), and (4).

$$\dot{Q} + \dot{m}h_1 = \dot{m}(h + ke)_2$$

Divide by $\dot{m}$ $$q + h_1 = h_2 + ke_2$$

The enthalpy of steam is found from the steam tables.

$h_1 = 3165.6$ kJ/kg $h_2 = 2875.1$ kJ/kg

Substitute in the first law equation.

$$(-250 \text{ kJ/kg}) + (3165.6 \text{ kJ/kg}) = (2875.1 \text{ kJ/kg}) + \frac{(v_2 \text{ m/s})^2}{(2)(1000 \text{ J/kJ})}$$

$\underline{v_2 = 284.6 \text{ m/s}}$

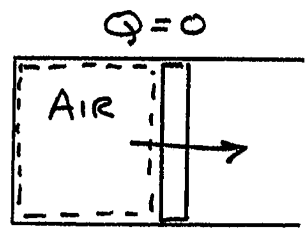
Problem 6.13

Air in a piston-cylinder occupies 0.12 m^3 at 552 kPa. The air expands in a reversible adiabatic process,doing work on the piston until the volume is 0.24 m^3. Determine (a) the work of the system; (b) the net work if the atmospheric pressure is 101 kPa.

Given: Air in a piston/cylinder expands in a reversible adiabatic process. The initial and final states are known.

Find: The system work and the net work.

Sketch and Given Data:



$V_1 = 0.12\ m^3$ $\quad p_1 = 552\ kPa$

$V_2 = 0.24\ m^3$

$P_{atm} = 101\ kPa$

Assumptions:

1) The air in the piston/cylinder is a closed system
2) The process is reversible adiabatic, $pV^k = C$.
3) The heat flow is zero.
4) Changes in kinetic and potential energies are zero.
5) Air is an ideal gas.

Analysis: From equation 6.19b the work for a reversible adiabatic process is

$$W = \frac{p_2V_2 - p_1V_1}{1 - k}$$

For $pV^k = C$,

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^k = (552\ \text{kPa})\left(\frac{0.12}{0.24}\right)^{1.4} = 209.2\ \text{kPa}$$

$$W = \frac{(209.2\ \text{kN/m}^2)(0.24\ \text{m}^3) - \left(552\ \frac{\text{kN}}{\text{m}^2}\right)(0.12\ \text{m}^3)}{1 - 1.4}$$

a) $\underline{W = 40.1\ \text{kJ}}$

The net work is

$$W_{net} = W - W_{atm}$$

$$W_{atm} = P_{atm}\,(V_2 - V_1) = \left(101\ \frac{kN}{m^2}\right)(0.24 - 0.12\ m^3)$$

$$W_{atm} = 12.1\ kJ$$

b) $W_{net} = 40.1 - 12.1 = \underline{28\ kJ}$

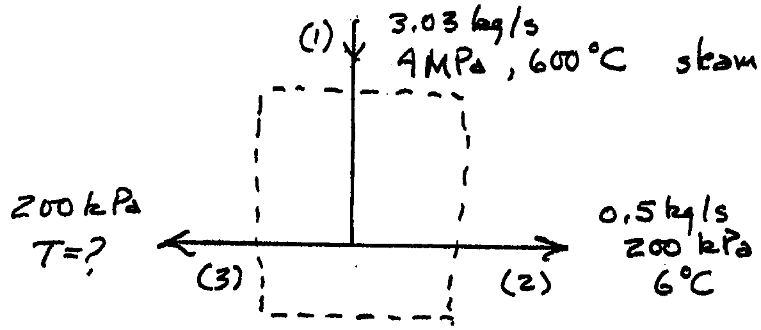
Problem 6.17

An adiabatic device looks like an inverted T with 3.03 kg/s of steam at 4 MPa and 600°C entering from the top, and two streams, one at 0.5 kg/s, 0.2 MPa, and 6°C exiting horizontally, and the other at 0.2 MPa and an unknown temperature, also exiting horizontally. Determine the unknown temperature.

Given: Steam flows through an adiabatic open system splitting into two streams at the exit.

Find: The temperature of one of the exit streams.

Sketch and Given Data:



Assumptions:
1) The device is an adiabatic open system with steady flows into and out of it.
2) Heat and work are zero.
3) Changes in kinetic and potential energies are zero.
4) Steam is a pure substance.

Analysis: Perform a first law analysis on the system

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 = \dot{W} + \dot{m}_2(h + ke + pe)_2 + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions (2) and (3)

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

From the steam tables $h_1 = 3672.9 \frac{kJ}{kg}$, $h_2 = 24.6$ kJ/kg

From the conservation of mass, $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$,

$$\dot{m}_3 = 3.03 - 0.5 = 2.53 \text{ kg/s}$$

Substituting the first law yields

$(3.03 \text{ kg/s})(3672.9 \text{ kJ/kg}) = (0.5 \text{ kg/s})(24.6 \text{ kJ/kg}) + (2.53 \text{ kg/s})(h_3)$

$h_3 = 4393.9 \text{ kJ/kg}$

$p_3 = 200 \text{ kPa}$

From the superheat steam tables

$T_3 = \underline{900.2°C}$

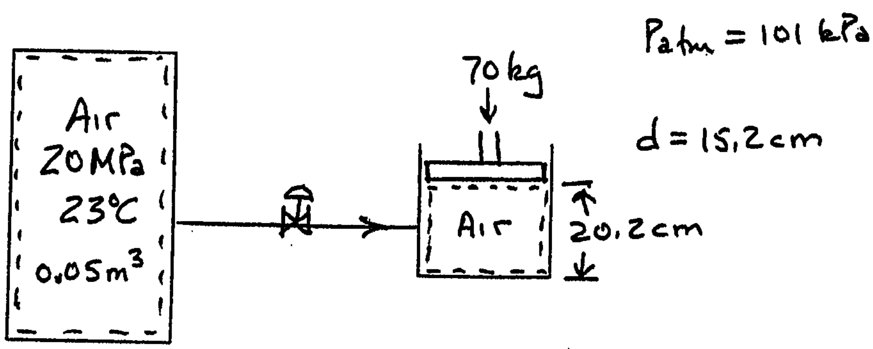
Problem 6.21

A pneumatic lift system is being demonstrated at a sales show. The total load is 70 kg, and the lift piston is 15.2 cm in diameter and has an 20.2-cm stroke. A portable air bottle with an initial pressure of 20 MPa and a temperature of 23°C is to be used as the pneumatic supply. A regulator reduces the pressure from the bottle to the lift system. Neglecting all volume in the lines from the bottle to the piston, determine the number of times the piston can operate per air bottle if the air in the bottle remains at 23°C and the volume of the bottle is 0.05 m³.

Given: A piston/cylinder contains air at a constant pressure used to raise a lift system. The air is supplied from a storage tank of known volume, temperature and pressure.

Find: The number of lifts that can occur until insufficient supply air is available.

Sketch and Given Data:



Assumptions: 1) Air is an ideal gas.

Analysis: In this problem, air leaves the air bottle, is reduced in pressure and enters the piston/cylinder. If we determine the total mass of air available in the air bottle and divide this by the air used lifting cycle, we can find the number of lifts possible.

The pressure in the piston/cylinder is found by dividing the force acting on the piston by its area and adding atmospheric pressure.

$$F = ma = \frac{(70 \text{ kg})(9.8 \text{ m/s}^2)}{(1000 \text{ n/kN})} = 0.868 \text{ kN}$$

$$A = \frac{\pi}{4}d^2 = \frac{\pi}{4}(0.154)^2 = 0.01863 \text{ m}^2$$

$$p = 101.3 \text{ kPa} + \frac{0.686 \text{ kN}}{0.01863} = 138.1 \text{ kPa}$$

$$V = \frac{\pi}{4}D^2L = \frac{\pi}{4}(0.154)^2(0.202) = 0.003762 \text{ m}^3$$

$$m = \frac{pV}{RT} = \frac{(138.1 \text{ kN/m}^2)(0.003762 \text{ m}^3)}{(0.287 \text{ kJ/kg-K})(296 \text{ K})} = 0.006116 \text{ kg/lift}$$

The mass in the tank is

$$m_T = \frac{pV}{RT} = \frac{(20000 - 138 \text{ kN/m}^2)(0.05 \text{ m}^3)}{(0.287\text{kJ/kg.K})(296\text{K})} = 11.69 \text{ kg}$$

The number of lifts is.

$$N = \frac{(11.69 \text{ kg})}{(0.006116 \text{ kg/lift})} = 1911.3 \text{ or } 1911 \text{ lifts}$$

Comments:

1) It is necessary to subtract the cylinder pressure from 20 MPa as air cannot flow from the bottle to the lift at a pressure less than this.

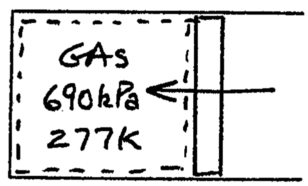
Problem 6.25

An ideal gas with a molecular weight of 6.5 kg/Kgmol is compressed in a reversible manner from 690 kPa and 277 K to a final specific volume of 0.47 m³/kg according to $p = 561 + 200v + 100v^2$, where p is the pressure in kPa and v is the specific volume in m³/kg. The specific heat at constant volume is 0.837 kJ/kg·K. Determine (a) the work; (b) the heat; (c) the final temperature; (d) the initial specific volume.

Given: An ideal gas is compressed in a reversible process from initial to final states. The gas constants are given.

Find: The work of compression, the heat transfer, the final temperature and the initial specific volume of the gas.

Sketch and Given Data:



$v_2 = 0.47\ m^3/kg$

$M = 6.5\ kg/kgmol$

$p = 561 + 200v + 100v^2\ kPa$

$c_v = 0.837\ kJ/kg\text{-}K$

Assumptions:
1) The gas is an ideal gas with constant specific heats.
2) The process is reversible.
3) Changes in kinetic and potential energies are zero.

Analysis: Determine the individual gas constant.

$$R = \frac{\bar{R}}{M} = \frac{(8.3143\ \text{kJ/kg mol-K})}{(6.5\ \text{kg/kg mol})} = 1.279\ \frac{\text{kJ}}{\text{kg.K}}$$

From the ideal gas equation of state.

d) $$v_1 = \frac{RT_1}{p_1} = \frac{\left(1.279\ \frac{\text{kJ}}{\text{kg-K}}\right)(277\ \text{K})}{(690\ \text{kN/m}^2)} = \underline{0.5135\ \text{m}}^3\text{/kg}$$

$$p_2 = 561 + 200v + 100\ v^2\ \text{kPa}$$

$$p_2 = (561) + (200)(0.47) + (100)(0.47)^2 = \underline{677.1\ \text{kPa}}$$

c) $$T_2 = \frac{P_2 v_2}{R} = \frac{(677.1\ \text{kN/m}^2)\left(0.47\ \frac{\text{m}^3}{\text{kg}}\right)}{(1.279\ \text{kJ/kg-K})} = 248.8\ \text{K}$$

The work is found by integrating the p(v) function from v_1 to v_2.

$$w = \int p dv = \int_{0.5135}^{0.47} (561 + 200v + 100v^2\ \text{kN/m}^2)(dv\ \text{m}^3/\text{kg})$$

a) $$w = \left[561v = 100v^2 + 33.3v^3\right]_{0.5135}^{0.47} = -29.7\ \text{kJ/30kg}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions (3) and divide by m, yielding

$$q = \Delta u + w$$

For an ideal gas $\Delta u = c_v(T_2 - T_1)$

$$q = c_v(T_2 - T_1) + w = (0.837\ \text{kJ/kg-K})(248.8 - 277\ \text{K}) - 29.7\ \frac{\text{kJ}}{\text{kg}}$$

b) q = <u>-53.3 kJ/kg</u>

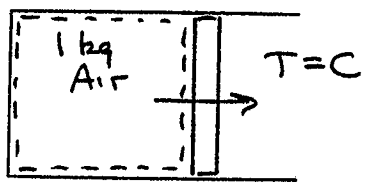
Problem 6.29

One kilogram of air expands at a constant temperature from a pressure of 800 kPa and a volume of 2 m^3 to a pressure of 200 kPa. Determine (a) the work; (b) the heat; (c) the change of internal energy; (d) the change of enthalpy.

Given: One kilogram of air expands at constant temperature between two known states.

Find: The heat and work and the change of enthalpy and internal energy.

Sketch and Given Data:



$P_1 = 800$ kPa
$V_1 = 2\ m^3$
$P_2 = 200$ kPa

Assumptions:
1) The air is a closed system.
2) Neglect changes in kinetic and potential energies.
3) Air is an ideal gas.
4) The process is reversible and isothermal.

Analysis: For an ideal gas $\Delta U = mc_v (T_2 - T_1)$ and $\Delta H = mc_p(T_2 - T_1)$. If the temperature is constant, as it is in this problem,

d) $\underline{\Delta H = 0}$

c) $\underline{\Delta U = 0}$

From equation 6.9

$$W = p_1V_1 \ln\left(\frac{V_2}{V_1}\right) = p_1V_1 \ln\left(\frac{p_1}{P_2}\right)$$

$$W = \left(800\ \frac{kN}{m^2}\right)(2\ m^3)\ln\left(\frac{800}{200}\right)$$

a) $W = \underline{2218\ kJ}$

From the first law

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions (2) and result (c).

b) $Q = W = \underline{2218\ \text{kJ}}$

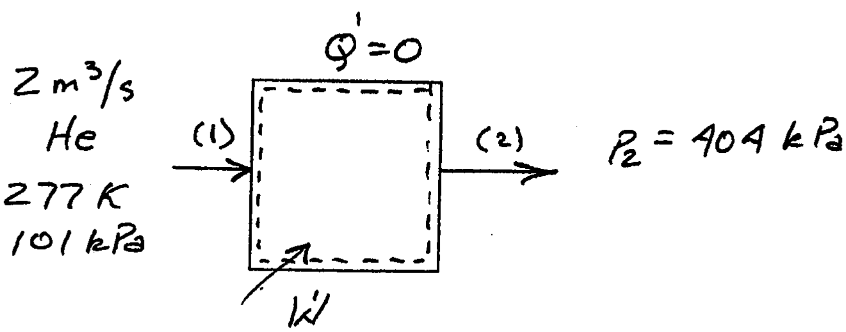
Problem 6.33

Two cubic meters per second of helium at 277 K and 101 kPa are compressed to 404 kPa in a reversible adiabatic manner. Determine (a) the final temperature; (b) the power required.

Given: A compressor has a steady volume flowrate of helium enter it and leave at a higher pressure, reversibly and adiabatically.

Find: The discharge temperature of the helium and the power required for compression.

Sketch and Given Data:



Assumptions:
1) The compression is an open system with steady flow through it.
2) The heat flow is zero.
3) Changes in kinetic and potential energies are zero.
4) Helium is an ideal gas.

Analysis: A reversible adiabatic process for an ideal gas relates temperature and pressure variation as

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{k-1/k}$$

a) $$T_2 = (277\ \mathrm{K})\left(\frac{404}{101}\right)^{\frac{0.666}{1.666}} = 482.1\ \mathrm{K}$$

The power required may be found from Equation 6.23 or from a first law analysis. The equation is

$$\dot{W} = \frac{k}{k-1}\,\dot{m}RT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]$$

The mass flowrate is determined from the ideal gas law

$$\dot{m} = \frac{p_1 \dot{V}_1}{RT_1} = \frac{(101\ \text{kN/m}^2)(2\ \text{m}^3/\text{s})}{(2.077\ \text{kJ/kg.K})(277\ \text{K})} = 0.3511\ \text{kg/s}$$

The power becomes

$$\dot{W} = \frac{1.666}{0.666}(0.3511\ \text{kg/s})(2.077\ \text{kJ/kg-K})(277\ \text{K})\left[1 - \left(\frac{404}{101}\right)^{\frac{0.666}{1.666}}\right]$$

$$\dot{W} = -374.2\ \text{kW}$$

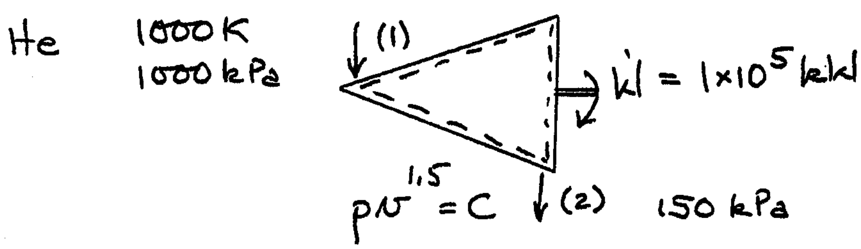
Problem 6.37

Helium expands polytropically through a turbine according to the process $pV^{1.5} = C$. The inlet temperature is 1000 K, the inlet pressure is 1000 kPa, and the exit pressure is 150 kPa. The turbine produces 1×10^5 kW. Determine (a) the exit temperature; (b) the heat transferred (kW); (c) the mass flowrate.

Given: Helium, an ideal gas, expands steadily through a turbine in a polytropic process from inlet to exit states.

Find: The exit helium temperature, the heat flux and the mass flowrate.

Sketch and Given Data:



Assumptions:
1) Helium, an ideal gas, flows steadily though the open system formed by the gas turbine.
2) Changes in kinetic and potential energies are zero.

Analysis: The problem is a steady-state system. Determine the exit temperature from the polytropic temperature and pressure relationship.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

a) $$T_2 = (1000\ \text{K})\left(\frac{150}{1000}\right)^{\frac{0.5}{1.5}} = \underline{531.3\ \text{K}}$$

The power from the turbine is given by Equation 6.23.

$$\dot{W} = \frac{n}{n-1}\,\dot{m}RT_1\left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$(+1 \times 10^5 \text{ kW}) = \frac{1.5\ (\dot{m}\text{kg/s})(2.077\text{ kJ/kg-K})(1000\text{ K})}{0.5}\left[1 - \left(\frac{150}{1000}\right)^{\frac{0.5}{1.5}}\right]$$

c) $\dot{m} = 34.24$ kg/s

The first law for a steady-state open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumption (2).

$$\dot{Q} = \dot{W} + \dot{m}(h_2 - h_1)$$

For an ideal gas, $\Delta h = c_p\,\Delta T$

$$\dot{Q} = \dot{W} + \dot{m}c_p(T_2 - T_1)$$

$$\dot{Q} = (1 \times 10^5\text{ kW}) + (34.24\text{ kg/s})(5.1954\text{ kJ/kg.K})(531.3 - 1000\text{ K})$$

b) $\dot{Q}$ = 16 623 kW (heat in)

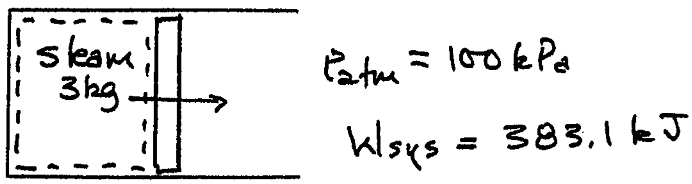
Problem 6.41

In the previous problem the atmospheric pressure is 100 kPa. Determine the net system work.

Given: The atmospheric pressure against which the piston is Problem 6.40 expands.

Find: The net work.

Sketch and Given Data:



Assumptions: 1) The air pressure remains constant at 100 kPa.

Analysis: From the previous problem we found the system work to be 383.1 kJ. The net work is

$$W_{net} = W_{sys} - W_{surr}$$

$$W_{surr} = \int p_{surr}\, dV = p_{surr}\,(V_2 - V_1) = m p_{surr}(v_2 - v_1)$$

Using the data values from Problem 6.40,

$$W_{surr} = (3\text{ kg})(100\text{ kN/m}^2)(1.0316 - 0.6059\text{ m}^3\text{/kg})$$

$$W_{surr} = 127.7\text{ kJ}$$

$$W_{net} = 383.1 - 127.7 = \underline{255.4\text{ kJ}}$$

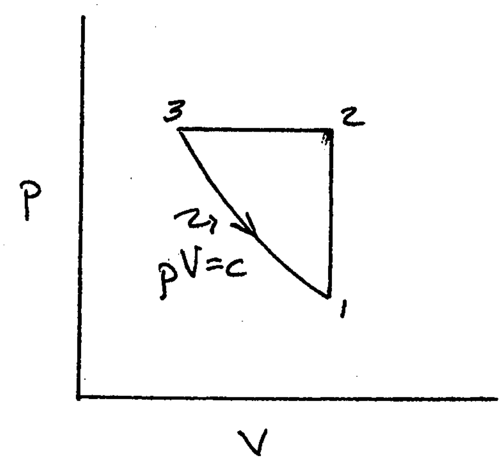
Problem 6.45

Two kilograms of helium operate on a three-process cycle where the processes are; constant volume (1-2); constant pressure (2-3); and constant temperature (3-1). Given that p_1 = 100 kPa, T_1 = 300 K, and v_1/v_3 = 5, determine (a) the pressure, specific volume and temperature around the cycle; (b) the work for each process; (c) the heat added.

Given: Helium, an ideal gas, is a closed system that operates on a three-process cycle. The processes and certain states are defined.

Find: The temperature, pressure and volume for each state point and the work for each process as well as the total heat added.

Sketch and Given Data:



Assumptions:
1) Helium is a closed system
2) Changes in kinetic and potential energies are zero.
3) Helium is an ideal gas.
4) The processes are reversible.

Analysis: The first law for any process is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2).

$$Q = \Delta U + W$$

For an ideal gas $\Delta U = mc_v (T_2 - T_1)$

Determine T, p and v at each state.

State 1

$$p_1 = 100 \text{ kPa} \qquad T_1 = 300 \text{ K}$$

$$v_1 = \frac{RT_1}{P_1} = \frac{(2.077 \text{ kJ/kg-K})(300 \text{ K})}{(100 \text{ kN/m}^2)} = 6.231 \text{ m}^3\text{/kg}$$

State 3

$$T_3 = T_1 = 300 \text{ K} \qquad v_3 = \frac{v_1}{5} = \frac{6.231}{5} = 1.246 \text{ m}^3\text{/kg}$$

a) $$p_3 = \frac{RT_3}{v_3} = \frac{(2.077 \text{ kJ/kg-K})(300 \text{ K})}{(1.246 \text{ m}^3\text{/kg})} = 500 \text{ kPa}$$

State 2

$$p_2 = p_3 = 500 \text{ kPa} \quad v_2 = v_1 = 6.231 \text{ m}^3\text{/kg}$$

$$T_2 = p_2\frac{v_2}{R} = \frac{(500 \text{ kN/m}^2)(6.231 \text{ m}^3\text{/kg})}{(2.077 \text{ kJ/kg-K})} = 1500 \text{ K}$$

Determine the work for each process.

$$W_{1\text{-}2} = 0 \text{ as } dV = 0$$

$$W_{2\text{-}3} = \int_2^3 pdV = p_2(V_3 - V_2) \text{ for } p = c$$

$$W_{2\text{-}3} = mp_2(v_3 - v_2) = (2 \text{ kg})\left(500 \frac{\text{kN}}{\text{m}^2}\right)(1.246 - 6.231 \text{ m}^3\text{/kg})$$

b) $$W_{2\text{-}3} = -4985 \text{ kJ}$$

$$W_{3\text{-}1} = p_3V_3 \ln\left(\frac{V_1}{V_3}\right) = mRT_3 \ln\left(\frac{v_1}{v_3}\right)$$

$$W_{3\text{-}1} = (2 \text{ kg})(2.077 \text{ kJ/kg-K})(300 \text{ K})\ln(5) = 2005.7 \text{ kJ}$$

For an isothermal process, Q = W for an ideal gas;

$$Q_{3\text{-}1} = W_{3\text{-}1} = 2005.7 \text{ kJ}$$

$$Q_{1\text{-}2} = \Delta U + W = \Delta U \text{ as } W_{1\text{-}2} = 0$$

$$Q_{1\text{-}2} = mc_v(T_2 - T_1) = (2 \text{ kg})(3.1189 \text{ kJ/kg-K})(1500 - 300 \text{ K})$$

$$Q_{1\text{-}2} = 7485.4 \text{ kJ}$$

$$Q_{2\text{-}3} = \Delta H = mc_p(T_3 - T_2) = (2 \text{ kg})\left(5.1954 \frac{\text{kJ}}{\text{kg-K}}\right)(300 - 1500 \text{ K})$$

$$Q_{2\text{-}3} = -12469 \text{ kJ}$$

The total heat added is

c) $Q_{in} = 2005.7 + 7485.4 = \underline{9491.1 \text{ kJ}}$

Comments:

1) As a check on your work, notice That $\sum Q = \sum W$. In this case $\sum Q = -12469 + 9491.1 = -2977.9$ kJ and $\sum W = 0 - 4985 + 2005.7 = -2979.3$. The difference in the values is because of round-off errors.

2) The work is negative because this is a power consuming cycle. Notice it proceeds in a counter-clockwise direction. Power producing cycles proceed in a clockwise direction.

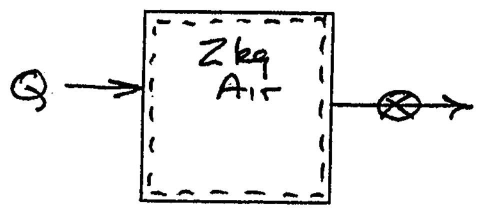
Problem 6.49

The tank in the preceding problem is now heated so that the temperature remains constant at 325 K. Determine the heat added.

Given: An adiabatic tank at known temperature and pressure is heated as it discharges so the air temperature in the tank is constant.

Find: The heat required.

Sketch and Given Data:



$P_1 = 3000$ kPa
$T_1 = 325$ K
$T_2 = 325$ K
$P_2 = 500$ kPa

Assumptions:
1) Air is an ideal gas.
2) Changes in kinetic and potential energies are zero.
3) The final tank pressure is 500 kPa.

Analysis: It is very complicated to analyze the instantaneous heat needed to maintain the air's temperature at 325 K. Consider, however, the process in two stages. The first stage is the discharge of the tank and the second stage is the heating of the air to 325 K.
Let state 1 be the initial state, state 2 be the state before reheating and state 3 the state where the air has been heated to 325 K and the pressure 500 kPa. Since the final pressure is 500 kPa, which occurs after heat has been added at constant volume. The pressure before heat addition is less than this. Find the mass at the final state.

The initial tank volume is

$$V_1 = \frac{mRT_1}{P_1} = \frac{(2\ \text{kg})(0.287\ \text{kJ/kg-K})(325\ \text{K})}{(3000\ \text{kN/m}^2)} = 0.06218\ \text{m}^3$$

At the final state

$$m_3 = \frac{P_3V_3}{RT_3} = \frac{(500\ \text{kN/m}^2)(0.06218\ \text{m}^3)}{(0.287\ \text{kJ/kg-K})(325\ \text{K})} = 0.3333\ \text{kg}$$

At the intermediary state, state 2, $m_2 = m_3$. Find the temperature at state 2.

$$T_2 = T_1 \left(\frac{m_2}{m_1}\right)^{k-1} = (325\ \text{K})\left(\frac{0.3333}{2.0}\right)^{0.4} = 158.7\ \text{K}$$

The first law for a closed system, the air being reheated is a closed system, is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2), and $W = 0$ for $V = c$.

$$Q = \Delta U$$

$$\Delta U = mc_v(T_3 - T_2) = (0.3333\ \text{kg})\left(0.7176\ \frac{\text{kJ}}{\text{kg-K}}\right)(325 - 158.7\ \text{K})$$

$$\Delta U = 39.8\ \text{kJ}$$

$Q =$ <u>39.8 kJ</u>

Problem 6.53

Air, initially at 120 kPa and 320 K, occupies 0.11 m^3 and is compressed isothermally until the volume is halved and then compressed at constant pressure until the volume decreases to one-quarter the initial volume. Sketch the processes on a p-V diagram, determine the total heat and total work for the two processes.

Given: Air, a closed system and ideal gas, is compressed in two stages.

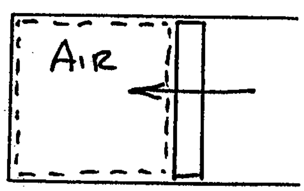
Find: The total heat and work required.

Sketch and Given Data:

$P_1 = 120$ kPa

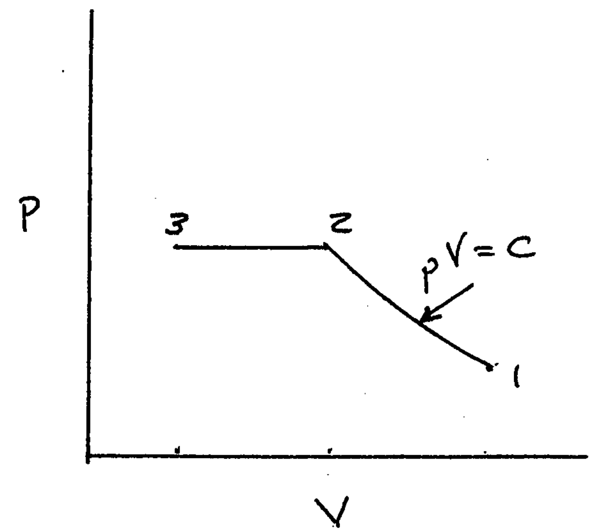
$T_1 = 320$ K

$V_1 = 0.11$ m^3



$V_2 = 0.5 V_1$

$V_3 = 0.25 V_1$



Assumptions:
1) Air is an ideal gas and forms a closed system.
2) Changes in kinetic and potential energies are zero.
3) The processes are reversible.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$Q = \Delta U + W$$

The work for an isothermal process where $V_2 = 1/2V_1$ is

$$W = p_1V_1 \ln\left(\frac{V_2}{V_1}\right) = \left(120\ \frac{kN}{m^3}\right)(0.11\ m^3)\ln(0.5) = -9.15\ kJ$$

For an isothermal process for an ideal gas

$$Q_{1\text{-}2} = W_{1\text{-}2} = -9.15\ kJ$$

For a constant pressure process for an ideal gas
T/V = C, hence

$$T_3 = T_2\left(\frac{V_3}{V_2}\right) = (320\ K)\left(\frac{1}{2}\right) = 160\ K$$

For p = c,

$$Q = \Delta H = mc_p(T_3 - T_2)$$

The mass is

$$m = \frac{p_1V_1}{RT_1} = \frac{(120\ kN/m^2)(0.11\ m^3)}{(0.287\ kJ/kg\text{-}K)(320\ K)} = 0.1437\ kg$$

$$Q = (0.1437\ kg)(1.0047\ kJ/kg\text{-}K)(160 - 320K) = -23.1\ kJ$$

The work may be found from the first law.

$$\Delta U = mc_v(T_3 - T_2) = (0.1437\ kg)(0.7176\ kJ/kg\text{-}K)(160 - 320\ K)$$

$$\Delta U = -16.5$$

$$Q = \Delta U + W$$

$$-23.1 = -16.5 + W$$

$$W = -6.6\ kJ$$

$$Q_{total} = -23.1 - 9.15 = \underline{-32.35\ kJ}$$

$$W_{total} = -9.15 - 6.6 = \underline{-15.75\ kJ}$$

Problem 6.57

A piston/cylinder containing 1.5 kg of water vapor operates on a three process cycle. At state 1 the water is a saturated vapor at 10 MPA, it expands adiabatically to a pressure of 1000 kPa and a quality of 0.7817. At this point a constant pressure process occurs until the specific volume at state 3 equals that at state 1. Finally from state 3 to state 1 constant volume heating occurs. Sketch the cycle on a T-v diagram. Determine the work and heat for each process as well as the net work for the cycle.

Given: Steam, a pure substance, forms a closed system which undergoes a three process cycle. The processes are known as are the state points.

Find: The heat and work for each process and the net work for the cycle.

Sketch and Given Data:

Steam 1.5 kg

$P_1 = 10\ MPa$ sat vapor

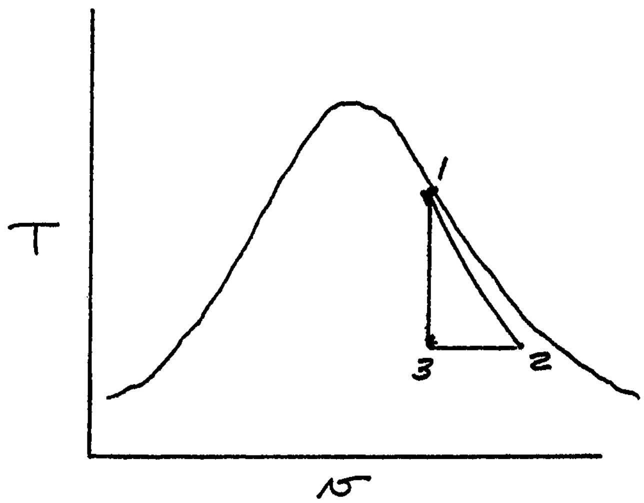
$P_2 = 1000\ kPa$

$x_2 = 0.7817$

$Q_{1-2} = 0$

$v_3 = v_1$

$P_3 = P_2$



Assumptions:
1) Steam is a pure substance and is a closed system.
2) Changes in kinetic and potential energies are zero.
3) All processes are reversible.

Analysis: Locate the cycle state points form the steam tables.

$p_1 = 10$ MPa	$p_2 = 1000$ kPa	$x_2 = 0.7818$
$h_1 = 2725.2$ kJ/kg	$h_2 = 2338.2$ kJ/kg	
$u_1 = 2544.9$ kJ/kg	$u_2 = 2186.2$ kJ/kg	
$v_1 = 0.018029\ m^3/kg$	$v_2 = 0.15224\ m^3/kg$	
$p_3 = 1000$ kPa $v_3 = v_1$		
$h_3 = 938.8$ kJ/kg		
$u_3 = 920.7$ kJ/kg		
$x_3 = 0.0874$		

For process 1-2, Q = 0. The first law is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2).

$$W_{1-2} = \Delta U = m(u_2 - u_1) = (1.5 \text{ kg})(2186.0 - 2544.9 \text{ kJ/kg})$$

$$W_{1-2} = 538.4 \text{ kJ}$$

For process 2-3, the pressure is constant

$$Q_{2-3} = \Delta H = m(h_3 - h_2) = (1.5 \text{ kg})(938.8 - 2338.2 \text{ kJ/kg})$$

$$Q_{2-3} = -2099.1 \text{ kJ}$$

$$\Delta U = m(u_3 - u_2) = (1.5 \text{ kg})(920.7 - 2186.0 \text{ kJ/kg})$$

$$\Delta U = -1898.0 \text{ kJ}$$

$$Q = \Delta U + W$$

$$-2099.1 = -1898 + W$$

$$W_{2-3} = -201.1 \text{ kJ}$$

For the process 3-1, V = c, hence $W_{3-1} = 0$ and

$$Q_{3-1} = \Delta U = m(u_1 - u_3) = (1.5 \text{ kg})(2544.9 - 920.7 \text{ kJ/kg})$$

$$Q_{3-1} = 2436.3 \text{ kJ}$$

The net work is

$$W_{net} = \sum W = 538.4 - 201.1 = 337.3 \text{ kJ}$$

A check is that $W_{net} = Q_{net}$

$$Q_{net} = 0 - 2099.1 + 2436.3 = 337.2 \text{ kJ}$$

The difference is due to round-off errors.

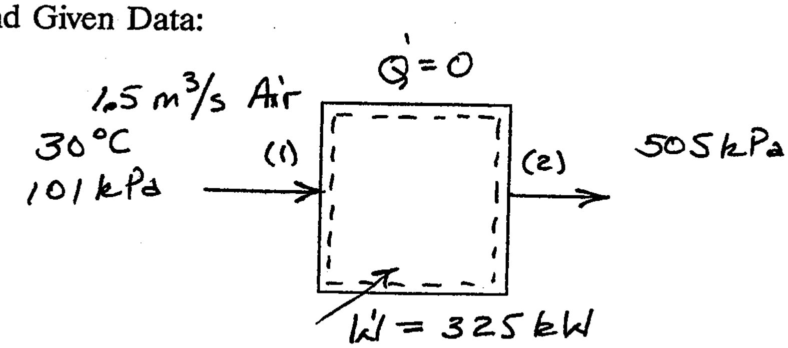
Problem 6.61

An adiabatic compressor receives 1.5 m^3/s of air at 30 C and 101 kPa. The discharge pressure is 505 kPa and the power supplied is 325 kW, what is the discharge temperature?

Given: Air is compressed in an adiabatic compressor steadily. The power, flowrate and initial conditions are known.

Find: The discharge temperature.

Sketch and Given Data:



Assumptions:
1) The compressor is a steady-state open system
2) Changes in kinetic and potential energies are zero.
3) The heat flow is zero.
4) Air is an ideal gas.

Analysis: The first law for a steady-state open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions (2) and (3)

$$\dot{W} = \dot{m}(h_1 - h_2)$$

For an ideal gas $\Delta h = c_p \Delta T$ and

$$\dot{m} = \frac{p_1 \dot{V}_1}{RT_1} = \frac{(101 \text{ kN/m}^2)(1.5 \text{ m}^3/\text{s})}{(0.287 \text{ kJ/kg-K})(303 \text{ K})} = 1.742 \text{ kg/s}$$

$$\dot{W} = \dot{m} c_p (T_1 - T_2)$$

$$(-325 \text{ kW}) = (1.742 \text{ kg/s})(1.0047 \text{ kJ/kg-K})(\Delta T \text{ K})$$

$\Delta T = -185.7°C$ $\quad$ $T_2 = \underline{215.7°C}$

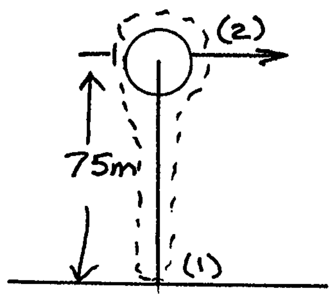
Problem 6.65

A pump delivers 50 liters/sec of water. The intake to the pump is 75 m below the final discharge. The inlet and discharge pressure is essentially atmospheric and the temperature of the water remains constant at 20 C during the process. Determine the power required by the pump.

Given: Water flows steadily through a pump which is an open steady system. Intake occurs 75 m below the discharge; temperature is constant.

Find: The power required.

Sketch and Given Data:



$\dot{V}_1 = 50$ lit/sec

$T = 20°C$

$g = 9.8$ m/s^2

Assumptions:

1) The pump is an open system with water flowing steadily through it.
2) The heat flow is zero.
3) The change of kinetic energy is zero.
4) The temperature remains constant, hence the change of enthalpy of the water is zero.

Analysis: The first law for a open steady system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions (2), (3), and (4) yields

$$\dot{W} = \dot{m}(pe_1 - pe_2)$$

The specific volume of water from the steam tables is

$$v = 0.001002 \text{ m}^3\text{/kg}$$

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{(0.050 \text{ m}^3\text{/kg})}{(0.001002 \text{ m}^3\text{/kg})} = 49.9 \text{ kg/s}$$

$$\dot{W} = \dot{m}g(z_1 - z_2) = \frac{(49.9\ \text{kg/s})(9.8\ \text{m/}_{\text{s}^2})(-75\ -0_{\text{m}})}{(1000\ \text{J/}_{\text{kJ}})}$$

$$\dot{W} = \underline{-36.7\ \text{kW}}$$

Comment: Physically, the pump would have to have several stages to lift water 75 m. A more typical arrangement is to have the pump near the water supply and the discharge at the elevation required.

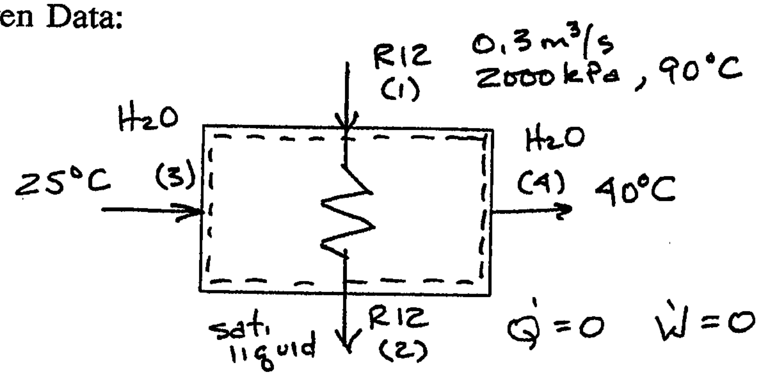
Problem 6.69

An adiabatic counterflow heat exchanger receives 0.3 m^3/s of R12 at 2000 kPa and 90°C and discharges it as a saturated liquid at 2000 kPa. Water enters at 25°C and leaves at 40°C. Determine the water flowrate in kg/s and the heat transfer form the refrigerant to the water in kW.

Given: An adiabatic heat exchanger is a steady, open system. Water cools condensing R12.

Find: The heat transfer to the water and the water flowrate.

Sketch and Given Data:



Assumptions:
1) The heat exchanger is a steady open system.
2) There is no heat ion to the surroundings.
3) The work is zero.
4) Changes in kinetic and potential energies are zero.
5) Water and R12 are pure substances.

Analysis: The first law for the R12's control volume is

$$\dot{Q} + \dot{m}_{R12}(h + ke + pe)_1 = \dot{W} + \dot{m}_{R12}(h + ke + pe)_2 \quad .$$

Apply assumptions (3) and (4)

$$\dot{Q} = \dot{m}_{R12}\,(h_2 - h_1)$$

From the R12 Tables.

$$h_1 = 228.1 \text{ kJ/kg} \qquad h_2 = 110.1 \text{ kJ/kg}$$

$$v_1 = 0.009\,406 \text{ m}^3\text{/kg}$$

$$\dot{m}_{R12} = \frac{\dot{V}_1}{v_1} = \frac{(0.3 \text{ m}^3\text{/s})}{(0.009\,406 \text{ m}^3\text{/kg})} = 31.9 \text{ kg/s}$$

$$\dot{Q} = (31.9\ \text{kg/s})(110.1 - 228.1\ \text{kJ/kg}) = \underline{-3764.2\ \text{kW}}$$

The heat into the water is +3764.2 kW.

The first law for the water's control volume is

$$\dot{Q} + \dot{m}_w(h + ke + pe)_3 = \dot{W} + \dot{m}_w(h + ke + pe)_4$$

Apply assumptions (3) and (4). From the steam tables

$h_3 = 104.0$ kJ/kg $\qquad h_4 = 167.3$ kJ/kg

$(+3764.2\ \text{kW}) = (\dot{m}_w\ \text{kg/s})(167.3 - 104.0\ \text{kJ/kg})$

$\dot{m}_w = \underline{59.5\ \text{kg/s}}$

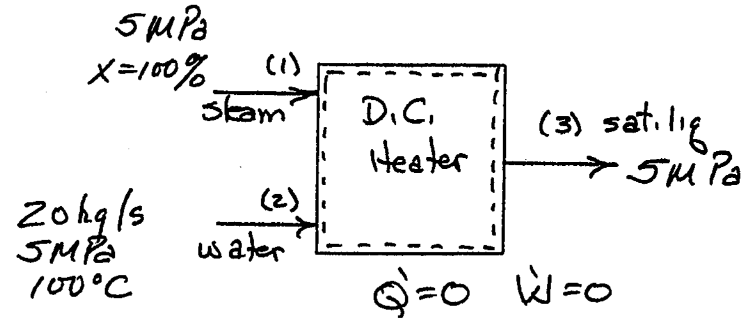
Problem 6.73

A direct contact heat exchanger operates by combining 20 kg/s of water at 5 MPa and 100 degrees with saturated steam at 5 MPa to produce a saturated liquid at 5 MPa. Determine the total mass flowrate leaving the heat exchanger.

Given: A heat exchanger is an open system where the mixing of two streams, one steam and the other water, produces a saturated liquid output.

Find: The total flowrate leaving the heat exchanger.

Sketch and Given Data:



Assumptions:
1) The direct contact heat exchanger is a steady, open system.
2) The heat and work are zero.
3) Changes in kinetic and potential energies are zero.
4) Water is a pure substance.

Analysis: The first law for a steady-state open system is

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2 + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions (2) and (3)

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

From the conservation of mass, $\dot{m}_3 = \dot{m}_1 + \dot{m}_2$

From the steam tables

h_1 = hg @ 5 MPa = 2794.6 kJ/kg $\quad$ $h_2 = h_f$ @ 100°C = 419.6 kJ/kg

$h_3 = h_f$ @ 5 MPa = 1154.5 kJ/kg

Substituting in the first law yields

$$(\dot{m}_1 \text{ kg/s})(2794.6 \text{ kJ/kg}) + (20 \text{ kg/s})(419.6 \text{ kJ/kg}) = (\dot{m}_1 + 20 \text{ kg/s})(1154.5 \text{ kJ/kg})$$

$$\dot{m}_1 = 8.97 \text{ kg/s}$$

$$\dot{m}_3 = 20 + 8.97 = \underline{28.97 \text{ kg/s}}$$

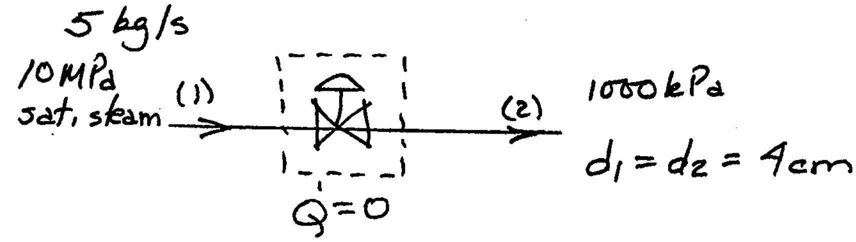
Problem 6.77

An adiabatic pressure reducing valve has equal inlet and exit diameters of 4 cm and receives 5 kg/s of steam at saturated steam at 10 MPa and reduces the pressure to 1000 kPa. Determine the exit velocity and temperature of the steam leaving the valve.

Given: A valve receives steam and reduces it pressure. There is a velocity change across the valve.

Find: The steam's exit velocity and temperature.

Sketch and Given Data:



Assumptions:
1) The valve is a steady, open system.
2) The heat and work are zero.
3) The change os potential energy is zero.
4) Steam is a pure substance.

Analysis: The first law for a steady-state open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$h_1 + ke_1 = h_2 + ke_2$$

From the steam tables $h_1 = 2725.2 \dfrac{kJ}{kg}$ $\quad v_1 = 0.01803 \text{ m}^3/\text{kg}$

From the conservation of mass

$$\dot{m} = \frac{A\mathrm{v}}{v} = \frac{\left(\frac{\pi}{4}\,0.04^2\ \mathrm{m}^2\right)(\mathrm{v\,m/s})}{(0.01803\mathrm{m}^3/\mathrm{kg})} = (5\ \mathrm{kg/s})$$

$$\mathrm{v}_1 = 71.7\ \mathrm{m/s}$$

$$h_1 + ke_1 = \left(2725.2\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) + \frac{(71.7\ \mathrm{m/s})^2}{(2)(1000\ \mathrm{J/kJ})} = 2727.8\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$h_2 + ke_2 = 2727.8$$

$$\mathrm{v}_2 = \frac{\dot{m}\,v_2}{A_2} = \frac{(5\ \mathrm{kg/s})(v_2\ \mathrm{m}^3/\mathrm{kg})}{(0.001257\ \mathrm{m}^2)} = 3978\ v_2\ \mathrm{m/s}$$

$$h_2 + \frac{1}{2}\frac{(3978\ v_2)^2}{(1000)} = 2727.8\ \mathrm{kJ/kg} \quad \text{(A)}$$

The pressure, p_2, is 1000 kPa. This requires that a quality is assumed, the specific volume and enthalpy calculated until Equation (A) is satisfied.

For example, $x_2 = 0.90$

$$h_2 = 2576.7\ \mathrm{kJ/kg},\ v_2 = 0.1751\ \frac{\mathrm{m}^3}{\mathrm{kg}},\ h_2 + ke_2 = 2819.4\ \frac{\mathrm{kJ}}{\mathrm{kg}}$$

$$x_2 = 0.865$$

$$h_2 = 2506.2\ \mathrm{kJ/kg},\ v_2 = 0.1683\ \mathrm{m}^3/\mathrm{kg},\ h_2 + ke_2 = 2730.2\ \mathrm{kJ/kg}$$

which is close enough.

$$\mathrm{v}_2 = (3978)(0.1683) = 669.5\ \mathrm{m/s}$$

$$T_2 = T_{sat} = \underline{179.9°\mathrm{C}}$$

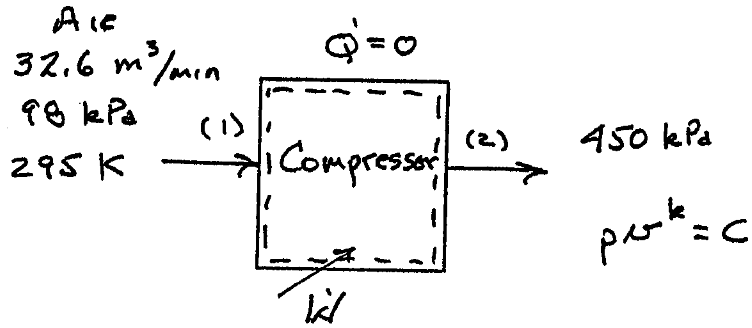
Problem 6.79

A gas turbine compressor unit receives 32.6 m^3/min of air at 98 kPa and 295 K and compresses it in a reversible adiabatic process to 450 kPa. Determine the power required to do this.

Given: A compressor is a steady open system, compressing air in a reversible adiabatic process.

Find: The power required.

Sketch and Given Data:



Assumptions:
1) The compressor is a steady open system.
2) The heat flow is zero.
3) Changes in kinetic and potential energies are zero.
4) Air is an ideal gas.

Analysis: The first law for a steady-state open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{W} = \dot{m}(h_1 - h_2)$$

For an ideal gas, $\Delta h = c_p \Delta T$ and

$$\dot{m} = \frac{p_1 \dot{V}_1}{RT_1} = \frac{(98 \text{ kN/m}^2)(0.543 \text{ m}^3\text{/s})}{(0.287 \text{ kJ/kg-K})(295 \text{ K})} = 0.629 \text{ kg/s}$$

For a reversible adiabatic a process with an ideal gas.

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (295\ \text{K})\left(\frac{450}{98}\right)^{\frac{0.4}{1.4}} = 456\ \text{K}$$

The power is

$$\dot{W} = \dot{m}c_p(T_1 - T_2) = (0.629\ \text{kg/s})\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right)(295\ -\ 456\ \text{K})$$

$$\dot{W} = \underline{-101.7\ \text{kW}}$$

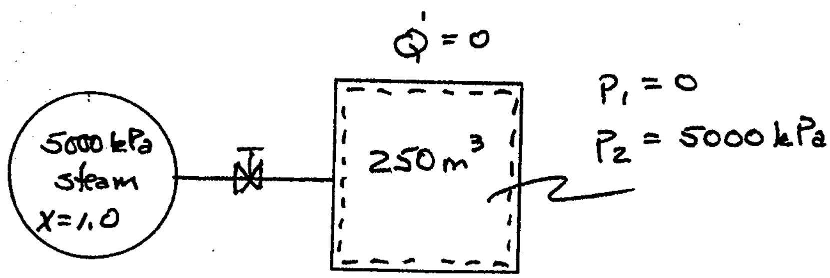
Problem 6.83

An initially evacuated 250 m³ adiabatic tank is charged with dry saturated steam at 5000 kPa until the pressure in the tank is 5000 kPa. Determine the mass is steam in the tank and its temperature when the pressure is 5000 kPa.

Given: A tank, initially empty, is filled with steam from a constant pressure supply.

Find: The mass of steam in the tank and its final temperature for a given pressure.

Sketch and Given Data:



Assumptions:
1) There is no heat or work transfer.
2) The tank forms a control volume.
3) The initial and final steam states are equilibrium states.

Analysis: From equation 6.36

$$m_L h_L = m_2 u_2 - m_1 u_1$$

For $m_1 = 0$, $m_L = m_2$. or

$$h_L = u_2$$

From the steam tables

$$h_L \; h_g \; @ \; 5 \text{ MPa} = 2794.6 \text{ kJ/kg}$$

Therefore $u_2 = 2794.6$ kJ/kg. The pressure is 5 MPa.

From the steam tables (superheat region), find that T_2 = <u>342.3°C.</u> The specific volume is $v_2 = 0.05102$ m³/kg. Hence, the mass in the tank is.

$$m = \frac{V}{v} = \frac{(250 \text{ m}^3)}{(0.05102 \text{ m}^3/\text{kg})} = \underline{4900 \text{ kg}}$$

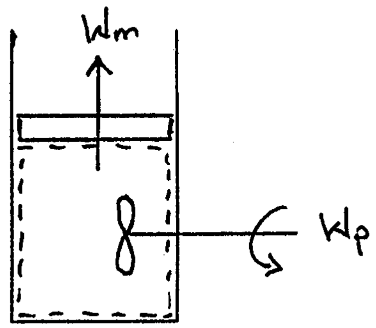
Problem *6.1

A constant-pressure insulated closed system receives paddle work. The pressure is 100 psia and the paddle turns 10,000 revolutions with an average torque of 0.5 ft-lbf. The piston moves 0.2 ft^3. Find the change of internal energy of the fluid in Btu's.

Given: A closed system receives paddle work and expands at constant pressure. The torque of the paddle wheel is given.

Find: The change of internal energy of the system.

Sketch and Given Data:



$P_1 = 100$ psia

$N = 10{,}000$ rev.

$\tau = 0.5$ ft-lbf

$\Delta V = 0.2\ ft^3$

Assumptions:
1) The substance in the system is a closed system.
2) Changes in kinetic and potential energies are zero.
3) The heat flow is zero.
4) The pressure is constant at 100 psia.

Analysis: The first law for a closed system with paddle work is

$$Q = \Delta U + \Delta KE + \Delta PE + W_m + W_p$$

Apply assumptions 2 and 3.

$$0 = \Delta U + W_m + W_p$$

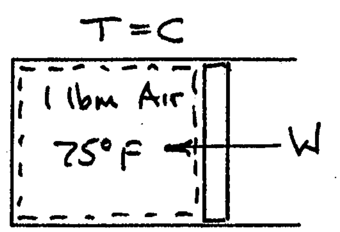
Problem *6.3

One pound of air is compressed at a constant temperature of 75°F from 15 to 100 psia. Determine: (a) the change of internal energy: (b) the work in ft-lbf; (c) the heat in Btu's.

Given: Air forms a closed system and is compressed isothermally.

Find: The change of internal energy, the work and the heat.

Sketch and Given Data:



P_1 = 15 psia
P_2 = 100 psia

Assumptions:
1) Air is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies are zero.

Analysis: For an ideal gas, $\Delta u = c_v \Delta T$. The process is

a) constant temperature, hence $\Delta U = 0$.

For an isothermal process the work is from Equation 6.9

$$W = p_1 V_1 \ln\left(\frac{V_2}{V_1}\right) = mRT_1 \ln\left(\frac{p_1}{p_2}\right)$$

$$W = (1 \text{ lbm})(53.34 \text{ ft-lb}_f/\text{lbm-R})(535 \text{ R})\left(\frac{15}{100}\right)$$

b) $W = \underline{-54137.9 \text{ ft-lb}_f}$

The first law is $Q = \Delta U + \Delta KE + \Delta PE + W$

Apply assumptions (3), plus $\Delta U = 0$.

$$Q = W = \frac{-(54\ 137.9 \text{ ft-lb}_f)}{(778.16 \text{ ft-lb}_f/\text{Btu})} = -69.57 \text{ Btu}$$

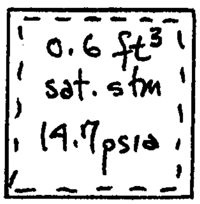
Problem *6.7

A steel tank has a volume of 0.6 ft³ and is filled with saturated steam at 14.7 psia. The tank is cooled to 100°F - determine the final pressure and heat transfer.

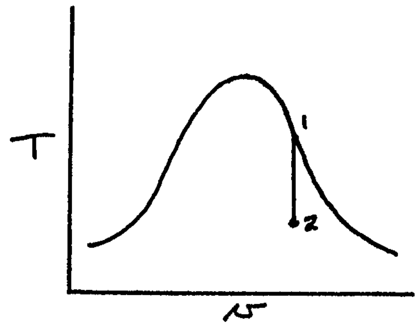
Given: A tank containing steam is cooled.

Find: The final pressure and the heat transferred.

Sketch and Given Data:



$T_2 = 100$ F



Assumptions:
1) The steam in the tank is a closed system.
2) The work is zero (V = C).
3) Changes in kinetic and potential energies are zero.
4) Steam is a pure substance.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = \Delta U = m(u_2 - u_1)$$

From the steam tables at state 1 find

$$v_1 = v_g \text{ 4.7 psia} = 26.78 \text{ ft}^3/\text{lbm}$$

$$u_1 = u_g \text{ @ 14.7 psia} = 1077.6 \text{ Btu/lbm}$$

The mass of steam in the tank is

$$m = \frac{V_1}{v_1} = \frac{0.6 \text{ ft}^3}{26.78 \text{ ft}^3/\text{lbm}} = 0.0224 \text{ lbm}$$

The specific internal energy at state 2 is found by knowing the specific volume and temperature.

$$u_2 = 142.7 \text{ Btu/lbm} \quad x_2 = 0.0765$$

and $$p_2 = p_{sat} = 0.95 \text{ psia}$$

The heat transfer is

$$Q = (0.0224 \text{ lbm})(142.7 - 1077.6 \text{ Btu/lbm}) = \underline{-20.9 \text{ Btu}}$$

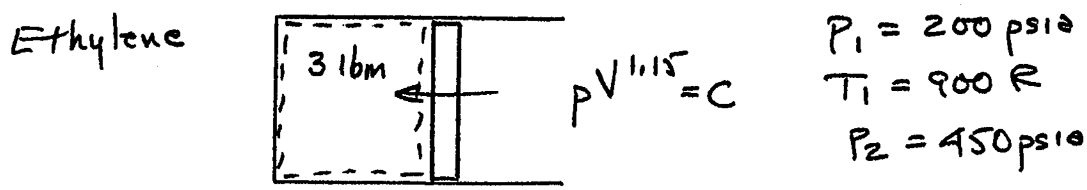
Problem *6.11

Ethylene is compressed according to $pV^{1.15} = C$ from 200 psia and 900 R to 450 psia. The mass of ethylene is 3 lbm. Determine the final temperature, the work and heat for the process.

Given: Ethylene, an ideal gas, is compressed polytropically.

Find: The final temperature, the work required and the heat transfer.

Sketch and Given Data:



Assumptions:
1) Ethylene is a closed system.
2) Changes in kinetic and potential energies are zero.
3) Ethylene is an ideal gas.
4) The process is reversible.

Analysis: For a polytropic process.

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

a) $$T_2 = (900\ \text{R})\left(\frac{450}{200}\right)^{\frac{0.15}{1.15}} = 1000.4\ \text{R}$$

The work for a polytropic process, closed system is given by Equation 6.19b.

$$W = \frac{mR(T_2 - T_1)}{1-n} = \frac{(3\ \text{lbm})(55.09\ \text{ft-lb}_f/\text{lbm-R})(1000.9 - 900\ \text{R})}{(-0.15)(778.16\ \text{ft-lb}_f/\text{Btu})}$$

b) $W = -142.2$ Btu

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$Q = \Delta U + W$$

For an ideal gas

$$\Delta U = mc_v(T_2 - T_1) = (3 \text{ lbm})\left(0.2946 \frac{\text{Btu}}{\text{lbm-R}}\right)(1000.4 - 900 \text{ R})$$

$$\Delta U = 88.7 \text{ Btu}$$

The heat transfer is

$$Q = 88.7 - 142.2 = -53.5 \text{ Btu (heat out)}$$

Problem 6.15*

A system holds 2 lbm of neon in a poston cylinder where the initial pressure is 25 psia and the initial temperature is 80 F. The system operates on a three-process cycle is comprised of the following processes: 1-2 constant volume heating unitl the pressure is 100 psia; 2-3 expansion according to $pV^{1.67} = C$; 3-1 constatn pressure compression. Sketch the cycle on a p-V diagram and determine the net work and heat added.

Given: Neon, an ideal gas and closed system, operates on a three-process cycle. The processes and certain states are given.

Find: The net work and heat added.

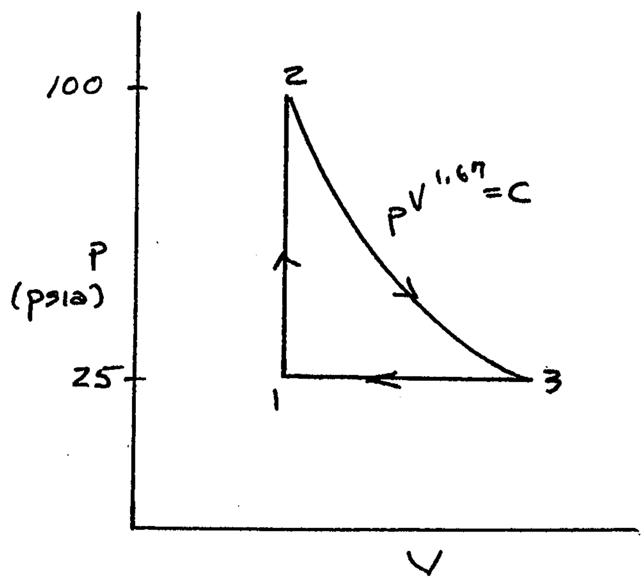
Sketch and Given Data:

2 lbm Neon

$P_1 = 25$ psia

$T_1 = 80$ F

$P_2 = 100$ psia



Assumptions:
1) Neon is and ideal gas and forms a closed system.
2) Changes in kinetic and potential energies are zero.
3) The processes are reversible.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$Q = \Delta U + W$$

For a constant volume process for an ideal gas T/p = C

$$T_2 = T_1\left(\frac{p_2}{p_1}\right) = (540\ R)\left(\frac{100}{25}\right) = 2160\ R$$

$$W_{1\text{-}2} = 0$$

$$Q_{1\text{-}2} = \Delta U + W = \Delta U$$

For an ideal gas

$$\Delta U = mc_v(T_2 - T_1) = (2\ lbm)\left(0.1476\ \frac{Btu}{lbm\text{-}R}\right)(2160 - 540\ R)$$

$$= 478.2\ Btu$$

$$Q_{1\text{-}2} = 478.2\ Btu$$

For process 2-3, n = k Thus $Q_{2\text{-}3} = 0$ and

$$W_{2\text{-}3} = \frac{p_3V_3 - p_2V_2}{1-n} = \frac{MR(T_3 - T_2)}{1-n}$$

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{n-1}{n}}$$

$$T_3 = (2160\ R)\left(\frac{25}{100}\right)^{\frac{0.67}{1.67}} = 1238.5\ R$$

$$W_{2\text{-}3} = \frac{(2\ lbm)\left(0.0984\ \frac{Btu}{lbm\text{-}R}\right)(1238.5 - 2160\ R)}{(-0.67)} = 270.7\ Btu$$

For process 3-1, the pressure is constant, hence

$$Q_{3\text{-}1} = H_1 - H_3 = mc_p(T_1 - T_3) \text{ for an ideal gas}$$

$$\Delta H = (2lbm)(0.246\ Btu/lbm\text{-}R)(540 - 1238.5\ R) = -343.7\ Btu$$

$$Q_{3\text{-}1} = -343.7\ Btu$$

The work is

$$W_{3\text{-}1} = \int_3^1 p dV = p(V_1 - V_3) = mR(T_1 - T_3)$$

$$W_{3\text{-}1} = (2 \text{ lbm})(0.0984 \text{ Btu/lbm-R})(540 - 1238.5 \text{ R}) = -137.5 \text{ Btu}$$

The net work is

$$W_{net} = 270.7 - 137.5 = 133.2 \text{ Btu}$$

The heat added is

$$Q_{1\text{-}2} = 478.2 \text{ Btu}$$

Comments: The net work equals the net heat transfer within the round-off error created by k = 1.67 rather than 1.6666.

Problem 6.19*

A four process cycle using 2 lbm of water operates with the following processes: 1-2 constant volume heating from 80 psia and 320 F to 400 psia; 2-3 constant pressure cooling until the water is a saturated vapor; 3-4 constant volume cooling; 4-1 isothermal expansion where Q_{4-1} = 1395 Btu's. Sketch the cycle on the T-v diagram. Determine the specific volume and internal energy at each state and the net work and total heat added for the cycle.

Given: Steam, a pure substance, forms a closed system and operates on a four process cycle. The processes are reversible.

Find: The specific internal energy and volume at each state and the net work and total heat added for one cycle.

Sketch and Given Data:

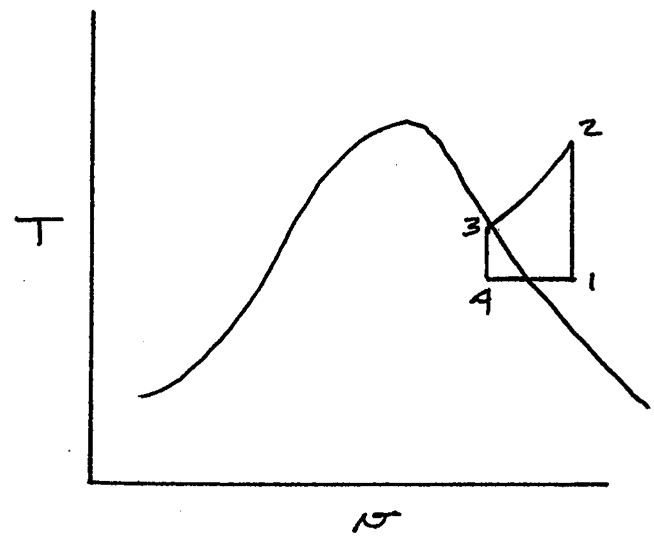
2 lbm H_2O

$P_1 = 80$ psia

$T_1 = 320$ F

$P_2 = 400$ psia

$Q_{4-1} = 1395$ Btu



Assumptions:
1) Steam is a pure substance and forms a closed system.
2) Changes in kinetic and potential energies are zero.
3) All processes are reversible.

Analysis: Locate the cycle state points from the steam tables.

$p_1 = 80$ psia $\quad T_1 = 320$ F $\quad p_2 = 400$ psia $\quad v_2 = v_1$

$u_1 = 1105.3$ Btu/lbm $\quad u_2 = 2525.0 \dfrac{\text{Btu}}{\text{lbm}}$

$v_1 = 5.543$ ft³/lbm $\quad T_2 = 3256.$ F

$u_3 = 1119.4$ Btu/lbm

$p_3 = 400$ psia sat vapor

$v_3 = 1.162$ ft³/lbm

$h_3 = 1205.4$ Btu/lbm

$h_2 = 2935.4 \dfrac{\text{Btu}}{\text{lbm}}$ Btu

$T_4 = T_1 = 320$ F $\quad v_4 = v_3$

$u_4 = 480.4$ Btu/lbm

$p_4 = 89.7$ psia

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption (2)

$$Q = \Delta U + W$$

For process 1-2, V = c, hence $W_{1\text{-}2} = 0$

$$Q_{1\text{-}2} = m(u_2 - u_1) = (2 \text{ lbm})(2525.0 - 1105.3 \text{ Btu/lbm}) = 2839.4 \text{ Btu}$$

For process 2-3, p = c, hence

$$Q_{2\text{-}3} = m(h_3 - h_2) = (2 \text{ lbm})(1205.4 - 2935.4 \text{ Btu/lbm}) = -3460 \text{ Btu}$$

$$W_{2\text{-}3} = \int_2^3 p dV = pm(v_3 - v_2)$$

$$= \frac{\left(400 \dfrac{\text{lb}_f}{\text{in}^2}\right)\left(144 \dfrac{\text{in}^2}{\text{ft}^2}\right)(2 \text{ lbm})\left(1.162 - 5.543 \dfrac{\text{ft}^3}{\text{lbm}}\right)}{(778.16 \text{ ft-lb}_f\text{/Btu})}$$

$$W_{2\text{-}3} = -648.6 \text{ Btu}$$

For process 3-4, V = c, hence $W_{3\text{-}4} = 0$

$$Q_{3\text{-}4} = m(u_4 - u_3) = (2 \text{ lbm})\left(480.4 - 1119.4 \frac{\text{Btu}}{\text{lbm}}\right) = -1278 \text{ Btu}$$

For process 4-1, $Q_{4\text{-}1} = 1395$ Btu

$$\Delta U = m(u_1 - u_4) = (2 \text{ lbm})\left(1105.3 - 480.4 \frac{\text{Btu}}{\text{lbm}}\right) = 1249.8 \text{Btu}$$

The first law

$$Q = \Delta U + W$$

$$1395 = 1249.8 + W$$

$$W_{4\text{-}1} = 145.2 \text{ Btu}$$

The net work is

$$W_{net} = \sum W = 0 - 648.6 + 0 + 145.2 = -503.4 \text{ Btu}$$

The net heat is

$$Q_{net} = \sum Q = 2839.4 - 3460 - 1278 + 1395 = -503.6 \text{ Btu}$$

The heat added is

$$Q_{in} = 2839.4 + 1395 = \underline{4234.4 \text{ Btu}}$$

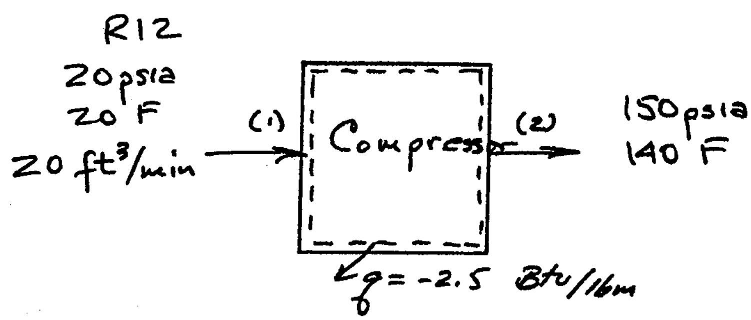
Problem 6.23*

A refrigeration compressor receives R12 at 20 psia and 20 F and discharges it at 150 psia and 140 F. The refrigerant flowrate at inlet conditions is 20 ft³/min. The heat transfer from the compressor to the surroundings is 2.5 Btu per lbm of refrigerant. Determine the power required and the volume flowrate at exit conditions.

Given: A refrigeration compressor is an open system with R12 flowing steadily through it. The refrigerant flow and heat transfer are known.

Find: The power required and the volume flowrate at exit conditions.

Sketch and Given Data:



Assumptions:
1) The compressor is a steady-state open system.
2) Changes in kinetic and potential energies are zero.
3) R12 is a pure substance.

Analysis: The first law for a steady open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumption (2)

$$\dot{m}q + \dot{m}h_1 = \dot{W} + \dot{m}h_2$$

From the R12 property tables

$h_1 = 80.4$ Btu/lbm $\qquad h_2 = 93.5$ Btu/lbm $\qquad v_2 = 0.298$ ft³/lbm

$v_1 = 2.039$ ft³/lbm

The mass flowrate is

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{(20 \text{ ft}^3/\text{min})}{(2.039 \text{ ft}^3/\text{lbm})} = 9.81 \text{ lbm/min}$$

$$\dot{W} = \dot{m}q + \dot{m}(h_1 - h_2) = (9.81 \text{ lbm/min})[-2.5 + (80.4 - 93.5) \text{ Btu/lbm}]$$

$$\dot{W} = -153.0 \text{ Btu/min} = -3.6 \text{ hp}$$

The volume flowrate at exit is

$$\dot{V}_2 = \dot{m}v_2 = (9.81 \text{ lbm/min})(0.298 \text{ ft}^3/\text{lbm}) = 2.92 \text{ ft}^3/\text{min}$$

Comments: Note that the volume flowrate is not constant, is not conserved; only mass flowrate is consumed.

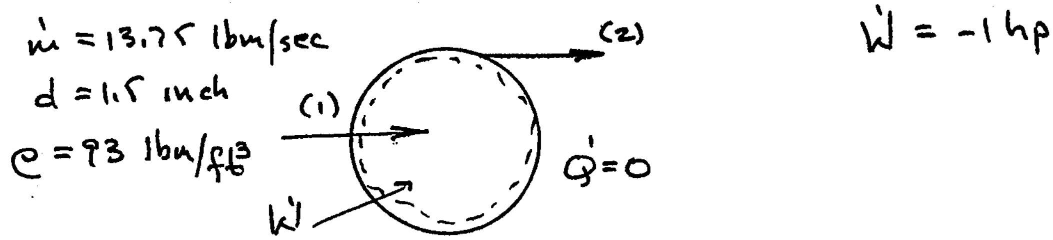
Problem 6.27*

An oil transfer pump uses 1 hp of power in transferring 13.75 lbm/s of oil through a 1.5 inch diameter pipe. The change in kinetic and potential energies is essentially zero and the process is adiabatic. Additionally, there is no appreciable temperature change in the oil which has a density of 93 lbm/ft^3. Determine the change in pressure from inlet to exit.

Given: An oil pump adiabatically raises the pressure of oil continuously.

Find: The pressure rise across the pump.

Sketch and Given Data:



Assumptions:
1) The heat flow is zero.
2) Changes in kinetic and potential energies are zero.
3) The oil is incompressible.
4) The change of internal energy is zero.
5) The pump is a steady, open system.

Analysis: The first law for a steady-state open system is

$$\dot{Q} + \dot{m}(u + p/\rho + ke + pe)_1 = \dot{W} + \dot{m}(u + p/\rho + ke + pe)_2$$

Apply assumptions (1), (2), (3), and (4).

$$\dot{m}\,\frac{(p_1 - p_2)}{\rho} = \dot{W}$$

$$\dot{W} = \frac{-\dot{m}(p_2 - p_1)}{\rho}$$

$$-(1\text{ hp})\left(550\ \frac{\text{ft-lb}_f}{\text{hp-sec}}\right) = \frac{-\left(13.75\ \frac{\text{lbm}}{\text{sec}}\right)\left(\Delta p\ \text{lb}_f/\text{in}^2\right)\left(144\ \text{in}^2/\text{ft}^2\right)}{\left(93\ \text{lbm/ft}^3\right)}$$

Δp = <u>25.8 psi</u>

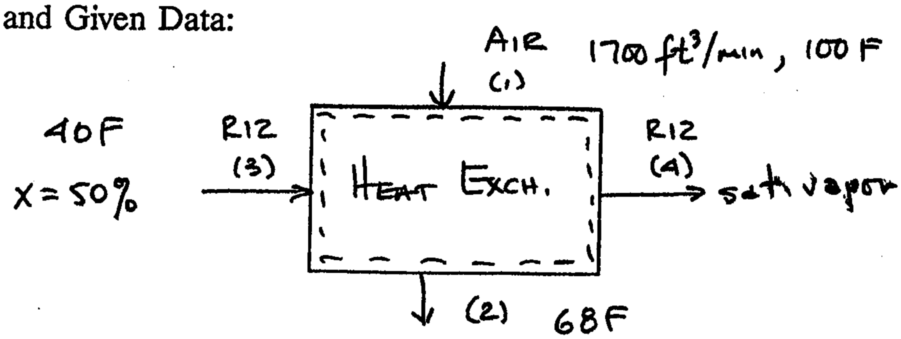
Problem 6.31*

An air conditioning system cooling unit is a heat exchanger that has air pass over coils that have refrigerant flowing through them. In one home 1700 ft^3/min of air enters the heat exchanger at 100 F and atmospheric pressure. It leaves at 68 F and atmospheric pressure. The cooling is accomplished by R12 evaporating at a temperature of 40 F and an initial quality of 50% to the saturated vapor. Determine the refrigerant flowrate the heat transfer between the air and refrigerant.

Given: A heat exchanger is an open, steady flow system. Air is cooled by flowing over coils in which R12 is evaporating.

Find: The R12 flowrate and the heat transfer air to R12.

Sketch and Given Data:



Assumptions:
1) The heat exchanger is a steady, open system.
2) The work is zero.
3) Changes in kinetic and potential energies are zero.
4) Air is an ideal gas.
5) R12 is a pure substance.
6) The heat transfer to the surroundings is zero.

Analysis: The first law for an open system is

$$\dot{Q} + \dot{m}_{R12}(h + ke + pe)_3 + \dot{m}_a(h + ke + pe)_1$$

$$= \dot{W} + \dot{m}_a(h + ke + pe)_2 + m_{41R12}(h + ke + pe)_4$$

Apply assumptions (2), (3), and (6) yields

$$\dot{m}_{R12}(h_4 - h_3) = \dot{m}_a(h_1 - h_2)$$

Air is an ideal gas, hence $\Delta h = c_p \Delta T$ and

$$\dot{m}_a = \frac{p_1 \dot{V}_1}{RT_1} = \frac{(14.7\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(1700\ \text{ft}^3/\text{min})}{\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(560\ \text{R})} = 120.5\ \text{lbm/min}$$

From the R12 tables

$$h_3 = 49.4\ \text{Btu/lbm} \qquad h_4 = 81.4\ \text{Btu/lbm}$$

$$\dot{m}_{R12} = \frac{(120.5\ \text{lbm/min})(0.24\ \text{Btu/lbm-R})(560 - 528\ \text{R})}{(81.4 - 49.4\ \text{Btu/lbm})}$$

$$\dot{m}_{R12} = 28.9\ \text{lbm/min}$$

The first law from the air's control volume subject to assumptions (2) and (3) is

$$\dot{Q} + \dot{m}_a h_1 = \dot{m}_a h_2$$

$$\dot{Q} = \dot{m}_a c_p (T_2 - T_1) = (120.5\ \text{lbm/min})(0.24\ \text{Btu/lbm-R})(528 - 560\ \text{R})$$

$$\dot{Q} = -925.4\ \text{Btu/min} \qquad \text{(heat out of air's CV)}$$

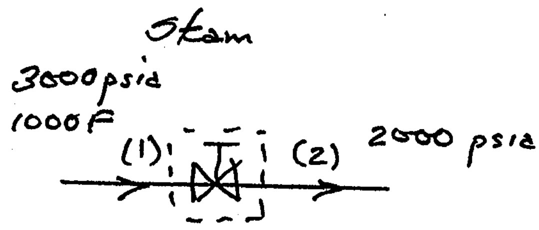
Problem 6.35*

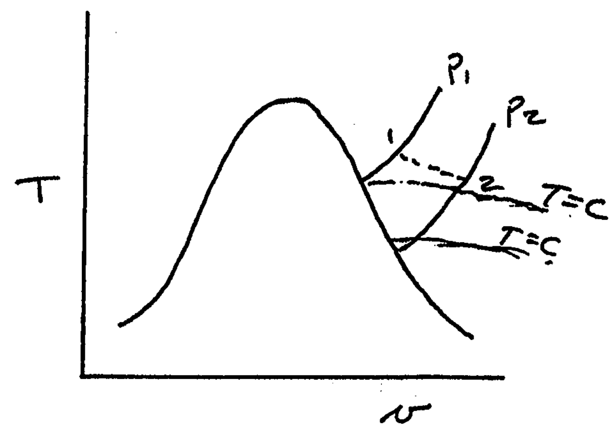
The steam entering a steam turbine flows through a control valve that regulates the flow. The steam entering the valve has a pressure of 3000 psia and a temperature of 1000 F. The pressure downstream of the valve is 2000 psia. What is the steam temperature downstream of the valve?

Given: Steam flows steadily through a regulatory valve and decreases in pressure.

Find: The steam temperature exiting the valve.

Sketch and Given Data:





Assumptions:
1) The valve is a steady, open system.
2) The heat and work are zero.
3) The change of kinetic and potential energies are zero.
4) Steam is a pure substance.

Analysis: The first law for a steady open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$h_1 = h_2$$

The process is a throttling process. From the steam tables. h_1 = 1442.6 Btu/lbm

Using $h_2 = h_1$ and p_2 = 2000 psia, enter the steam tables and find T_2 = 949°F.

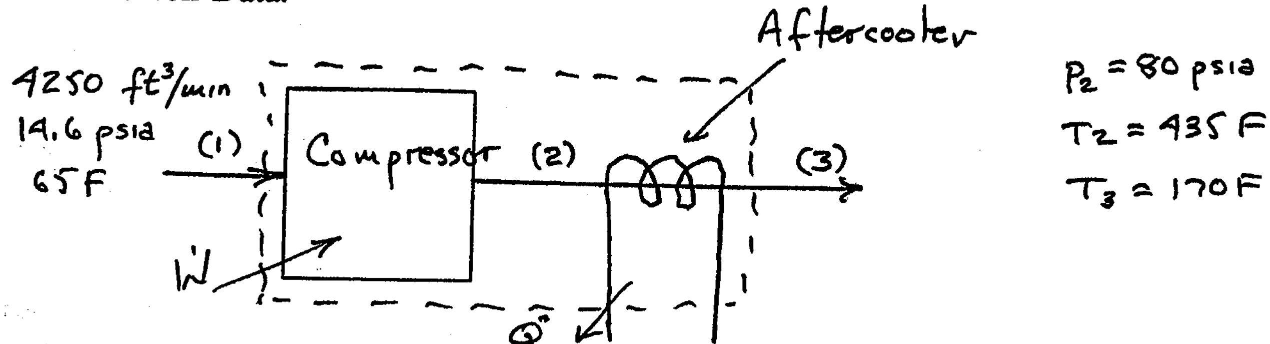
Problem 6.39*

An adiabatic axial flow compressor receives 4250 ft³/min of air at 14.6 psia and 65 F and compresses it to 80 psia and 435 F. The air leaves the compressor and enters an aftercooler where the temperature decreases to 170 F. Determine the compressor power in horsepower and the heat removed in the aftercooler in Btu/min.

Given: An air compressor is a steady open system receiving air at known conditions and discharging it at known conditions. An aftercooler reduces the air's temperature.

Find: The compressor power and heat rejected in the aftercooler.

Sketch and Given Data:



Assumptions:
1) The compressor and aftercooler are each steady open system.
2) The heat is zero in the compressor.
3) The work is zero in the aftercooler.
4) Changes in kinetic and potential energies are zero.
5) Air is an ideal gas.

Analysis: Consider the compressor. The first law for a steady open system is.

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions (2) and (4).

$$\dot{W} = \dot{m}(h_1 - h_2)$$

Air is an ideal gas, hence, $\Delta h = c_p \Delta T$. The mass flowrate is.

$$\dot{m} = \frac{p_1 \dot{V}_1}{RT_1} = \frac{\left(14.6\ \frac{lb_f}{in^2}\right)(4250\ ft^3/min)(144\ in^2/ft^2)}{\left(53.34\ \frac{ft\text{-}lb_f}{lbm\text{-}R}\right)(525\ R)} = 319.1\ lbm/min$$

$$\dot{W} = \dot{m}c_p(T_1 - T_2) = (319.1\ \text{lbm/min})\left(0.24\ \frac{\text{Btu}}{\text{lbm-R}}\right)(525 - 895\ \text{R})$$

$$\dot{W} = -28336\ \frac{\text{Btu}}{\text{min}} = \underline{-668.3\ \text{hp}}$$

Consider the aftercooler. The first law is

$$\dot{Q} + \dot{m}(h + ke + pe)_2 = \dot{W} + \dot{m}(h + ke + pe)_3$$

Apply assumptions (3) and (4).

$$\dot{Q} = \dot{m}(h_3 - h_3) = \dot{m}c_p(T_3 - T_2)$$

$$\dot{Q} = (319.1\ \text{lbm/min})(0.24\ \text{Btu/lbm-R})(630 - 895\ \text{R})$$

$$\dot{Q} = -20{,}294.8\ \text{Btu/min}$$

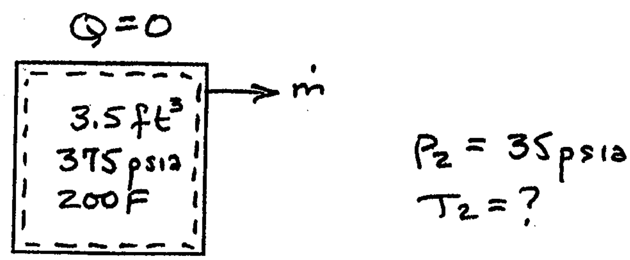
Problem 6.43*

A 3.5 ft^3 adiabatic tank contains air at 375 psia and 200 F. The tank develops a small leak and air escapes. Determine the mass remaining when the pressure is 35 psia and the temperature of the remaining air.

Given: A tank contains air at a high pressure. A leak occurs and air escapes.

Find: The mass of air remaining when the pressure in 35 psia. The temperature of the air in tank at this pressure.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) No heat or work occurs.
3) Change of kinetic and potential energies are zero.

Analysis: Determine the mass of air in the tank initially.

$$m = \frac{p_1 V_1}{RT_1} = \frac{\left(375\ \frac{lb_f}{in^2}\right)\left(144\ \frac{in^2}{ft^2}\right)(3.5\ ft^3)}{\left(53.34\ \frac{ft-lb_f}{lbm-R}\right)(660\ R)} = 5.37\ lbm$$

From Equation 6.34

$$\frac{m_2}{m_1} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}$$

$$m_2 = (5.37\ lbm)\left(\frac{35}{375}\right)^{\frac{1}{1.4}} = 0.987\ lbm\ remaining$$

From the reversible adiabatic relationships

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (660\ R)\left(\frac{35}{375}\right)^{\frac{0.4}{1.4}} = 335.2°R = -124.8°F$$

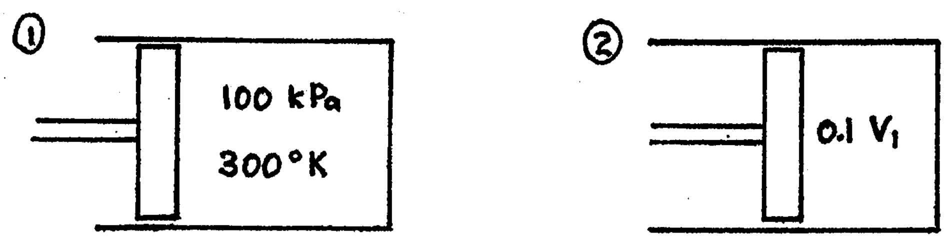
Problem C6.1

Air at 100 kPa and 300°K is compressed in a piston-cylinder to 10% of its initial volume. Develop a spreadsheet or TK Solver model to compute the final temperature and pressure for a range of polytropic coefficients between 0 and 2.0. Plot the final pressure and temperature as a function of n, first with linear scales and then with log-linear scales.

Given: Air compressed in a piston-cylinder to 10% of its initial volume.

Find: Final temperature and pressure for a range of polytropic coefficients.

Sketch and Given Data:



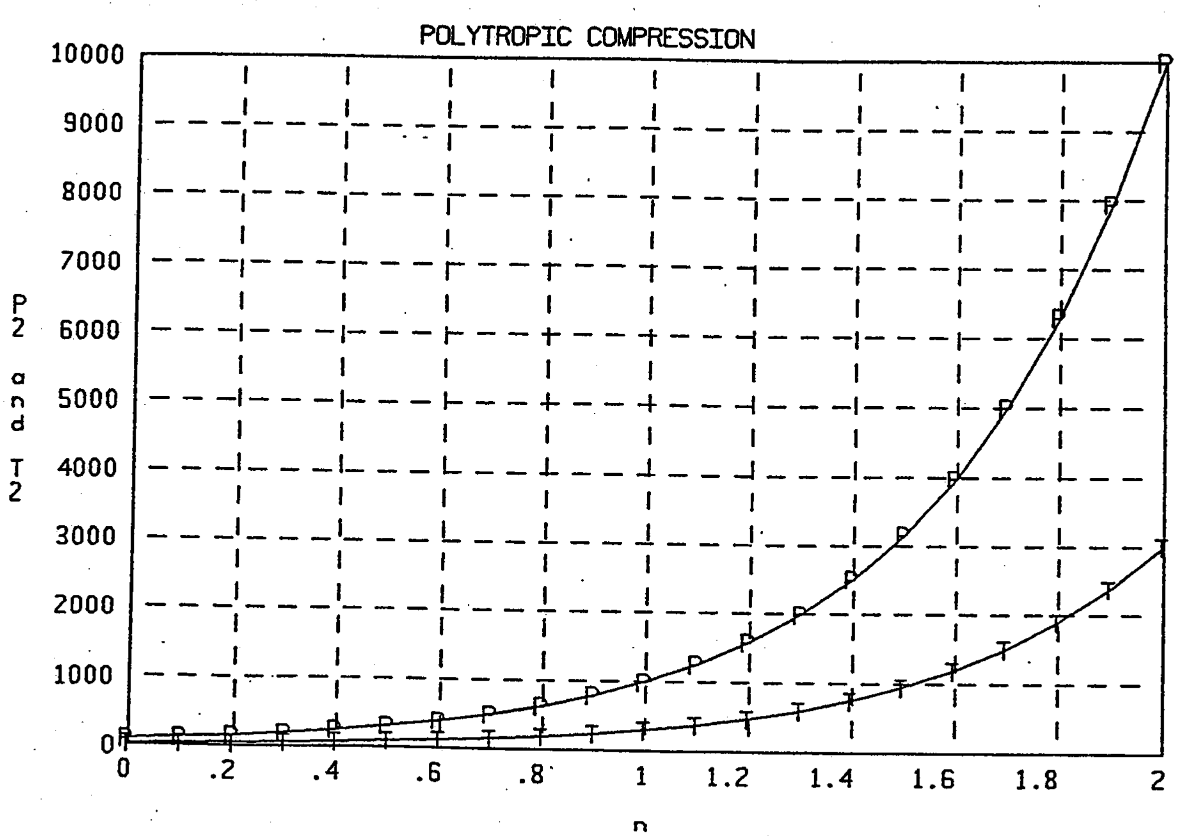
Assumptions: 1) The air is in equilibrium.

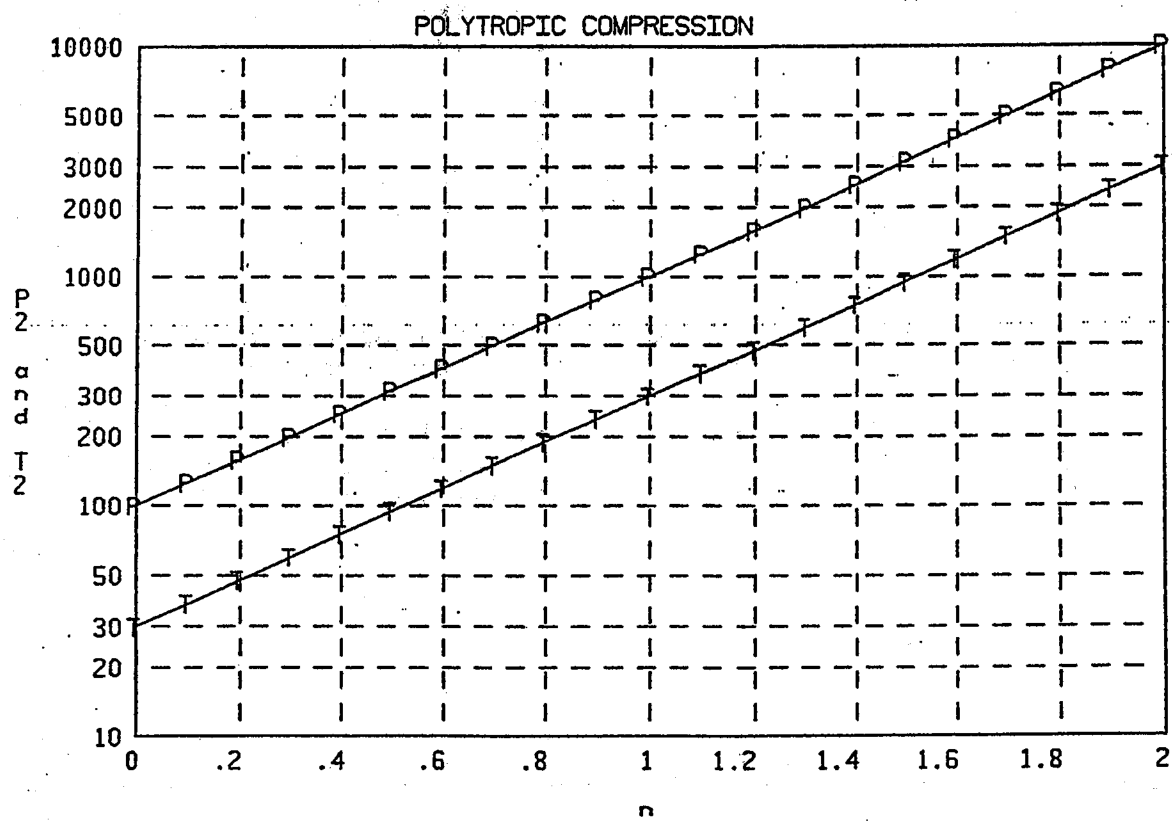
Analysis: Using TK Solver, enter the polytropic process equation, the ideal-gas equation for the initial and final points, and the relationship between initial and final volumes in the Rule Sheet. Use the List Solver for a range of polytropic coefficients and plot the results.

```
==================== RULE SHEET ====================
S Rule------------------------------------------------
  "Calculation Units are SI: kPa, degK, m3/kg, kJ/kg, kJ/kg-K
  P1*v1^n=P2*v2^n
  P1*v1=R*T1
  P2*v2=R*T2
  v2=v1/CR
```

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					Problem C6.1
					ENGINEERING THERMODYNAMICS 4/E
					M. David Burghardt & James A. Harbach
	10	CR			Compression Ratio
L	1	n			Polytropic Coefficient
	.287	R		kJ/kg-K	Gas Constant
	.7176	Cv		kJ/kg-K	Constant Volume Specific Heat
	1	m		kg	Mass
	100	P1		kPa	Initial Pressure
		v1	.861	m3/kg	Initial Specific Volume
	300	T1		degK	Initial Temperature
L		P2	1000	kPa	Final Pressure
		v2	.0861	m3/kg	Final Specific Volume
L		T2	300	degK	Final Temperature





Comments: 1) Using log-linear scales results in a linear plot. An examination of the polytropic process equation will indicate why.

CHAPTER SEVEN

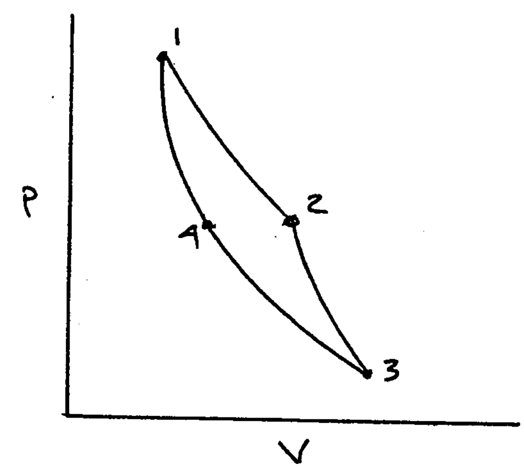
Problem 7.1

A Carnot engine operates with 0.136 kg of air as the working substance. The pressure and volume at the beginning of isothermal expansion are 2.1 MPa and 9.6 liters, respectively. The air behaves as an ideal gas, the sink temperature is 50°C, and the heat added is 32 kJ. Determine (a) the source temperature; (b) the cycle efficiency; (c) the pressure at the end of isothermal expansion; (d) the heat rejected to the sink per cycle.

Given: A Carnot engine operates on air where states are specified.

Find: The high cycle temperature, the efficiency, the heat out and the pressure at the end of heat addition.

Sketch and Given Data



$m = 0.136$ kg air

$P_1 = 2.1$ MPa

$V_1 = 9.6$ liters $= 0.0096\ m^3$

$T_C = 50°C$

$Q_{in} = 32$ kJ

Assumptions:

1) Air is an ideal gas.

2) The cycle operates on sketch shown.

Analysis: From the ideal gas knowing $p_1 = 2100$ kPa, $V_1 = 0.0096\ m^3$

(a) $$T_1 = \frac{p_1 V_1}{mR} = \frac{(2100\ kN/m^2)(0.0096\ m^3)}{(0.136\ kg)(0.287\ kJ/kg\text{-}K)} = \underline{516.5\ K}$$

The cycle efficiency is

(b) $$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{323}{516.5} = \underline{0.375 \text{ or } 37.5\%}$$

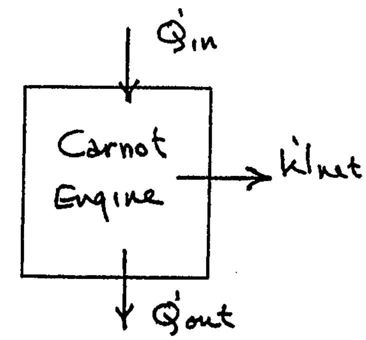
Problem 7.5

A Carnot engine operates between temperatures of 1000°K and 300°K. The engine operates at 2000 revolutions per minute and develops 200 kW. The total engine displacement is such that the mean effective pressure is 300 kPa. Determine (a) the cycle efficiency; (b) the heat supplied (kW); (c) the total engine displacement (m^3).

Given: A Carnot engine, its power, temperature limits and mean effective pressure.

Find: The cycle efficiency, heat input and total engine displacement volume.

Sketch and Given Data:



$T_H = 1000$ K
$T_C = 300$ K
2000 rpm
$\dot{W}_{net} = 200$ kW
$P_m = 300$ kPa

Assumptions: 1) The engine follows ideal Carnot cycle.

Analysis: The efficiency of a Carnot cycle is.

(a) $$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{300}{1000} = \underline{0.70}$$

The heat added is found from the efficiency.

(b) $$\eta_{Th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \qquad 0.70 = \frac{(200\text{ kW})}{\dot{Q}_{in}} \qquad \dot{Q}_{in} = \underline{285.7\text{ kW}}$$

The work per cycle is

$$(\dot{W}_{net}\text{ kW}) = (N\text{ cycles/sec})(W_{net}\text{ kJ/cycle})$$

$$(200\text{ kW}) = (33.33\text{ cycles/sec})(W_{net}\text{ kJ/cycle})$$

$$W_{net} = 6\text{ kJ}$$

The mean effective pressure is

$$p_m = \frac{W_{net}}{V_{PD}}$$

$$\left(300\ \frac{kN}{m^2}\right) = \frac{(6\ kNm)}{(V_{PD}\ m^3)}$$

(c) $V_{PD} = 0.020\ m^3 =$ <u>20 liters</u>

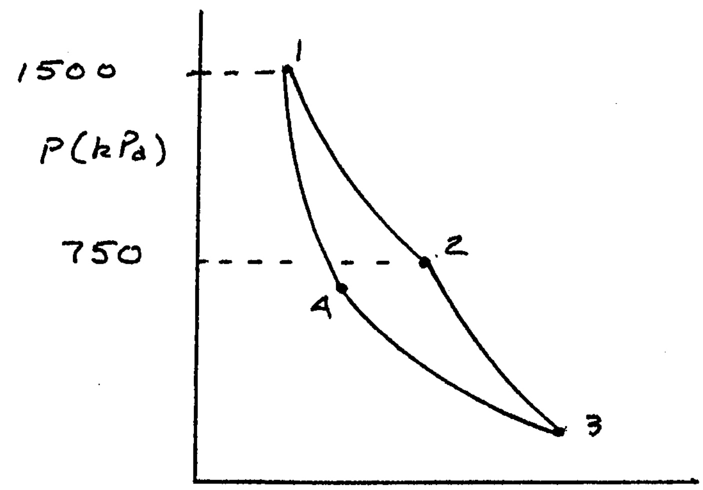
Problem 7.9

A Carnot engine operates between temperature limits of 1200°K and 400°K, using 0.4 kg of air and running at 500 rev/min. The pressure at the beginning of heat addition is 1500 kPa and at the end of heat addition is 750 kPa. Determine (a) the heat added per cycle; (b) the heat rejected; (c) the power; (d) the volume at the end of heat addition; (e) the meat effective pressure; (f) the thermal efficiency.

Given: A Carnot cycle engine, its temperature limits, rpm and mass of air.

Find: The heat flow in and out of the engine, the power produced, the efficiency and mean effective pressure and V_2.

Sketch and Given Data:



$T_H = 1200\text{ K}$
$T_c = 400\text{K}$
0.4 kg air
500 rpm

Assumptions:
1) Air is an ideal gas.
2) The cycle operates on sketch shown.

Analysis: The cycle thermal efficiency is.

(f) $$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{400}{1200} = 0.667$$

The heat added occurs in process 1 - 2,

$$Q_{1\text{-}2} = W_{1\text{-}2} = p_1V_1\ln\left(\frac{V_2}{V_1}\right) = mRT_1\ln\left(\frac{p_1}{p_2}\right)$$

(a) $$Q_{1\text{-}2} = (0.4\text{ kg})\left(0.287\ \frac{\text{kJ}}{\text{kg-K}}\right)(1200\text{ K})\ln\left(\frac{1500}{750}\right) = 95.5\text{ kJ/cycle}$$

The work per cycle is.

$$W_{net} = \eta_{Th}\, Q_{in} = (0.667)(95.5\ kJ) = 63.7\ kJ/cycle$$

The power is.

(c) $$\dot{W} = N*W_{net} = \left(8.333\ \frac{cyc}{sec}\right)\left(63.7\ \frac{kJ}{cyc}\right) = \underline{530.8\ kW}$$

The heat rejected per cycle is

$$Q_{in} + Q_{out} = W_{net}$$

(b) $$Q_{out} = 63.7 - 95.5 = \underline{-31.8\ kJ/cycle}$$

The process for heat addition is constant temperature; for an ideal gas this is described by pV = C.

$$V_1 = \frac{mRT_1}{p_1} = \frac{(0.4\ kg)\left(0.287\ \frac{kJ}{kg-K}\right)(1200\ K)}{(1500\ kN/m^2)} = 0.0918\ m^3$$

(d) $$V_2 = V_1\left(\frac{p_1}{p_2}\right) = 2V_1 = 0.1837\ m^3$$

The volume at the end of expansion or BDC is needed to find the mean effective pressure. The process 2 - 3 is reversible adiabatic, hence,

$$\frac{T_2}{T_3} = \left(\frac{V_3}{V_2}\right)^{k-1}$$

$$V_3 = V_2\left(\frac{T_2}{T_3}\right)^{\frac{1}{k-1}} = (0.1837\ m^3)\left(\frac{1200}{400}\right)^{\frac{1}{0.4}} = 2.8636\ m^3$$

$$V_{PD} = V_3 - V_1 = 2.8636 - 0.0918 = 2.7718\ m^3$$

(e) $$p_m = \frac{W_{net}}{V_{PD}} = \frac{63.7\ k(N\ m)}{(2.7718\ m^3)} = 23.0\ kPa$$

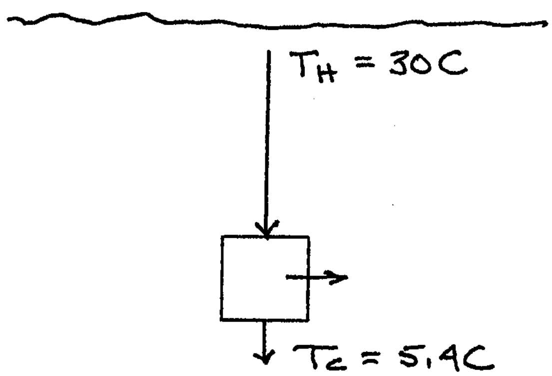
Problem 7.13

A nonpolluting power plant can be constructed using the temperature difference in the ocean. At the surface of the ocean in tropical climates, the average water temperature year-round is 30°C. At a depth of 305 m, the temperature is 5.4°C. Determine the maximum thermal efficiency of such a power plant.

Given: The temperature difference for a ocean thermal difference power plant.

Find: Maximum power plant efficiency.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: The maximum thermal efficiency would be that of a Carnot cycle operating between this temperature limits.

$$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{277.5}{303} = 0.084 = \underline{8.4\%}$$

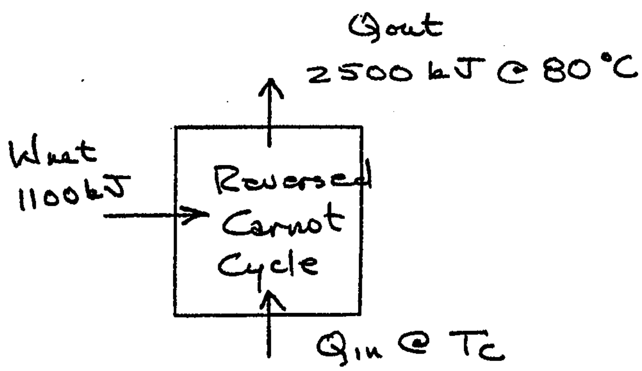
Problem 7.17

A Carnot refrigerator rejects 2500 kJ of heat at 80°C while using 1100 kJ of work. Find (a) the cycle low temperature; (b) the COP; (c) the heat absorbed.

Given: A refrigerator runs on the reversed Carnot cycle with known heat flow and work required.

Find: The cycle low temperature, the COP and the heat input.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: From the conservation of energy for the cycle.

$$Q_{in} + Q_{out} = W_{net}$$

$$Q_{in} - 2500 = -1100 \text{ kJ}$$

(c) $$Q_{in} = \underline{1400 \text{ kJ}}$$

(b) $$(COP)_c = \frac{Q_{in}}{W_{net}} = \frac{1400}{1100} = \underline{1.27}$$

$$COP_c = 1.27 = \frac{T_c}{T_H - T_c} = \frac{T_c}{353 - T_c}$$

(a) $$T_c = \underline{197.7} \text{ K}$$

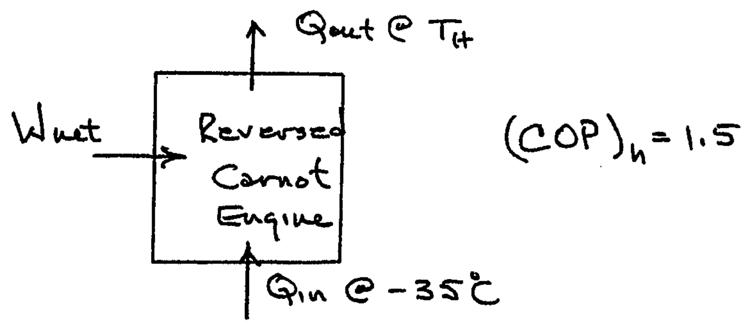
Problem 7.21

A Carnot heat pump is being considered for home heating in a location where the outside temperature may be as low as -35°C. The expected COP for the heat pump is 1.50. To what temperature could this unit provide heat?

Given: A reversed Carnot cycle acts as a heat pump. The low temperature and $(COP)_h$ are known.

Find: The high cycle temperature.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: The $(COP)_h$ for a reversed Carnot cycle is.

$$(COP)_h = \frac{Q_{out}}{W_{net}} = \frac{T_H}{T_H - T_c}$$

$$1.5 = \frac{T_H}{T_H - T_c} = \frac{T_H}{T_H - 238}$$

T_H = <u>714 K</u>

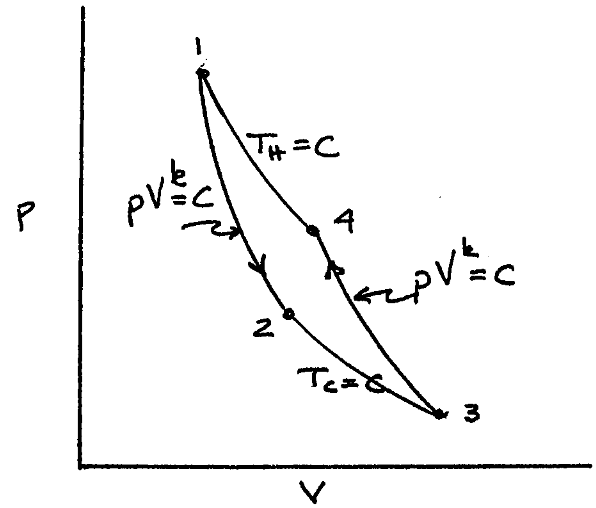
Problem 7.25

Derive the expression for the $(COP)_h$ for a heat pump operating on the reversed Carnot cycle.

Given: A reversed Carnot cycle acting as a heat pump.

Find: Derive $(COP)_h$

Sketch and Given Data:



Assumptions:
1) Substance is an ideal gas.
2) The cycle operates on sketch shown.

Analysis:

$$(COP)_h = \frac{Q_{out}}{W_{net}} = \frac{Q_{out}}{Q_{in} + Q_{out}}$$

Heat is rejected from 4 - 1.

$$Q_{out} = p_4 V_4 \ln\left(\frac{V_1}{V_4}\right) = mRT_H \ln\left(\frac{V_1}{V_4}\right)$$

Heat is added from 2 - 3.

$$Q_{in} = p_2 V_2 \ln\left(\frac{V_3}{V_2}\right) = mRT_c \ln\left(\frac{V_3}{V_2}\right)$$

For reversible adiabatic processes, 1 - 2, and 3 - 4.

$$\frac{T_1}{T_2} = \frac{T_H}{T_c} = \left(\frac{V_2}{V_1}\right)^{k-1}$$

$$\frac{T_4}{T_3} = \frac{T_H}{T_c} = \left(\frac{V_3}{V_4}\right)^{k-1}$$

$$\therefore \quad \frac{V_2}{V_1} = \frac{V_3}{V_4} \qquad \text{or} \qquad \frac{V_1}{V_4} = \frac{V_2}{V_3}$$

$$(COP)_h = \frac{mRT_H \ln\left(\frac{V_1}{V_4}\right)}{mRT_c \ln\left(\frac{V_3}{V_2}\right) + mRT_H \ln\left(\frac{V_1}{V_4}\right)}$$

However, $\ln\left(\frac{V_3}{V_2}\right) = -\ln\left(\frac{V_1}{V_4}\right)$

$$(COP)_h = \frac{T_H}{T_H - T_c}$$

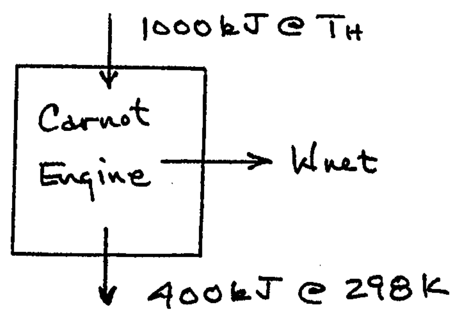
Problem 7.29

A Carnot heat engine receives 1000 kJ of heat from a heat reservoir at an unknown temperature and rejects 400 kJ of heat to a low temperature reservoir at 25°C. Determine the high temperature and the thermal efficiency.

Given: A Carnot engine receives a known amount of heat and rejects a known amount of heat at 25°C.

Find: The cycle efficiency and the high cycle temperature.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: For a Carnot engine, the thermal efficiency is

$$\eta_{Th} = \frac{Q_{in} + Q_{out}}{Q_{in}} = \frac{1000 - 400}{1000} = \underline{0.60}$$

$$\eta_{Th} = \frac{T_H - T_c}{T_H}$$

$$0.6 = 1 - \frac{298}{T_H}$$

$$T_H = \underline{745\text{ K}}$$

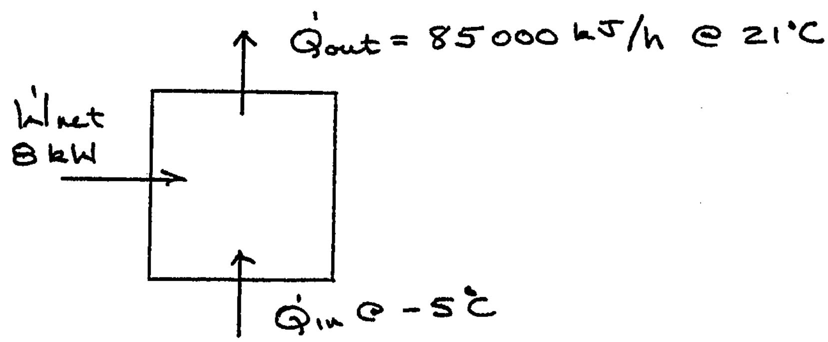
Problem 7.33

A 8 kW heat pump is designed to maintain a house at 21°C when the outside temperature is -5C. The heat loss from the house is estimated to be 85 000 kJ/h for these temperature conditions. Can the heat pump provide the necessary heat?

Given: A heat pump, the cycle temperature limits and the heating requirements.

Find: Whether heat pump has sufficient capacity.

Sketch and Given Data;



Assumptions: 1) The cycle operates on sketch shown.

Analysis: Determine the $(COP)_h$ for the actual unit and for a reversed Carnot cycle heat pump. If the actual $(COP)_h$ is less than the Carnot cycle heat pump, then it is possible to provide the cooling.

Actual $$(COP)_h = \frac{\dot{Q}_{out}}{\dot{W}_{net}} = \frac{(23.61\ \text{kW})}{(8\ \text{kW})} = \underline{2.95}$$

Carnot $$(COP)_h = \frac{T_H}{T_H - T_c} = \frac{294}{294 - 268} = \underline{11.3}$$

Yes, the heat pump can provide required heat.

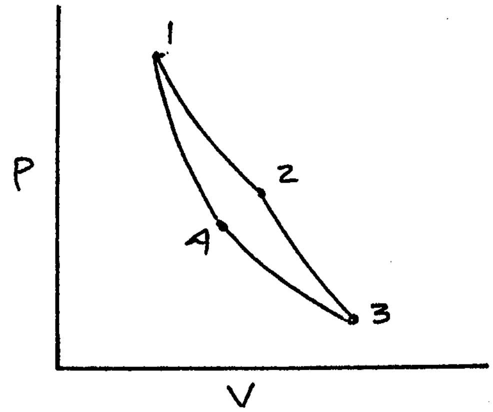
Problem 7.37

Show for a Carnot cycle engine using an ideal gas as the working substance that $V_4V_2 = V_1V_3$.

Given: A Carnot cycle using an ideal gas.

Find: That $V_4V_2 = V_1V_3$.

Sketch and Given Data:



Assumptions:
1) Substance is an ideal gas.
2) The cycle operates on sketch shown.

Analysis: For the reversible adiabatic processes.

$$\frac{T_1}{T_2} = \frac{T_H}{T_c} = \left(\frac{V_2}{V_1}\right)^{k-1}$$

$$\frac{T_4}{T_3} = \frac{T_H}{T_c} = \left(\frac{V_3}{V_4}\right)^{k-1}$$

$$\therefore \frac{V_2}{V_1} = \frac{V_3}{V_4}$$

$$V_4V_2 = V_1V_3$$

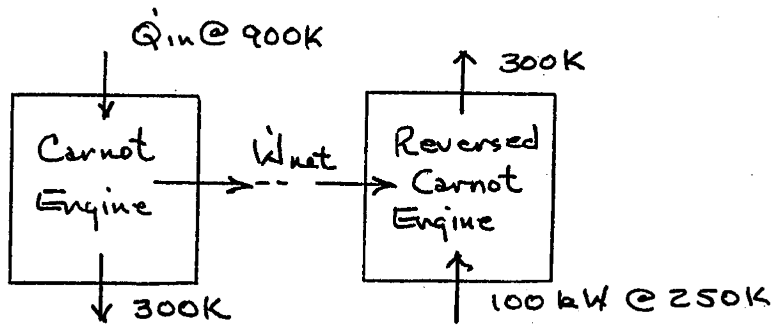
Problem 7.41

A reversed Carnot engine operates between 250 K and 300 K and receives 100 kW of heat at the lower temperature. The power to drive the reversed engine comes from a Carnot engine operating between 900 K and 300 K. Determine the heat input to the Carnot engine.

Given: A Carnot engine drives a reversed Carnot engine. The heat input to the reversed engine is known as are the temperature limits of both engines.

Find: The heat supplied to the Carnot engine.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: For the reversed cycle engine,

$$(COP)_c = \frac{T_c}{T_H - T_c} = \frac{250}{300 - 250} = 5.0$$

$$(COP)_c = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{100 \text{ kW}}{\dot{W}_{net}} = 5$$

$$\dot{W}_{net} = 20 \text{ kW}$$

This is equal to the power output from the Carnot engine.

$$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{300}{900} = 0.667$$

$$\eta_{Th} = 0.667 = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{20 \text{ kW}}{\dot{Q}_{in}}$$

$$\dot{Q}_{in} = \underline{30 \text{ kW}}$$

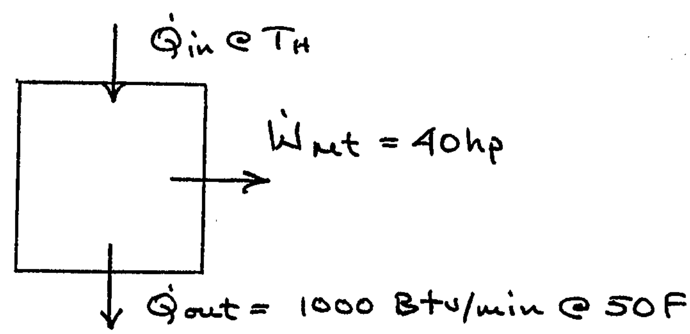
Problem *7.1

A Carnot engine rejects 1000 Btu/min at 50°F and produces 40 hp. Determine the temperature of heat addition and the amount of heat flow into the engine.

Given: A Carnot engine, the heat out, temperature out and power produced.

Find: The high cycle temperature and the heat added.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: Convert the power to Btu/min

$$\dot{W}_{net} = (40 \text{ hp})\left(42.4 \frac{\text{Btu}}{\text{min-hp}}\right) = 1696 \text{ Btu/min}$$

$$\dot{Q}_{in} + \dot{Q}_{out} = \dot{W}_{net}$$

$$\dot{Q}_{in} = 1696 + 1000 = \underline{2696 \text{ Btu/min}}$$

$$\eta_{Th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{1696}{2696} = 0.629$$

$$\eta_{Th} = 0.629 = 1 - \frac{T_c}{T_H} = 1 - \frac{510}{T_H}$$

$$T_H = \underline{1375°R = 915°F}$$

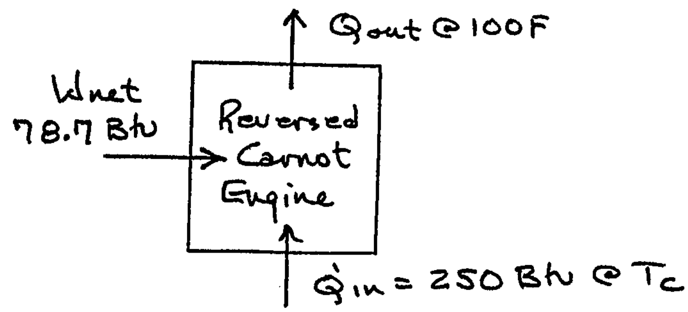
Problem *7.5

The engine in problem *7.4 is used to drive a heat pump which receives 250 Btu's from the low temperature heat reservoir. It rejects heat at 100°F; determine the temperature of the heat that is added.

Given: A Carnot engine drives a reversed Carnot engine. Acting as a heat pump. The heat in is given as the high temperature.

Find: The low temperature of the reversed Carnot engine.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: Determine the $(COP)_h$ from the energies, then find T_c.

$$(COP)_h = \frac{Q_{out}}{W_{net}} \qquad Q_{out} = W_{net} + Q_{in} = 328.7 \text{ Btu}$$

$$(COP)_h = \frac{328.7}{78.7} = 4.18$$

$$(COP)_h = 4.18 = \frac{T_H}{T_H - T_c} = \frac{560}{560 - T_c}$$

$$T_c = 426°R = -34°F$$

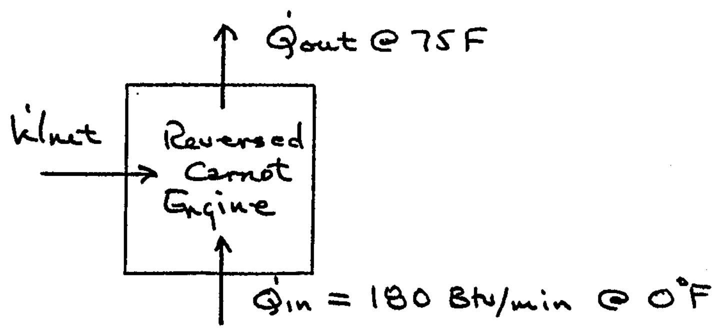
Problem 7.9*

Determine the minimum power required to provide 180 Btu/min of cooling at 0°F while the surrounding air is at 75°F.

Given: A reversed Carnot cycle, the cooling load and the temperature limits.

Find: The power required.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: For a reversed Carnot cycle.

$$(COP)_c = \frac{T_c}{T_H - T_c} = \frac{460}{535 - 460} = 6.13$$

$$(COP)_c = 6.13 = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{(180 \text{ Btu/min})}{\dot{W}_{net}}$$

$$\dot{W}_{net} = \underline{29.36 \frac{\text{Btu}}{\text{min}} = 0.69 \text{ hp}}$$

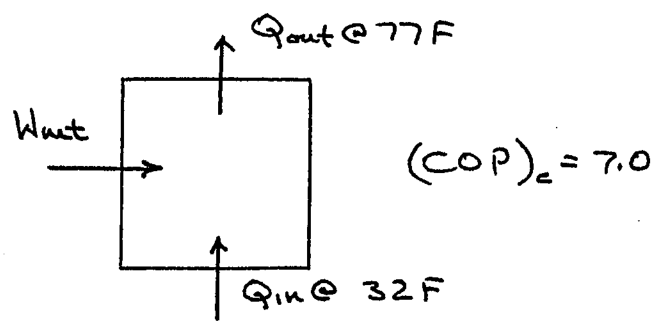
Problem 7.13*

The inventor of a new refrigerator claims to have maintained at cooled space at 32°F in surrounding air of 77°F while maintaining a COP_c of 7.0. Is this reasonable?

Given: The $(COP)_c$ of a refrigerator and the temperature limits it operates between.

Find: Whether the $(COP)_c$ is reasonable.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: Find the $(COP)_c$ of a reversed Carnot cycle. If the actual refrigerator is less than this, the claims are reasonable.

$$(COP)_c = \frac{T_c}{T_H - T_c} = \frac{492}{537 - 492} = 10.9$$

Therefore, claims are reasonable.

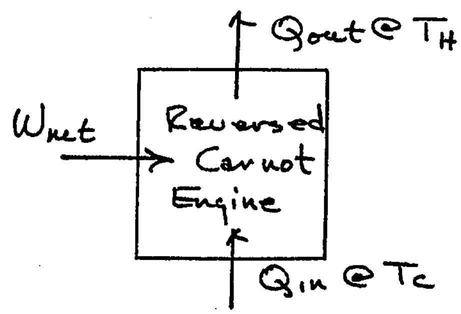
Problem 7.17*

It is desired to double the $(COP)_c$ of a reversed Carnot engine by raising the temperature of heat addition for a fixed high temperature. What percent must the low temperature be raised?

Given: A reversed Carnot engine with a fixed high temperature and a variable low temperature.

Find: The percent T_c must be raised to double the $(COP)_c$.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: The $(COP)_c$ is

$$(COP)_c = \frac{T_c}{T_H - T_c}$$

$$5.0 = \frac{T_c}{T_H - T_c}$$

$$T_c = 5/6\ T_H = 0.833\ T_H$$

$$10.0 = \frac{T''_c}{T_H - T''_c}$$

$$T''_c = 0.909\ T_H$$

The percent change in T_c is $\%\ \text{change} = \frac{(0.909 - 0.833)(100)}{0.833} = 9.1\%$

Problem 7.21*

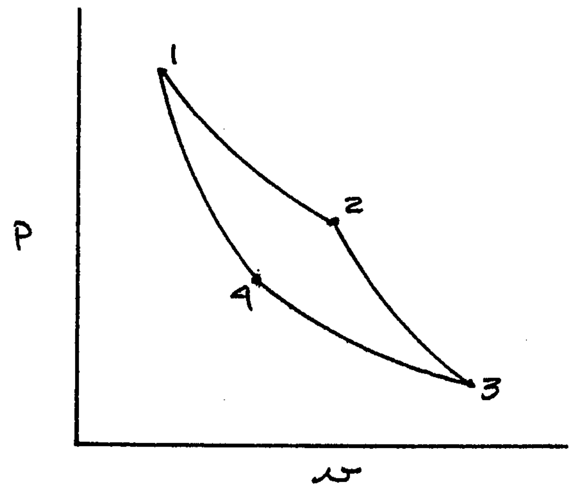
A Carnot cycle engine using 1 lbm of air has the following conditions: heat addition beginning at 2200 psia and 2200 R and continuing until the pressure is 1400 psia; isothermal compression from 14.7 psia and 540 R and continuing until the pressure is 23.1 psia. Determine:

a) the heat transfer into the cycle;
b) the heat transfer from the cycle;
c) the work for each of the processes;
d) the cycle efficiency.

Given: A Carnot engine with its cycle state points.

Find: The heat flows, the process work and the cycle efficiency.

Sketch and Given Data:



1 lbm air
P_1 = 2200 psia
T_1 = 2200 R
P_2 = 1400 psia
P_3 = 14.7 psia
T_3 = 540 R
P_4 = 23.1 psia

Assumptions:
1) Air is an ideal gas.
2) The cycle operates on sketch shown.

Analysis: The Carnot cycle efficiency is.

d) $$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{540}{2200} = \underline{0.755}$$

Proceed around the cycle, solving for the heat and work terms. The process 1 - 2 is constant temperature.

$$Q_{1\text{-}2} = W_{1\text{-}2}$$

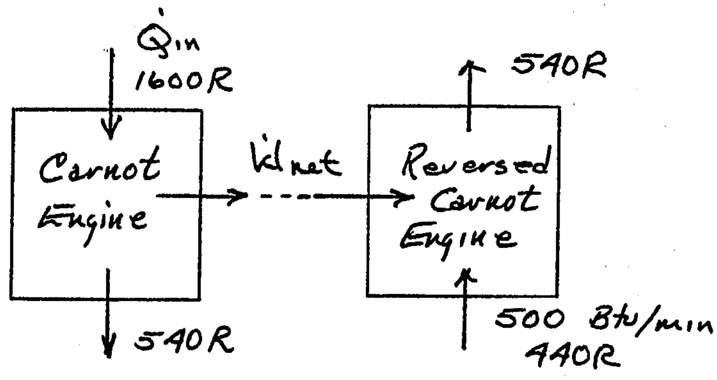
Problem 7.25*

A reversed Carnot engine operates between 440 R and 540 R and receives 500 Btu/min of heat at the lower temperature. The power to drive the reversed engine comes from a Carnot engine operating between 1600 R and 540 R. Determine the heat input to the Carnot engine.

Given: A Carnot engine drives a reversed Carnot engine. The heat input to the reversed engine is known as are the temperature limits of both engines.

Find: The heat supplied to the Carnot engine.

Sketch and Given Data:



Assumptions: 1) The cycle operates on sketch shown.

Analysis: For the reversed cycle engine,

$$(COP)_c = \frac{T_c}{T_H - T_c} = \frac{440}{540 - 440} = 4.4$$

$$(COP)_c = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{500 \text{ Btu/min}}{\dot{W}_{net}} = 4.4$$

$$\dot{W}_{net} = 2200 \text{ Btu/min}$$

This is equal to the power output from the Carnot engine.

$$\eta_{Th} = 1 - \frac{T_c}{T_H} = 1 - \frac{540}{1600} = 0.663 = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{2200\frac{\text{Btu}}{\text{min}}}{\dot{Q}_{in}}$$

$$\dot{Q}_{in} = 3318 \text{ Btu/min}$$

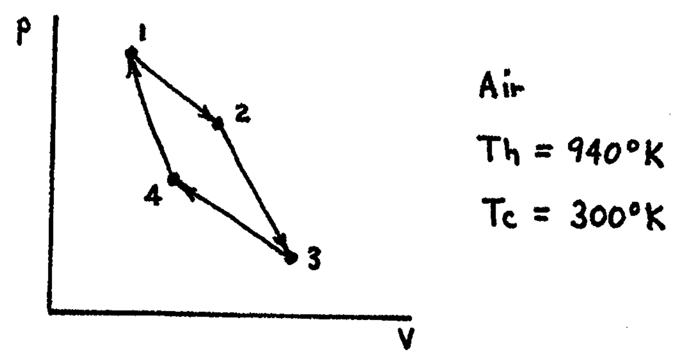
Problem C7.1

Develop a TK Solver or spreadsheet model to analyze the Carnot cycle. For the cycle conditions in Example 7.3, vary the heat supplied to the cycle between 25 and 300 kJ/kg and plot the pressures at the end of the heat addition and expansion processes.

Given: Carnot cycle operating on air between temperatures of 940°K and 300°K.

Find: Pressures at end of heat addition and expansion processes for a range of heat supplied between 25 to 300 kJ/kg.

Sketch and Given Data:



Assumptions:
1) Air is in equilibrium.
2) Air behaves as an ideal gas.

Analysis: Using TK Solver, enter the cycle equations as shown on the Rule Sheet below. The equations include the ideal gas equation for each point, equations, for the constant temperature and reversible adiabatic processes, and the first law relationships. Using the List Solver, P2 and P3 are calculated for a range of heat inputs. Plot results.

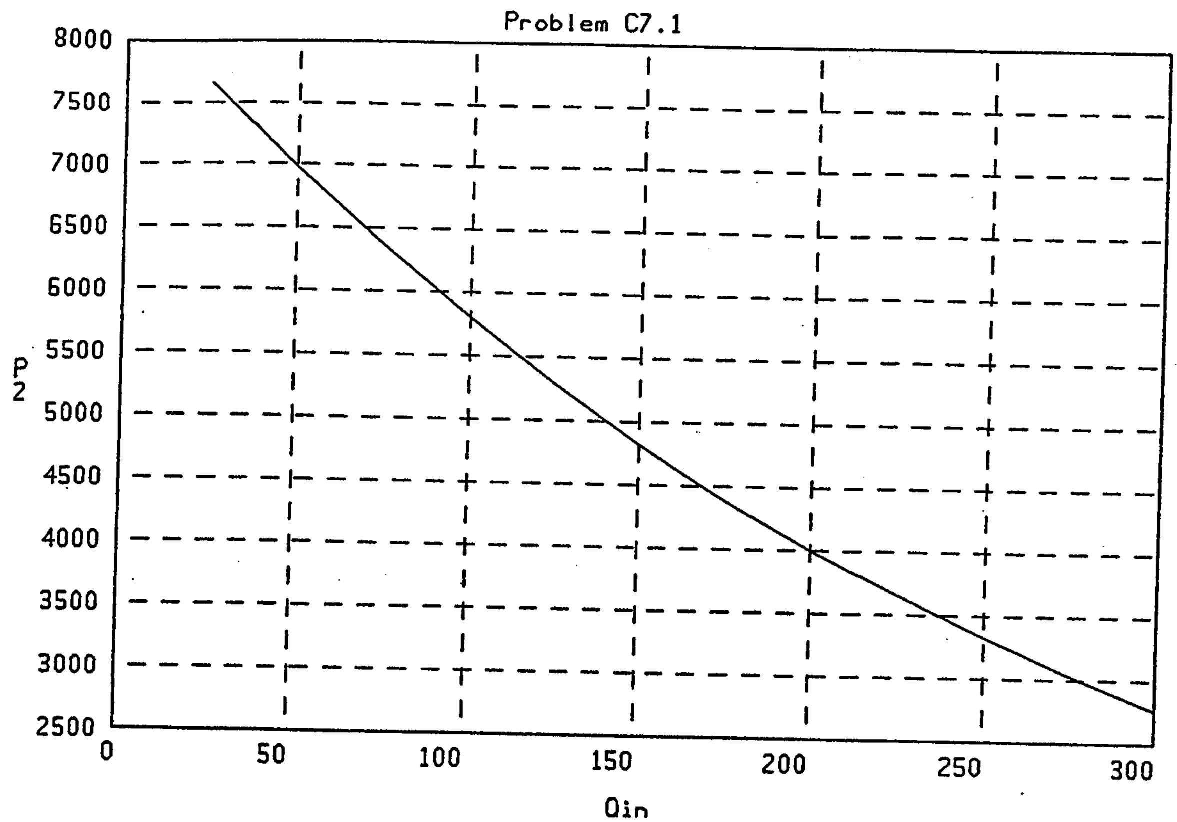
VARIABLE SHEET

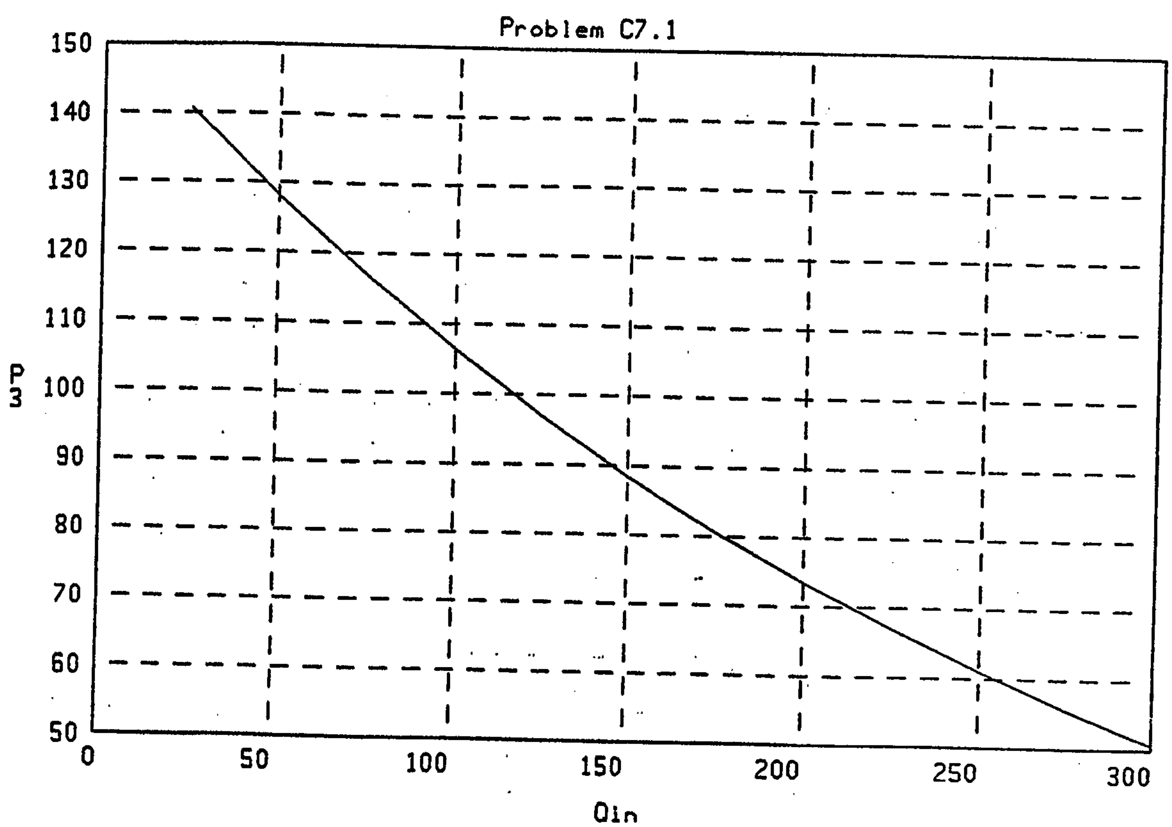
St	Input	Name	Output	Unit	Comment
					Problem C7.1
					ENGINEERING THERMODYNAMICS 4/E
					M. David Burghardt & James A. Harbach
	.287	R		kJ/kg-K	Gas Constant
	1.4	k			Specific Heat Ratio
	940	Th		degK	Temperature - High
	300	Tc		degK	Temperature - Low
L	84	Q12		kJ/kg	Heat Supplied
		Q34	-26.809	kJ/kg	Heat Rejected
		Wnet	57.191	kJ/kg	Net Work
		Eth	.68085		Thermal Efficiency
		COPref	.46875		COP of Refrigeration System
		COPhp	1.4688		COP of Heat Pump System
	8400	P1		kPa	Pressure
		v1	.032117	m3/kg	Specific Volume
		T1	940	degK	Temperature
L		P2	6152.6	kPa	Pressure
		v2	.043848	m3/kg	Specific Volume
		T2	940	degK	Temperature
L		P3	112.99	kPa	Pressure
		v3	.76203	m3/kg	Specific Volume
		T3	300	degK	Temperature
		P4	154.26	kPa	Pressure
		v4	.55814	m3/kg	Specific Volume
		T4	300	degK	Temperature

RULE SHEET

S Rule

```
P1*v1=R*T1
P2*v2=R*T2
P3*v3=R*T3
P4*v4=R*T4
Q12=P1*v1*LN(v2/v1)
Q34=P3*v3*LN(v4/v3)
P2*v2^k=P3*v3^k
P4*v4^k=P1*v1^k
T1=T2
T3=T4
Th=T1
Tc=T3
Wnet=Q12+Q34
Eth=(Th-Tc)/Th
COPref=Tc/(Th-Tc)
COPhp=Th/(Th-Tc)
```


Problem C7.1
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
P 2
0
50
100
150
200
250
300
Qin


Problem C7.1
150
140
130
120
110
100
90
80
70
60
50
P 3
0
50
100
150
200
250
300
Qin

CHAPTER EIGHT

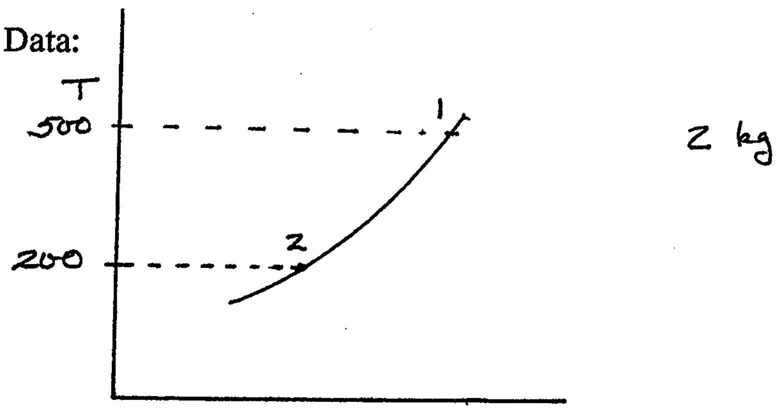
Problem 8.1

Two kilograms of a gas are cooled from 500°C to 200°C at constant pressure in a heat exchanger. Determine the change of entropy for (a) air; (b) carbon dioxide; (c) helium.

Given: An ideal gas is cooled at constant pressure.

Find: The entropy change.

Sketch and Given Data:



Assumptions:
1) The gases are ideal gases.
2) The process is constant pressure.

Analysis: The change of entropy of an ideal gas is

$$S_2 - S_1 = m\, c_p \ln\left(\frac{T_2}{T_1}\right) - mR \ln\left(\frac{P_2}{P_1}\right)$$

for constant pressure

$$S_2 - S_1 = m\, c_p \ln\left(\frac{T_2}{T_1}\right)$$

(a) Air

$$S_2 - S_1 = (2\text{ kg})\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{473}{773}\right) = -0.987\ \frac{\text{kJ}}{\text{K}}$$

(b) Carbon dioxide

$$(S_2 - S_1) = (2\ \text{kg})\left(0.844\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{473}{773}\right) = -0.829\ \frac{\text{kJ}}{\text{K}}$$

(c) Helium

$$(S_2 - S_1) = (2\ \text{kg})\left(5.1954\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{473}{773}\right) = -5.104\ \frac{\text{kJ}}{\text{K}}$$

Comments:

1) The change of entropy is negative because the heat leaves the system reversibly. The change of entropy varies dramatically from substance to substance for the same temperature limits.

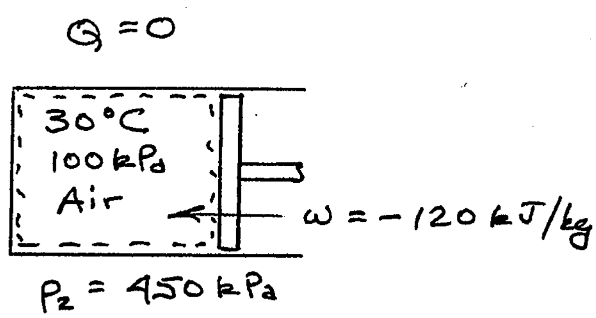
Problem 8.5

A piston-cylinder arrangement has been developed to compress air adiabatically from 30°C and 100 kPa with 120 kJ/kg of work. Is this possible?

Given: Air is supposedly compressed adiabatically between two states.

Find: If the process is possible.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The process is illustrated in the sketch.
3) Air is a closed system.
4) Q = 0
5) Neglect changes in kinetic and potential energies.

Analysis: The first law for a closed system

$$q = \Delta u + w$$

$$\Delta u = -w = -(-120) = +120 \text{ kJ/kg}$$

For an ideal gas.

$$\Delta u = c_v\,(T_2 - T_1) = (0.7176 \text{ kJ/kg-K})(\Delta T \text{ K}) = 120 \ \frac{\text{kJ}}{\text{kg}}$$

$$\Delta T = 167.2 \text{ K}$$

$$T_2 = 470.2 \text{ K}$$

Knowing the temperatures and pressures at both states, calculate the entropy change. It must be greater than or equal to zero for the process to be possible.

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)$$

$$s_2 - s_1 = \left(1.0047\ \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{470.2}{303}\right) - \left(0.287\ \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{450}{100}\right)$$

$$s_2 - s_1 = 0.01\ kJ/kg\text{-}K$$

hence the process is possible.

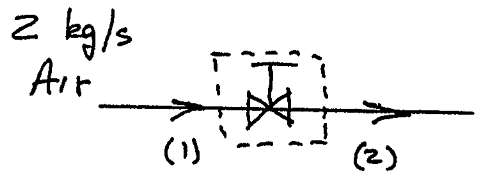
Problem 8.9

When air is throttled, there is an entropy increase. For 2 kg/s of air the entropy increases by 0.06 kW/K. Determine the pressure ratio of final to initial for this to occur.

Given: Air is throttled across a valve and the entropy change is given.

Find: The pressure ratio across the valve.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.
4) The system is a steady-state open system.

Analysis: The expression for the entropy change for an ideal gas is

$$\dot{m}(s_2 - s_1) = \dot{m}\, c_p \ln\left(\frac{T_2}{T_1}\right) - \dot{m}\, R \ln\left(\frac{p_2}{p_1}\right)$$

For a throttling process, $h_2 = h_1$, and for an ideal gas $c_p\, T_2 = c_p\, T_1$, hence $T_2 = T_1$.

$$\dot{m}(s_2 - s_1) = -\dot{m}\, R \ln\left(\frac{p_2}{p_1}\right)$$

$$\left(0.06\ \frac{kW}{K}\right) = -(2\ kg/s)(0.287\ kJ/kg\text{-}K) \ln\left(\frac{p_2}{p_1}\right)$$

$$\frac{p_2}{p_1} = 0.90$$

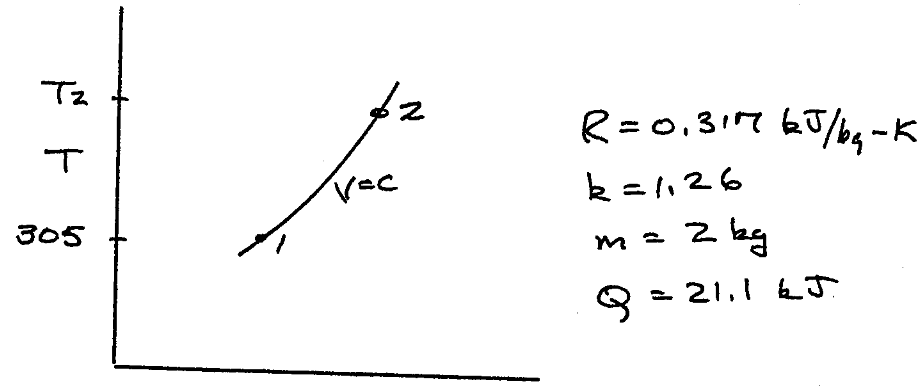
Problem 8.13

Two kilograms of an ideal gas, R = 317 J/kg K and k = 1.26, are contained in a rigid cylinder; 21.1 kJ of heat are added to the gas, which has an initial temperature of 305°K. Determine (a) the final temperature; (b) the change of entropy; (c) the change of enthalpy; (d) the change if internal energy.

Given: An ideal gas is contained in a constant volume cylinder and heat is added.

Find: The change of entropy, enthalpy, internal energy and the final temperature.

Sketch and Given Data:



Assumptions:
1) The gas is ideal.
2) Neglect changes in kinetic and potential energies.
3) The system is closed.
4) The work is zero (V = c)

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 1, 2 and 4.

$$R = 0.317 \text{ kJ/kg-K} = c_p - c_v \qquad c_p = 1.5362 \text{ kJ/kg-K}$$

$$k = 1.26 = c_p/c_v \qquad c_v = 1.2192 \text{ kJ/kg-K}$$

$$Q = m(u_2 - u_1) = mc_v(T_2 - T_1)$$

$$(21.1 \text{ kJ}) = (2 \text{ kg})(1.2192 \text{ kJ/kg-K})(T_2 - 305)$$

(a) $T_2 = 313.6$ K

(d) $\Delta U = Q = 21.1$ kJ

$$\Delta H = mc_p(T_2 - T_1) = (2\ \text{kg})\left(1.5362\ \frac{\text{kJ}}{\text{kg-K}}\right)(313.6 - 305\ \text{K})$$

(c) $\Delta H = \underline{26.4\ \text{kJ}}$

$$\Delta S = m\ c_v\ \ln\left(\frac{T_2}{T_1}\right) + m\ R\ \ln\left(\frac{V_2}{V_1}\right)^{\nearrow 0}$$

(b) $\Delta S = (2\ \text{kg})\left(1.2192\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{313.6}{305}\right) = \underline{0.068}\ \frac{\text{kJ}}{\text{K}}$

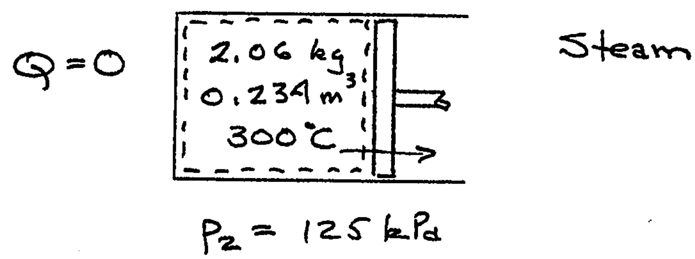
Problem 8.17

If 2.06 kilograms of steam expand adiabatically from a volume of 0.234 m^3 and a temperature of 300°C to a pressure of 125 kPa, determine (a) for reversible adiabatic expansion the work, the initial pressure, and the final quality; (b) for irreversible expansion--where the final quality is 100%--find the work, the initial pressure, and the change of entropy.

Given: Steam expands adiabatically in a closed system from an initial to a final state.

Find: The work done, the initial pressure and final steam quality for isentropic expansion. Find the work, initial pressure and entropy change for an irreversible process.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and a closed system.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.

Analysis: The specific volume at state 1 is

$$v_1 = \frac{V}{m} = \frac{(0.234\text{m}^3)}{(2.06\text{ kg})} = 0.1136\ \text{m}^3/\text{kg}$$

From STEAM.TK or the superheat tables, knowing T_1 = 300°C

u_1 = 2769.0 kJ/kg $\qquad$ s_1 = 6.7160 kJ/kg-K

p_1 = <u>2197.8 kPa</u>

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3

$$W = -\Delta U = -m(u_2 - u_1)$$

The final steam state is found knowing p_2 and $s_2 = s_1$. From the saturated region, or using STEAM.TK.

$u_2 = 2314.9$ kJ/kg $\qquad x_2 = \underline{0.904}$

$W = -(2.06 \text{ kg})(2314.9 - 2769.0 \text{ kJ/kg}) = \underline{+935.4}$ kJ

(b) For the irreversible case where $p_2 = 125$ kPa

$u_2 = u_g = 2513.6$ kJ/kg $\qquad s_2 = s_g = 7.2834$ kJ/kg-K

The initial state is the same as part (a). The work is,

$$W = -\Delta U = -m(u_2 - u_1) = -(2.06 \text{ kg})(2513.6 - 2769.0 \text{ kJ/kg})$$

$W = \underline{+526.1 \text{ kJ}}$

$$\Delta S = m(s_2 - s_1) = (2.06 \text{ kg})(7.2834 - 6.7160 \text{ kJ/kg-K})$$

$$\Delta S = 1.1688 \text{ kJ/K}$$

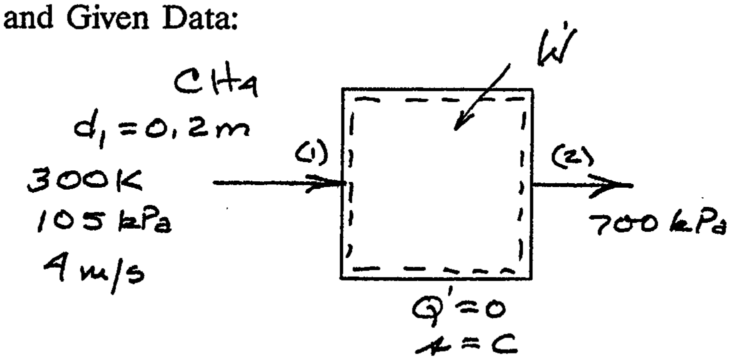
Problem 8.21

A natural gas pipeline distributes gas throughout the country, pumped by large gas-turbine-driven centrifugal compressors. Assume that the natural gas is methane, the pipe diameter is 0.2 m, and the gas enters the compressor at 300°K and 105 kPa. The velocity of the methane entering the compressor is 4 m/s. The compression process is isentropic and the discharge pressure is 700 kPa. Determine (a) the discharge temperature; (b) the mass flowrate; (c) the power required.

Given: Methane is compressed isentropically between two states in a steady flow compressed.

Find: The discharge temperature, flowrate and required power.

Sketch and Given Data:



Assumptions:
1) Methane is an ideal gas.
2) The compressor is a steady, open system.
3) Neglect changes in kinetic and potential energies.
4) The heat is zero.

Analysis: For an isentropic process for an ideal gas.

(a) $$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = (300 \text{ K})\left(\frac{700}{105}\right)^{\frac{0.321}{1.321}} = \underline{475.7 \text{ K}}$$

The conservation of mass equation is

$$\dot{m} = A\text{v}/v$$

The specific volume at state 1 is

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.5183 \text{ kJ/kg-K})(300 \text{ K})}{(105 \text{ kN/m}^2)} = 1.481 \text{ m}^3\text{/kg}$$

(b) $$\dot{m} = \frac{(\pi)(0.2\ m)^2(4\ m/s)}{(4)(1.481\ m^3/kg)} = \underline{0.0848\ kg/s}$$

The first law for an open steady system is

$$\dot{Q} + \dot{m}\ (h + ke + pe)_1 = \dot{W} = \dot{m}\ (h + ke + pe)_2$$

Apply assumptions 3 and 4

$$\dot{W} = \dot{m}(h_1 - h_2) = \dot{m}\ c_p(T_1 - T_2)$$

$$\dot{W} = (0.0848\ kg/s)(2.1347\ kJ/kg\text{-}K)(300 - 475.7\ K)$$

(c) $$\dot{W} = \underline{-31.8\ kW}$$

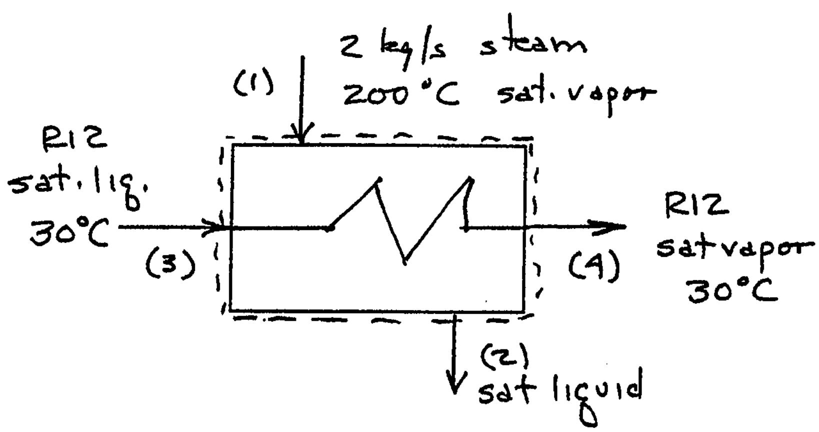
Problem 8.25

Two kg/s of saturated steam at 200°C are condensed to a saturated liquid. The coolant is R12, which is vaporized at 30°C. Determine (a) the mass flowrate of R12 vaporized; (b) the change of entropy of the steam and of R12.

Given: Steam is steadily condensed in a heat exchanger by R12 which vaporizes.

Find: The R12 flowrate, the entropy change of the steam and R12.

Sketch and Given Data:



Assumptions:
1) Steam and R12 are pure substances.
2) The heat exchanger is a steady open system.
3) Neglect changes in kinetic and potential energies.
4) The heat is zero.
5) The work is zero.

Analysis: From the R12 tables for saturated refrigerant.

$$h_3 = 64.539 \frac{\text{kJ}}{\text{kg}} \qquad h_4 = 199.475 \text{ kJ/kg}$$

$$s_3 = 0.2397 \frac{\text{kJ}}{\text{kg-K}} \qquad s_4 = 0.6848 \text{ kJ/kg-K}$$

From the steam tables for saturated steam.

$$h_1 = 2793.3 \text{ kJ/kg} \qquad h_2 = 852.6 \text{ kJ/kg}$$

$$s_1 = 6.4312 \text{ kJ/kg-K} \qquad s_2 = 2.3295 \text{ kJ/kg-K}$$

The first law for steady open systems is

$$\dot{Q} + \dot{m}_s\,(h + ke + pe)_1 + \dot{m}_{R12}\,(h + ke + pe)_3 = \dot{W} + \dot{m}_s\,(h + ke + pe)_2$$
$$+ \dot{m}_{R12}\,(h + ke + pe)_4$$

Apply assumptions 3, 4, and 5.

$$\dot{m}_s\,(h_1 - h_2) = \dot{m}_{R12}\,(h_4 - h_3)$$

$$\dot{m}_{R12} = \dot{m}_s \frac{(h_1 - h_2)}{h_4 - h_3}$$

(a) $$\dot{m}_{R12} = \frac{(2\ \text{kg/s})(2793.3 - 852.6\ \text{kJ/kg})}{(199.475 - 64.539\ \text{kJ/kg})} = 28.76\ \text{kg/s}$$

The steam entropy change is.

(b) $$\Delta\dot{S}_{stm} = \dot{m}_s\,(s_2 - s_1) = (2\ \text{kg/s})\left(2.3295 - 6.4312\ \frac{\text{kJ}}{\text{kg-K}}\right) = -8.20\ \frac{\text{kW}}{\text{K}}$$

The R12 entropy change is.

(b) $$\Delta\dot{S}_{R12} = \dot{m}_{R12}\,(s_4 - s_3) = (28.76\ \text{kg/s})\left(0.6848 - 0.2397\ \frac{\text{kJ}}{\text{kg-K}}\right) = +12.80\ \frac{\text{kW}}{\text{K}}$$

The net entropy change is.

$$\Delta\dot{S}_{net} = \sum \Delta\dot{S}_i = -8.20 + 12.80 = +4.6\ \frac{\text{kW}}{\text{K}}$$

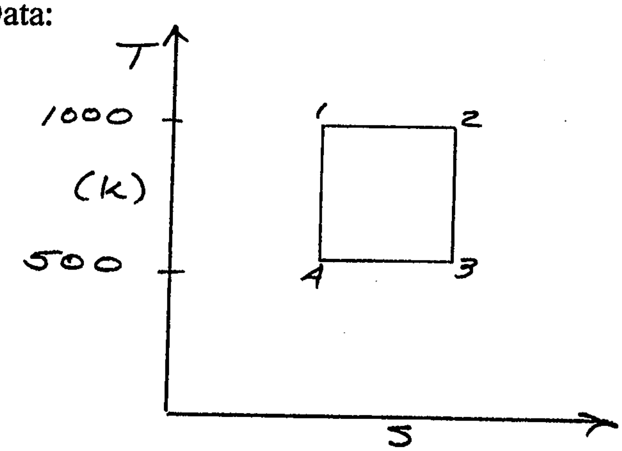
Problem 8.29

A Carnot cycle receives 1000 kJ of heat while operating between temperature limits of 1000°K and 500°K. Determine the entropy change during heat addition.

Given: A Carnot cycle receives heat at a known temperature.

Find: The entropy change during heat addition.

Sketch and Given Data:



Assumptions: 1) The process is illustrated in the sketch.

Analysis: For isothermal heat addition.

$$Q = T\Delta S$$

$$\Delta S = \frac{Q}{T} = \frac{1000\ \text{kJ}}{1000\ \text{K}} = \underline{1.0}\ \frac{\text{kJ}}{\text{K}}$$

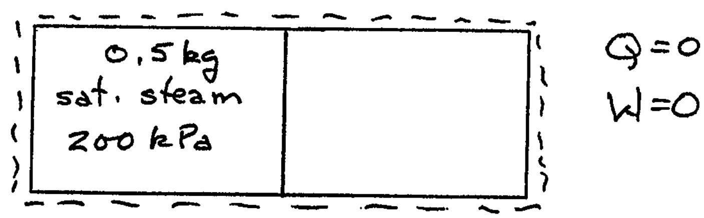
Problem 8.33

An adiabatic tank is partitioned into two equal volumes, one containing 0.5 kg of saturated steam at 200 kPa and the other totally evacuated. The partition is removed. What is the entropy change of the steam?

Given: An adiabatic tank contains two compartments, one holding saturated steam and the other empty. The partition between the compartments is removed.

Find: The steam's entropy change.

Sketch and Given Data:



Assumptions:
1) The two compartments form a constant volume closed system.
2) Steam is a pure substance.
3) Neglect changes in kinetic and potential energies.
4) Heat and work are zero.

Analysis: Determine the steam properties at state 1.

$$u_1 = 2529.6 \text{ kJ/kg} \qquad s_1 = 7.1267 \text{ kJ/kg-K} \qquad v_1 = 0.8858 \text{ m}^3\text{/kg}$$

The total system volume is

$$V = 2\, m v_1 = (2)(0.5 \text{ kg})\left(0.8858 \ \frac{\text{m}^3}{\text{kg}}\right) = 0.8858 \text{ m}^3$$

The specific volume at state 2 is

$$v_2 = \frac{V_2}{m} = \frac{(0.8858 \text{ m}^3)}{(0.5 \text{ kg})} = 1.7716 \text{ m}^3\text{/kg}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 3 and 4.

$$mu_2 = mu_1$$

Therefore state 2 is defined by knowing u_2 and v_2. From the superheated steam tables, find

$$s_2 = 7.4440 \qquad p_2 = 100 \text{ kPa}$$

The entropy change is

$$\Delta S = m(s_2 - s_1) = (0.5 \text{ kg})(7.4440 - 7.1267 \text{ kJ/kg-K})$$

$$\Delta S = \underline{0.159} \text{ kJ/K}$$

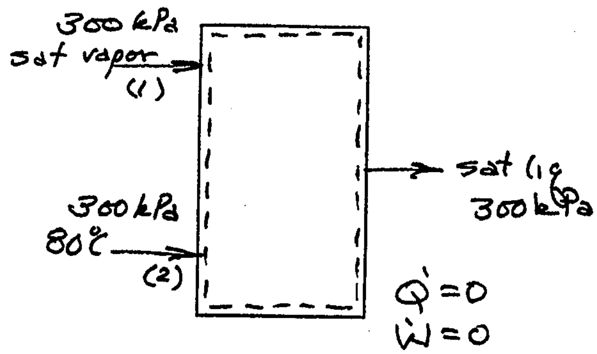
Problem 8.37

A direct contact heat exchanger receives saturated steam at 300 kPa and 20 kg/s of water at 300 kPa and 80°C. Water leaves the heat exchanger as a saturated liquid at 300 kPa. Determine the entropy production.

Given: A direct contact heat exchanger with steam and water states given.

Find: The entropy production.

Sketch and Given Data:



Assumptions:
1) Water is a pure substance.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energies.
4) The heat exchanger is a steady, open system.

Analysis: Determine the enthalpy and entropy values at the three condition.

$h_1 = h_g$ @ 300 kPa $= 2725.5\ \frac{kJ}{kg}$ $\qquad$ $s_1 = s_g$ @ 300 kPa = 6.9919 kJ/kg-K

$h_2 = h_f$ @ 80°C = 335.7 kJ/kg $\qquad$ $s_2 = s_f$ @ 80°C = 1.0751 kJ/kg-K

$h_3 = h_f$ @ 300 kPa = 561.2 kJ/kg $\qquad$ $s_3 = s_f$ @ 300 kPa $= 1.6698\ \frac{kJ}{kg-K}$

Determine the steam flowrate from a first law analysis on the control volume.

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2 = \dot{W} + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 2 and 3.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$$\dot{m}_3 = \dot{m}_1 + \dot{m}_2$$

$$(\dot{m}_1 \text{ kg/s})(2725.5 \text{ kJ/kg}) + (20 \text{ kg/s})(335.7 \text{ kJ/kg}) = (20 + \dot{m}_1 \text{ kg/s})(561.2 \text{ kJ/kg})$$

$$\dot{m}_1 = 2.08 \text{ kg/s} \qquad \dot{m}_3 = 22.08 \text{ kg/s}$$

Applying Equation 8.41

$$\frac{dS_{cv}}{dt} = \sum_{i=1}^{n} \frac{\dot{Q}_i}{T_i} + \dot{m}_{in}\, s_{in} - \dot{m}_{out}\, s_{out} + \Delta\dot{S}_{prod}$$

for steady-state, adiabatic conditions this reduces to

$$\dot{m}_{out}\, s_{out} - \dot{m}_{in}\, s_{in} = \Delta\dot{S}_{prod}$$

$$\Delta\dot{S}_{prod} = (22.08 \text{ kg/s})(1.6698 \text{ kJ/kg-K}) - (20 \text{ kg/s})\left(1.0751 \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$- \left(2.08 \frac{\text{kJ}}{\text{s}}\right)\left(6.9919 \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$\Delta\dot{S}_{prod} = 0.824 \frac{\text{kW}}{\text{K}}$$

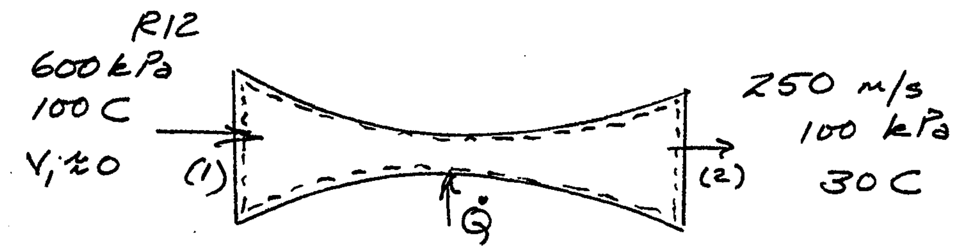
Problem 8.41

A non-adiabatic nozzle accelerates R12 from negligible inlet velocity to an exit velocity of 250 m/s. The inlet pressure is 600 kPa and inlet temperature is 100°C. The exit pressure is 100 kPa. The exit temperature of the refrigerant is 50°C. What heat must be added to the nozzle during the expansion process?

Given: A non adiabatic nozzle accelerates R12 to a final velocity while receiving heat.

Find: The heat added per unit mass.

Sketch and Given Data:



Assumptions:
1) The nozzle is an open, steady system.
2) R12 is a pure substance.
3) Change of potential energies are zero.
4) The work is zero.

Analysis: Determine the R12 property values from the tables.

$h_1 = 251.2$ kJ/kg $\qquad h_2 = 222.6$ kJ/kg

The first law analysis yields

$$\dot{Q} + \dot{m}\,(h + ke + pe)_1 = \dot{W} = \dot{m}\,(h + ke + pe)_2$$

Apply assumptions 3 and 4.

$$\dot{Q} = \dot{m}[(h_2 - h_1) + ke_2]$$

$$q = (h_2 - h_1) + ke_2$$

$$q = (222.6 - 251.2 \text{ kJ/kg}) + \frac{(250 \text{ m/s})^2}{(2)(1000 \text{ J/kJ})}$$

$$q = \underline{2.65} \text{ kJ/kg}$$

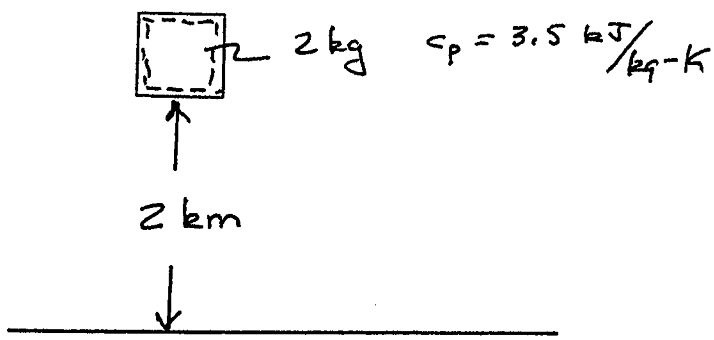
Problem 8.45

A two kilogram adiabatic container has an average specific heat of 3.5 kJ/kg-K and an initial temperature of 300°K and is dropped 2 km from a balloon. Determine the change of entropy of the container.

Given: An adiabatic container is dropped from an elevation and hits the ground.

Find: The entropy change of the container.

Sketch and Given Data:



Assumptions:
1) The container is a closed system.
2) The change of kinetic energy is zero.
3) The heat and work are zero.

Analysis: From a first law analysis find T_2.

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$0 = \Delta U + \Delta PE$$

$$0 = m\ c\ (T_2 - T_1) + m\ g\ (z_2 - z_1)$$

$$0 = (3.5\ \text{kJ/kg-K})(T_2 - 300\ \text{K}) + \frac{(9.8\ \text{m/s}^2)(0 - 2000\ \text{m})}{(1000\ \text{J/kJ})}$$

$$T_2 = 305.6\ \text{K}$$

$$\Delta S = m\ c\ \ln\left(\frac{T_2}{T_1}\right) = (2\ \text{kg})\left(3.5\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{305.6}{300}\right)$$

$$\Delta S = \underline{0.129\ \text{kJ/K}}$$

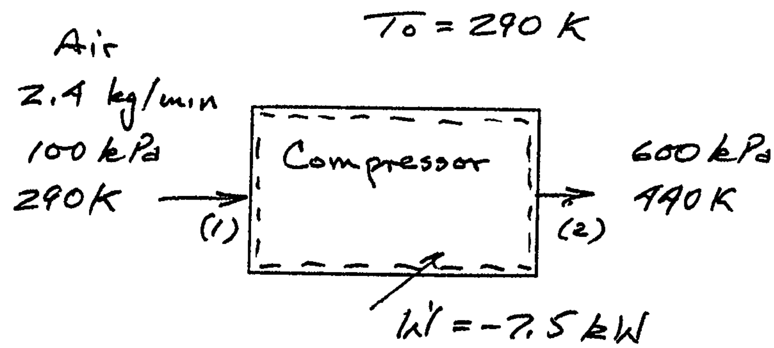
Problem 8.49

A 7.5 kW compressor handles 2.4 kg/min of air from 100 kPa and 290 K to 600 kPa and 440 K. The surroundings temperature is 290 K. Determine: a) the entropy change of the air in the compressor; b) the entropy change of the surroundings; c) the entropy production.

Given: An air compressor steadily compresses air between two states. The surroundings temperature is known.

Find: The entropy change of air passing through the compressor, the surroundings entropy change and the entropy production.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The compressor is a steady-state, open system.

Analysis: The compression process may not be assumed reversible as the actual power used is known. The first law for an open system may be used to find the heat transfer.

$$\dot{Q} + \dot{m}\,(h + ke + pe)_1 = \dot{W} = \dot{m}\,(h + ke + pe)_2$$

Apply assumption 2

$$\dot{Q} + \dot{m}\,h_1 = \dot{W} + \dot{m}\,h_2$$

$$\dot{Q} = \dot{W} + \dot{m}(h_2 - h_1) = \dot{W} + \dot{m}\,c_p(T_2 - T_1)$$

$$\dot{Q} = -(7.5\text{ kW}) + \left(\frac{2.4}{60}\,\frac{\text{kg}}{\text{s}}\right)\left(1.0047\,\frac{\text{kJ}}{\text{kg-K}}\right)(440 - 290\text{ K})$$

$$\dot{Q} = -1.47 \text{ kW (heat out)}$$

The entropy change of the air is

$$\Delta\dot{S}_{air} = \dot{m}(s_2 - s_1) = \dot{m}\ c_p \ln\left(\frac{T_2}{T_1}\right) - \dot{m}\ R \ln\left(\frac{p_2}{p_1}\right)$$

$$\Delta\dot{S}_{air} = (0.04 \text{ kg/s})\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{440}{290}\right)$$

$$- (0.04 \text{ kg/s})(0.287 \text{ kJ/kg-K}) \ln\left(\frac{600}{100}\right)$$

(a) $\Delta\dot{S}_{air} = \underline{-0.0038}$ kW/K

The entropy change of surroundings is

(b) $\Delta\dot{S}_{surr} = \dfrac{\dot{Q}}{T} = \dfrac{+1.47 \text{ kW}}{290 \text{ K}} = \underline{0.0051}\ \dfrac{\text{kW}}{\text{K}}$

(c) $\Delta\dot{S}_{prod} = \sum \Delta\dot{S}_i = +0.0051 - 0.0038 = \underline{0.0013}\ \dfrac{\text{kW}}{\text{K}}$

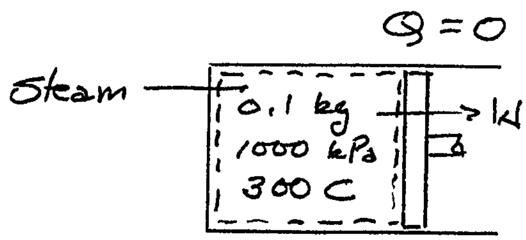
Problem 8.53

A piston/cylinder contains 0.1 kg of steam at 1000 kPa and 300°C and expands adiabatically to 100 kPa. What is the maximum work that the steam can produce in the expansion process?

Given: A piston/cylinder contains steam and expands adiabatically between two states.

Find: The maximum work.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and forms a closed system.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.

Analysis: The maximum work occurs where the process is reversible adiabatic, or isentropic. The first law is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3

$$-W = \Delta U = m(u_2 - u_1)$$

$u_1 = 2793.5$ kJ/kg $\qquad s_1 = 7.1228$ kJ/kg-K

$$s_2 = s_1 = 7.1228 \frac{kJ}{kg\text{-}K} \quad u_2 = 2424.9 \frac{kJ}{kg} \quad x_2 = 0.961$$

$$-W = (0.1\ kg)(2424.9 - 2793.5\ kJ/kg)$$

$$W = \underline{+36.9\ kJ}$$

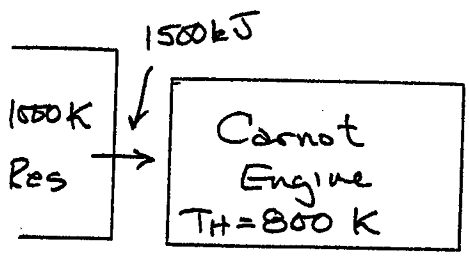
Problem 8.57

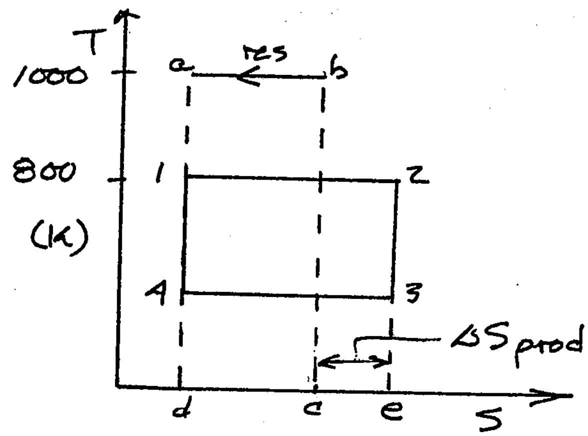
During the heat addition process of a Carnot Engine, the cycle temperature is 800°K and the reservoir supplying the heat is constant at 1000°K. 1500 kJ of heat are transferred. Determine the entropy change of the system, the reservoir and the entropy production.

Given: A constant temperature reservoir provides heat to a Carnot engine.

Find: The entropy change of the reservoir and engine and the entropy production.

Sketch and Given Data:





Assumptions: 1) The heat transfer occurs at constant temperature.

Analysis: For T = C heat transfer $\Delta S = Q/T$.

$$\Delta S_{res} = \frac{-1500 \text{ kJ}}{1000 \text{ K}} = \underline{-1.5} \text{ kJ/K}$$

$$\Delta S_{carnot} = \frac{+1500 \text{ kJ}}{800 \text{ K}} = \underline{+1.875} \text{ kJ/K}$$

$$\Delta S_{prod} = \sum \Delta S_i = 1.875 - 1.5 = \underline{+0.375} \frac{\text{kJ}}{\text{K}}$$

Note areas abcd and 12ed must be equal (first law). They can be only if there is a net entropy increase.

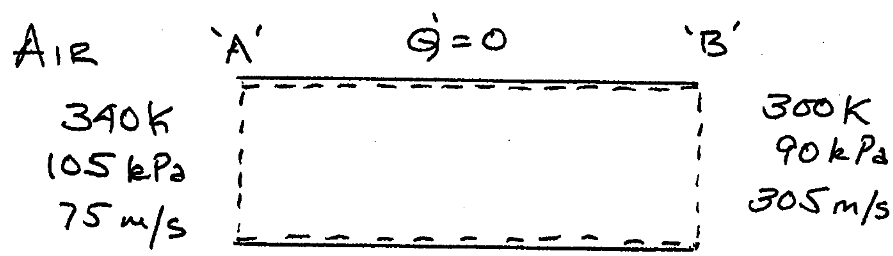
Problem 8.61

Air is flowing through an adiabatic, horizontal duct. Measurements at the "A" end indicate a temperature of 340°K, a pressure of 105 kPa and a velocity of 75 m/s. At the "B" end of duct the temperature is 300°K, the pressure is 90 kPa and the velocity is 305 m/s. What is the flow direction, A to B or B to A?

Given: Air is flowing through a duct from A to B with various properties given at each location.

Find: The flow direction.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The change in potential energy is zero.
3) The heat is zero.

Analysis: The flow could be expansive or compressive. Find the entropy change A to B. It must be greater than or equal to zero in the direction of flow for adiabatic flow from the second law.

$$s_B - s_A = c_p \ln\left(\frac{T_B}{T_A}\right) - R \ln\left(\frac{p_B}{p_A}\right)$$

$$s_B - s_A = \left(1.0047 \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{300}{340}\right) - \left(0.287 \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{90}{105}\right)$$

$$s_B - s_A = -0.082 \text{ kJ/kg-K}$$

The flow is not from A to B, rather it is compressive from <u>B to A.</u>

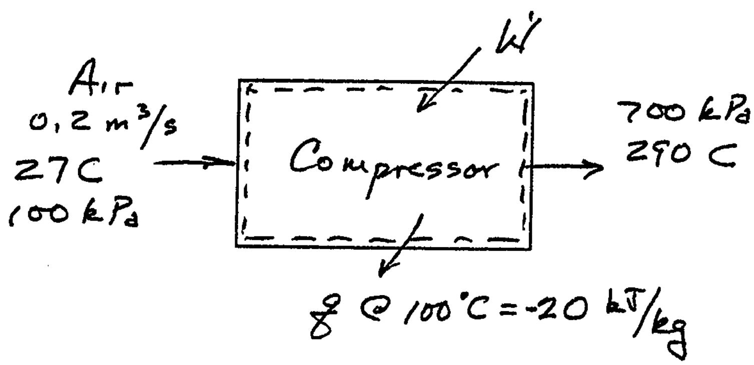
Problem 8.65

A compressor receives 0.2 m³/s of air at 27°C and 100 kPa and compresses it 700 kPa and 290°C. Heat loss per unit mass from the compressor surface at 100°C is 20 kJ/kg. Determine the power required, neglecting changes in potential and kinetic energies. Determine the entropy production for the compressor.

Given: Air is steadily compressed between two states. Heat transfer occurs from the compressor.

Find: The power required and the entropy production.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The compressor is a steady, open system.
3) Neglect changes in kinetic and potential energies.

Analysis: Perform a first law analysis to find the power. One cannot assume the process is reversible and evaluate the work from $-\int v dp$. The first law is.

$$\dot{Q} + \dot{m}\,(h + ke + pe)_1 = \dot{W} = \dot{m}\,(h + ke + pe)_2$$

Apply assumption 3.

$$\dot{Q} + \dot{m}\,h_1 = \dot{W} + \dot{m}\,h_2$$

$$\dot{m} = \frac{p_1\dot{V}}{RT_1} = \frac{(100\ \text{kN/m}^2)(0.2\ \text{m}^3/\text{s})}{(0.287\ \text{kJ/kg-K})(300\ \text{K})} = 0.232\ \text{kg/s}$$

$$\dot{W} = \dot{m}(h_1 - h_2) + \dot{Q} = \dot{m}\ c_p(T_1 - T_2) + \dot{m}q$$

$$\dot{W} = (0.232 \text{ kg/s})\left(1.0047 \ \frac{\text{kJ}}{\text{kg-K}}\right)(300 - 563)$$

$$+ (.232 \text{ kg/s})(-20 \text{ kJ/kg})$$

$$\dot{W} = \underline{-65.9 \text{ kW}}$$

From the second law for steady open systems, Equation 8.42

$$\dot{m}(s_2 - s_1) = \frac{\dot{Q}}{T} + \Delta\dot{S}_{prod}$$

$$\dot{m}(s_2 - s_2) = \dot{m}\ c_p \ \ln\left(\frac{T_2}{T_1}\right) - \dot{m}\ R\ \ln\left(\frac{p_2}{p_1}\right)$$

$$\dot{m}(s_2 - s_1) = \left(.232\ \frac{\text{kg}}{\text{s}}\right)\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{563}{300}\right)$$

$$- \left(0.232\ \frac{\text{kg}}{\text{s}}\right)\left(0.287\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{700}{100}\right)$$

$$\dot{m}(s_2 - s_1) = 0.0172 \text{ kW/K}$$

$$\frac{\dot{Q}}{T} = \frac{(0.232 \text{ kg/s})(-20 \text{ kJ/kg})}{(373 \text{ K})} = -0.0124\ \frac{\text{kW}}{\text{K}}$$

$$\Delta\dot{S}_{prod} = 0.0172 + 0.0124 = \underline{0.0296}\ \frac{\text{kW}}{\text{K}}$$

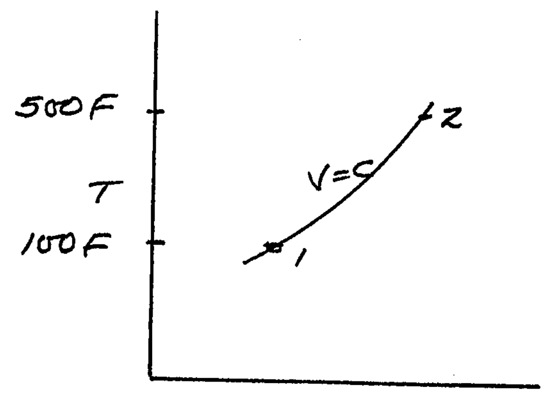
Problem *8.1

Oxygen is heated at constant volume from 50 psia and 100°F to 500°F. Determine the change of entropy per unit mass.

Given: A unit mass of oxygen is heated at constant volume.

Find: The change of entropy.

Sketch and Given Data:



Assumptions: 1) Oxygen is an ideal gas with constant specific heats and forms a closed system.

Analysis: The change of specific entropy for an ideal gas is

$$(s_2 - s_1) = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{V_2}{V_1}\right)^{0}$$

$$\Delta s = \left(0.1573 \frac{\text{Btu}}{\text{lbm-R}}\right) \ln\left(\frac{960}{560}\right) = 0.0848 \frac{\text{Btu}}{\text{lbm-R}}$$

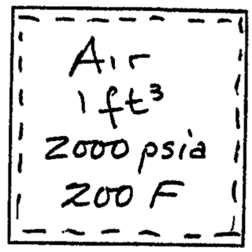
Problem *8.5

Air is contained in a 1 ft^3 tank at 2000 psia and 200°F. It is cooled by the surroundings until it reaches the surrounding temperature of 70°F. Considering the tank and the surroundings as an isolated system, what is the net entropy change?

Given: Air is cooled at constant volume. The surroundings temperature is known.

Find: The entropy production.

Sketch and Given Data:



$T_2 = 70°F$

$T_o = 70°F$

Assumptions:
1) Air is an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The work is zero.
4) The air forms a closed system.

Analysis: Find the mass of air in the tank and then its entropy change. The heat transferred is needed to find the surroundings entropy change.

$$m = \frac{p_1 V_1}{R T_1} = \frac{(2000\ lb_f/in^2)(144\ in^2/ft^2)(1\ ft^3)}{\left(53.34\ \frac{ft-lb_f}{lbm-R}\right)(660\ R)} = 8.18\ lbm$$

$$\Delta S_{air} = m\, c_v \ln\left(\frac{T_2}{T_1}\right) + m\, R \ln\left(\frac{V_2}{V_1}\right)^{\nearrow 0}$$

$$\Delta S_{air} = (8.18\ lbm)\left(0.1714\ \frac{Btu}{lbm-R}\right) \ln\left(\frac{530}{660}\right) = -0.308\ \frac{Btu}{R}$$

The heat transfer is found from the first law

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = \Delta U = m\ c_v\ (T_2 - T_1)$$

$$= (8.18\ \text{lbm})\left(0.1714\ \frac{\text{Btu}}{\text{lbm-R}}\right)(530 - 660\ \text{R})$$

$$Q = -182.3\ \text{Btu}$$

The amount of heat flows into the surroundings or

$$Q_{surr} = +182.3\ \text{Btu}$$

$$\Delta S_{surr} = \frac{Q}{T} = \frac{(182.3\ \text{Btu})}{(530\ \text{R})} = +0.344\ \frac{\text{Btu}}{\text{R}}$$

$$\Delta S_{prod} = 0.344 - 0.308 = \underline{+0.036}\ \frac{\text{Btu}}{\text{R}}$$

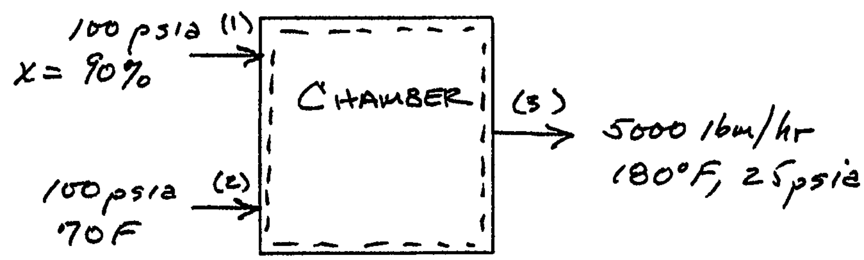
Problem *8.9

A chemical process requires 5000 lbm/hr of hot water at 180°F and 25 psia. Steam is available at 100 psia and 90% quality, and water is available at 100 psia and 70°F. The steam and water are mixed in an adiabatic chamber, with the hot water exiting. Determine the net entropy change.

Given: The adiabatic mixing of steam and water produces hot water at desired conditions. The steam and water states are known.

Find: The entropy production.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance.
2) The mixing chamber is a steady open system.
3) The heat and work are zero.
4) Neglect changes in kinetic and potential energies.

Analysis: Determine the enthalpy and entropy at states 1, 2, 3, steam at states 2 and 3 is a subcooled liquid.

$h_2 = h_f$ @ 70°F = 37.7 Btu/lbm $\qquad s_2 = s_f$ @ 70°F $= 0.0735 \dfrac{\text{Btu}}{\text{lbm-R}}$

$h_3 = h_f$ @ 180°F = 148.4 Btu/lbm $\qquad s_3 = s_f$ @ 180°F $= 0.2631 \dfrac{\text{Btu}}{\text{lbm-R}}$

$h_1 = 1098.9$ Btu/lbm $\qquad s_1 = 1.4904 \dfrac{\text{Btu}}{\text{lbm-R}}$

Perform a first law analysis to find the mass flowrates into the mixing chamber.

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2$$

$$= \dot{W} + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 3 and 4.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \qquad \text{and} \qquad \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

$$\left(5000 - \dot{m}_2 \frac{\text{lbm}}{\text{hr}}\right)\left(1098.9 \frac{\text{Btu}}{\text{lbm}}\right) + \left(\dot{m}_2 \frac{\text{lbm}}{\text{hr}}\right)\left(37.7 \frac{\text{Btu}}{\text{lbm}}\right)$$

$$= \left(5000 \frac{\text{lbm}}{\text{hr}}\right)\left(148.4 \frac{\text{Btu}}{\text{lbm}}\right)$$

$$\dot{m}_2 = 4478.4 \frac{\text{lbm}}{\text{hr}} \qquad \dot{m}_1 = 521.6 \frac{\text{lbm}}{\text{hr}}$$

The second law for open steady systems is

$$\dot{m}_{out} s_{out} - \dot{m}_{in} s_{in} = \Delta \dot{S}_{prod}$$

$$\Delta \dot{S}_{prod} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2$$

$$\Delta \dot{S}_{prod} = \left(5000 \frac{\text{lbm}}{\text{hr}}\right)\left(0.2631 \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$- \left(521.6 \frac{\text{lbm}}{\text{hr}}\right)\left(1.4904 \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$- \left(4478.4 \frac{\text{lbm}}{\text{hr}}\right)\left(0.0735 \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$\Delta \dot{S}_{prod} = \underline{+208.9} \frac{\text{Btu}}{\text{hr-R}}$$

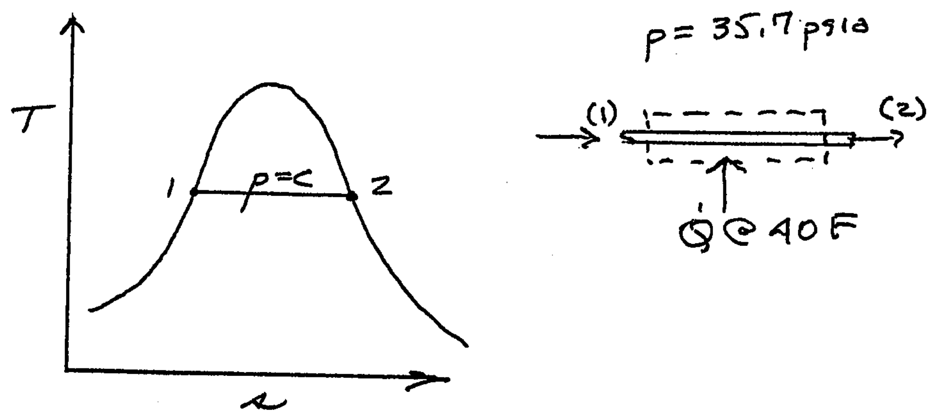
Problem 8.13*

In a home refrigerator, 5 lbm/min of R12 enter the evaporator coil as a saturated liquid at 35.7 psia and leave as a saturated vapor at the same pressure. The refrigerated space is maintained at a constant temperature of 40°F. Determine the rate of entropy change of the refrigerant and of the refrigerated space.

Given: R12 flows steadily through an evaporator at constant pressure, receiving heat from a space at 40°F.

Find: The rate of R12 entropy change and the rate of the entropy change in the refrigerated space.

Sketch and Given Data:



Assumptions:
1) R12 is a pure substance.
2) The evaporator is a steady, open system.
3) Neglect changes in kinetic and potential energies.
4) The work is zero.

Analysis: The entropy change of the refrigerant is

$$\Delta\dot{S}_{R12} = \dot{m}(s_2 - s_1) = (5 \text{ lbm/min})\left(0.17102 - 0.00983 \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$\Delta\dot{S}_{R12} = \underline{0.806} \frac{\text{Btu}}{\text{min-R}}$$

The heat flow into the refrigerant is found from the first law

$$\dot{Q} + \dot{m}\,(h + ke + pe)_1 = \dot{W} = \dot{m}\,(h + ke + pe)_2$$

Apply assumptions 3 and 4.

$$\dot{Q} = \dot{m}(h_2 - h_1)$$

$$\dot{Q} = (5\ \text{lbm/min})(75.11 - 4.236\ \text{Btu/lbm}) = 354.4\ \frac{\text{Btu}}{\text{min}}$$

The entropy change of the refrigerated space occurs at constant temperature, hence

$$\Delta\dot{S}_{space} = \frac{Q}{T} = \frac{-354.4\ \frac{\text{Btu}}{\text{min}}}{500\ \text{R}} = \underline{-0.709}\ \frac{\text{Btu}}{\text{min-R}}$$

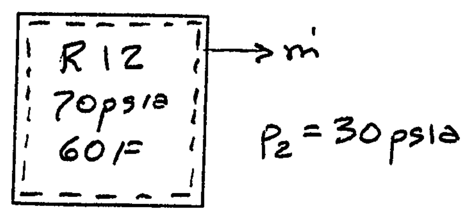
Problem 8.17*

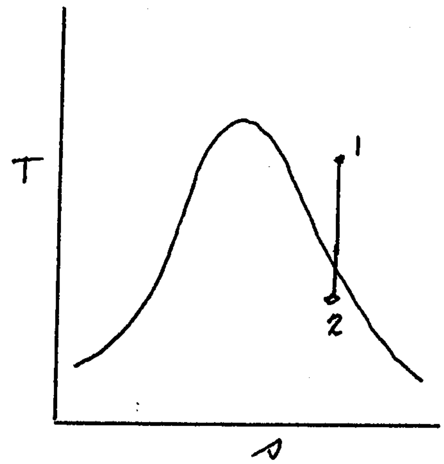
An insulated R12 container develops a leak. The refrigerant before the leak is at 70 psia and 60°F. Determine the per cent mass of refrigerant remaining when the pressure is 30 psia.

Given: A insulated, constant volume container, holds R12. A small leak develops.

Find: The percent R12 remaining when the pressure is 30 psia.

Sketch and Given Data:





Assumptions:
1) R12 is a pure substance.
2) The heat loss is zero.
3) Neglect changes in kinetic and potential energies.

Analysis: Refer to the discussion in Chapter 6 regarding to the discharge of a tank. The conditions in this problem match those in the development. The process is a reversible adiabatic process, or isentropic. Determine the initial states' entropy and specific volume and that of the final state, knowing $s_2 = s_1$.

$s_1 = 0.16556$ Btu/lbm-R $\quad v_1 = 0.58088$ ft³lbm

At 30 psia, $s = s_f + x\, s_{fg}$

$$0.16556 = 0.245 + (x_2)(0.1434)$$

$$x_2 = 0.9837$$

$$v_2 = 0.0112 + (0.9837)(1.2853) = 1.276 \text{ lbm}$$

Assume that the initial mass is 1 lbm. Hence

$$V_1 = m_1 v_1 = (1 \text{ lbm})(0.58088 \text{ ft}^3/\text{lbm}) = 0.58088 \text{ ft}^3$$

The volume remains constant, $V_2 = V_1$.

$$m_2 = \frac{V_2}{v_2} = \frac{(0.58088\ ft^3)}{(1.276\ ft^3/lbm)} = 0.455$$

The percent of mass remaining is

$$\left(\frac{m_2}{m_1}\right)(100) = \left(\frac{0.455}{1.00}\right)(100) = \underline{\underline{45.5\%}}$$

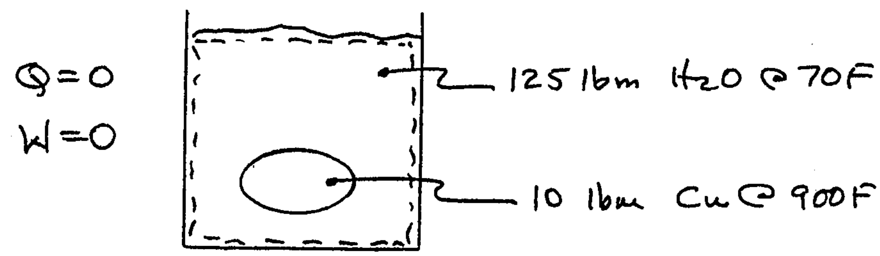
Problem 8.21*

A 10 lbm copper ingot, $c_p = 0.10$ Btu/lbm-F, is heated to 900°F and dropped into a 125 lbm adiabatic tank of water, initially at 70°F. Determine the entropy change for the water, the copper and the total entropy production.

Given: A copper ingot is quenched in an adiabatic tank of water.

Find: The entropy change of the copper, the water and the entropy production.

Sketch and Given Data:



Assumptions:
1) The copper and water in the tank form an isolated system.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energies.
4) Water is a pure substance.

Analysis: The equilibrium temperature of the copper and water is found from a first law analysis.

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$\Delta U = 0$$

$$U_{final} - U_{initial} = 0$$

$$m_w u_{w2} + m_c c_p T_2 - m_w u_{w1} - m_c c_p T_1 = 0$$

$$u_{w1} = u_f @ 70°F = 37.7 \text{ Btu/lbm}$$

$$s_{w1} = s_f @ 70°F = 0.0735 \text{ Btu/lbm-R}$$

- Combine the terms and solve for the equilibrium temperature.

$$(125 \text{ lbm})(u_2 - 37.7 \text{ Btu/lbm}) + (10 \text{ lbm})\left(0.10 \ \frac{\text{Btu}}{\text{lbm-R}}\right)(T_2 - 1360 \text{ R}) = 0$$

In this procedure, T_2 is guessed and u_2 looked up. The procedure iterates until it converges. A good first guess may be found by assuming the $c_v = c_p$ of water is 1.0 Btu/lbm-R. The first guess at T_2 is 76.6° F and the equation essentially balances.

$$u_2 = 44.3 \text{ Btu/lbm} \quad s_2 = s_f \text{ @ } 76.6°\text{F} = 0.0859 \text{ Btu/lbm-R}$$

$$\Delta S_w = m_w(s_2 - s_1) = (125 \text{ lbm})(0.0859 - 0.0735 \text{ Btu/lbm-R}) = 1.55 \text{ Btu/R}$$

$$\Delta S_{cu} = mc \ln\left(\frac{T_2}{T_1}\right) = (10 \text{ lbm})\left(0.10 \ \frac{\text{Btu}}{\text{lbm-R}}\right) \ln\left(\frac{536.6}{1360}\right) = -0.93 \text{ Btu/R}$$

$$\Delta S_{prod} = \sum_i \Delta S_i = 1.55 - 0.93 = \underline{0.62} \frac{\text{Btu}}{\text{R}}$$

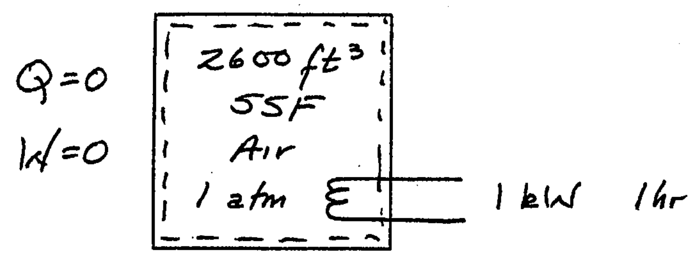
Problem 8.25*

A room with dimensions of 13 ft x 10 ft x 20 ft contains air at 55°F and 1 atmosphere pressure. A 1-kW electric heater is placed in the room and turned on for 1 hour. What is final air temperature assuming the room is adiabatic? What is the air's change of entropy?

Given: An adiabatic room contains air which is heated by an electric heater for a fixed time.

Find: The final air temperature and its' entropy change.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas and forms a closed system.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energies.
4) The process is constant volume.

Analysis: Determine the mass of air in the room from the ideal gas law.

$$m = \frac{p_1 V_1}{R T_1} = \frac{(14.7\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(2600\ \text{ft}^3)}{\left(53.34\ \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)(515\ \text{R})} = 200.3\ \text{lbm}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W + W_{electric}$$

Apply assumptions 3 and 4.

$$0 = \Delta U + W_{electric}$$

The electric work is

$$W_{electric} = -\left(1\ \frac{kJ}{s}\right)\left(3600\ \frac{s}{h}\right)(1\ h) = -3600\ kJ = 3412\ Btu$$

$$\Delta U = 3412\ Btu$$

$$m\ c_v(T_2 - T_1) = 3412\ Btu$$

$$(200.3\ lbm)(0.1714\ Btu/lbm\text{-}R)(T_2 - 515\ R) = 3412\ Btu$$

$$T_2 = 614.3\ R = 154.3°F$$

The entropy change is

$$\Delta S = m\ c_v\ \ln\left(\frac{T_2}{T_1}\right) + m\ R\ \ln\left(\frac{V_2}{V_1}\right) = m\ c_v\ \ln\left(\frac{T_2}{T_1}\right)$$

$$\Delta S = (200.3\ lbm)\left(0.1714\ \frac{Btu}{lbm\text{-}R}\right)\ \ln\left(\frac{614.3}{515}\right) = 6.05\ \frac{Btu}{R}$$

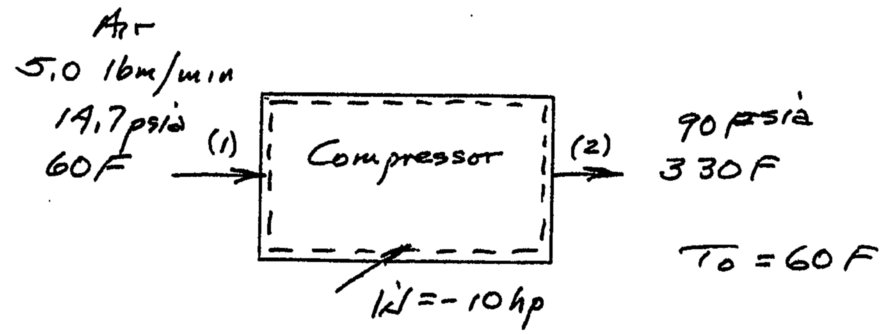
Problem 8.29*

A 10 hp compressor handles 5.0 lbm/min of air from 14.7 psia and 60°F to 90 psia and 330°F. The surroundings temperature is 60°F. Determine: a) the entropy change of the air in the compressor; b) the entropy change of the surroundings; c) the entropy production.

Given: An air compressor steadily compresses air between two states. The surroundings temperature is known.

Find: The entropy change of air passing through the compressor, the surroundings entropy change and the entropy production.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The compressor is a steady-state open, system.

Analysis: The compression process may <u>not</u> be assumed reversible as the actual power used is known. The first law for an open system may be used to find the heat transfer.

$$\dot{Q} + \dot{m}\,(h + ke + pe)_1 = \dot{W} = \dot{m}\,(h + ke + pe)_2$$

Apply assumption 2.

$$\dot{Q} + \dot{m}\,h_1 = \dot{W} + \dot{m}\,h_2$$

$$\dot{Q} = \dot{W} + \dot{m}(h_2 - h_1) = \dot{W} + \dot{m}c_p(T_2 - T_1)$$

$$\dot{Q} = (-10\text{ hp})(42.4\text{ Btu/hp-min})$$

$$+ 5\text{ lbm/min}\left(0.24\ \frac{\text{Btu}}{\text{lbm-R}}\right)(790 - 520\text{ R})$$

$$\dot{Q} = -100\text{ Btu/min (heat out)}$$

The entropy change of the air is

$$\Delta\dot{S}_{air} = \dot{m}(s_2 - s_1) = \dot{m}\ c_p \ln\left(\frac{T_2}{T_1}\right) - \dot{m}\ R \ln\left(\frac{p_2}{p_1}\right)$$

$$\Delta\dot{S}_{air} = (5\text{ lbm/min})(0.24\text{ Btu/lbm-R}) \ln\left(\frac{790}{520}\right)$$

$$- \frac{(5\text{ lbm/min})(53.34\text{ ft-lb}_f\text{/lbm-R})}{(778.16\text{ ft-lb}_f\text{/Btu})} \ln\left(\frac{90}{14.7}\right)$$

(a) $\Delta\dot{S}_{air} = -0.119\text{ Btu/min-R}$

The entropy change of surroundings is

(b) $\Delta\dot{S}_{surr} = \frac{\dot{Q}}{T} = \frac{+100\text{ Btu/min}}{520\text{ R}} = \underline{0.192}\text{ Btu/min-R}$

(c) $\Delta\dot{S}_{prod} = \sum \Delta\dot{S}_i = 0.192 - 0.119 = 0.073\ \frac{\text{Btu}}{\text{min-R}}$

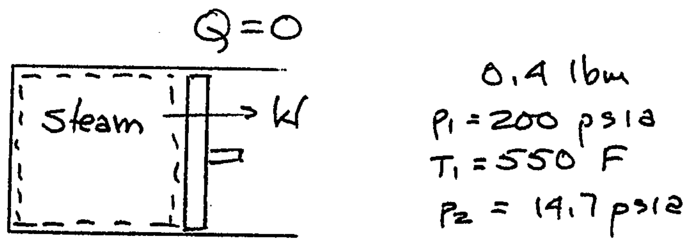
Problem 8.33*

A piston/cylinder contains 0.4 lbm of steam at 200 psia and 550°F and expands adiabatically to 14.7 psia. What is the maximum work that the steam can produce in the expansion process?

Given: A piston/cylinder contains steam and expands adiabatically between two states.

Find: The maximum work.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and forms a closed system.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.

Analysis: The maximum work occurs where the process is reversible adiabatic, or isentropic. The first law is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$-W = \Delta U = m(u_2 - u_1)$$

$u_1 = 1188.8$ Btu/lbm $\quad s_1 = 1.6513$ Btu/lbm

$s_2 = s_1 = 1.6513$ Btu/lbm $\quad u_2 = 1012.3$ Btu/lbm $\quad x_2 = 0.927$

$$W = -(0.4 \text{ lbm})(1012.3 - 1188.8 \text{ Btu/lbm}) = 70.6 \text{ Btu}$$

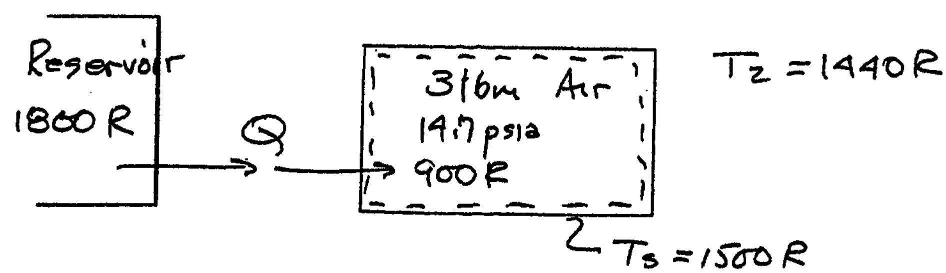
Problem 8.37*

A tank contains 3 lbm of air at 14.7 psia and 900 R. Heat is transferred until the air temperature is 1440 R from a constant temperature heat reservoir at 1800 R. The system's boundary was a constant temperature of 1500 R during the heat transfer process. Determine the system entropy production.

Given: A constant volume tank containing air receives heat from a constant temperature reservoir. The system boundary remains at 1500 R during the transfer process.

Find: The system entropy change.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas and forms a closed system.
2) The work is zero.
3) Neglect changes in kinetic and potential energies.

Analysis: The first law analysis allows us to calculate the heat required.

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = \Delta U \qquad \Delta U = m\, c_v(T_2 - T_1)$$

$$\Delta U = (3\ \text{lbm})(0.1714\ \text{Btu/lbm-R})(1440 - 900\ \text{R}) = 277.7\ \text{Btu}$$

$$Q = 277.7\ \text{Btu}$$

From Equation 8.28

$$S_2 - S_1 = \frac{Q_i}{T_i} + \Delta S_{prod}$$

$$S_2 - S_1 = m\ c_v\ \ln\left(\frac{T_2}{T_1}\right) + m\ R\ \ln\left(\frac{V_2}{V_1}\right)$$

$$S_2 - S_1 = (3\ \text{lbm})(0.1714\ \text{Btu/lbm-R})\ \ln\ (1440/900) = 0.242\ \frac{\text{Btu}}{\text{R}}$$

$$\frac{Q_i}{T_i} = \frac{277.7\ \text{Btu}}{1500\ \text{R}} = 0.185\ \text{Btu/R}$$

ΔS_{prod} = 0.242 - 0.185 = <u>0.057 Btu/R</u>

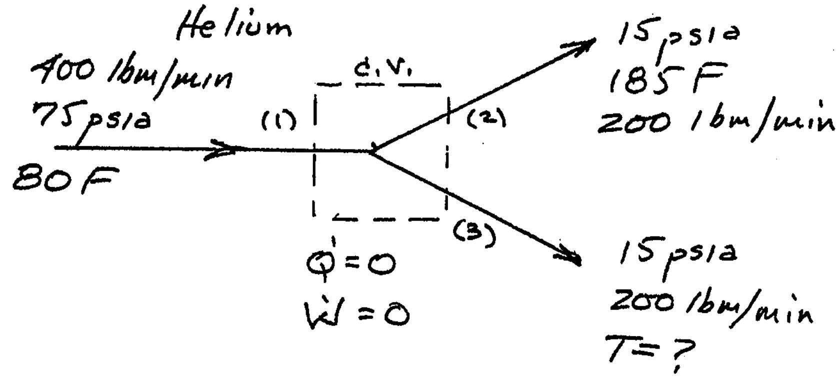
Problem 8.41*

400 lbm/min of helium at 74 psia and 80°F enter an insulated device where the work performed is zero. The fluid divides into two equal streams leaving the device, each at 15 psia, and one at 185°F and the other at a unknown temperature. Neglecting changes in kinetic and potential energies, what is the exit temperature of the second stream? Is it possible for the device to operate?

Given: Helium flows steadily into a device and splits into two different streams at different states.

Find: Whether the device is possible?

Sketch and Given Data:



Assumptions:
1) Helium is an ideal gas.
2) The device is a steady open system.
3) Neglect changes in kinetic and potential energies.
4) The heat and work are zero.

Analysis: Perform a first law analysis to find T_3. Then perform a second law analysis. For the device to be possible, there should be positive entropy production. The first law is

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 = \dot{W} + \dot{m}_2(h + ke + pe)_2 + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 3 and 4

$$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3$$

$$\dot{m}\ c_p\ T_1 = \dot{m}_2\ c_p\ T_2 + \dot{m}_3\ c_p\ T_3$$

$$(400\ \text{lbm/min})(540\ \text{R}) = (200\ \text{lbm/min})(645\ \text{R}) + (200\ \text{lbm/min})(T_3\ \text{R})$$

$$T_3 = 435\ \text{R} = -25\ \text{F}$$

From Equation 8.41 applied to steady adiabatic flow

$$\Delta\dot{S}_{prod} = \dot{m}_{out}s_{out} - \dot{m}_{in}s_{in}$$

Find the entropy change 1-2 and 1-3 and add together.

$$\dot{m}_2(s_2 - s_1) = \dot{m}_2\ c_p\ \ln\left(\frac{T_2}{T_1}\right) - \dot{m}_2\ R\ \ln\left(\frac{p_2}{p_1}\right)$$

$$\dot{m}_2(s_2 - s_1) = (200\ \text{lbm/min})(1.241\ \text{Btu/lbm-R})\ \ln\left(\frac{645}{540}\right)$$

$$- \frac{\left(200\ \dfrac{\text{lbm}}{\text{min}}\right)\left(386\ \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{778.16\ \dfrac{\text{ft-lb}_f}{\text{Btu}}}\ \ln\left(\frac{15}{75}\right)$$

$$\dot{m}_2(s_2 - s_1) = +203.8\ \frac{\text{Btu}}{\text{min-R}}$$

$$\dot{m}_3(s_3 - s_1) = \dot{m}_3\ c_p\ \ln\left(\frac{T_3}{T_1}\right) - \dot{m}_2\ R\ \ln\left(\frac{p_3}{p_1}\right)$$

$$\dot{m}_3(s_3 - s_1) = (200)(1.241)\ \ln\left(\frac{435}{540}\right) - \frac{(200)(386)}{778.16}\ \ln\left(\frac{15}{75}\right)$$

$$\dot{m}_3(s_3 - s_1) = 106.0\ \frac{\text{Btu}}{\text{min-R}}$$

$$\Delta\dot{S}_{prod} = 203.8 + 106.0 = 309.8\ \frac{\text{Btu}}{\text{min-R}}$$

The device is possible according to second law analysis. A device that performs this function is called a vortex tube.

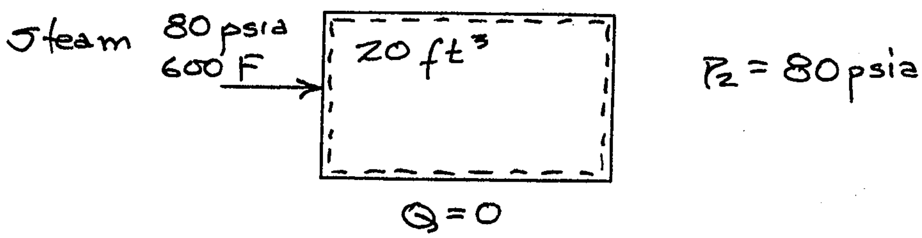
Problem 8.45*

A 20 ft^3 tank is initially evacuated. A valve connecting it to a very large supply of steam at 80 psia and 600°F is opened and steam flows into the tank until the pressure is 80 psia. If the process is adiabatic, determine the final steam temperature in the tank and the entropy produced in the tank.

Given: An initially evacuated adiabatic tank is filled with steam.

Find: The final steam temperature in the tank and the entropy production.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energies.

Analysis: Refer to Chapter Six on charging a tank. For the conditions in this problem.

$u_2 = h_{line} = h_1$
$h_1 = 1330.6$ Btu/lbm
$s_1 = 1.7835$ Btu/lbm-R

At 80 psia and $u_2 = 1330.6$ Btu/lbm, find from the steam tables that

$$s_2 = 1.9068 \frac{\text{Btu}}{\text{lbm-R}} \text{ and } v_2 = 10.06 \text{ ft}^3/\text{lbm} \qquad T_2 = 897.4°\text{F}$$

The mass of steam in the tank is

$$m = \frac{V_2}{v_2} = \frac{20 \text{ ft}^3}{10.06 \text{ ft}^3/\text{lbm}} = 1.99 \text{ lbm}$$

From the second law (Equation 8.28)

$$m(s_2 - s_1) = \Delta S_{prod} \quad \text{for} \quad Q = 0$$

$$\Delta S_{prod} = (199 \text{ lbm})(1.9068 - 1.7835 \text{ Btu/lbm-R})$$

$$\Delta S_{prod} = \underline{0.245} \frac{\text{Btu}}{\text{R}}$$

Problem C8.1

Using the ideal-gas relationships, develop a TK Solver or spreadsheet model to calculate the values of entropy function, relative pressure, and relative specific volume for air. Assume constant specific heat and that at 273°K the relative pressure is 1.0 and the entropy function is 2.42. Produce a table for temperatures between 300°K and 1500°K in increments of 50°K and compare your results with values in Table A.2. Explain any differences.

Given: Air between 300°K and 1500°K.

Find: Entropy function, relative pressure, and relative specific volume using ideal-gas relationships.

Assumptions: 1) The air is in equilibrium.

Analysis: Using a spreadsheet program, enter equations based on the following.

$$h = c_p\, dT \qquad \Phi_2 - \Phi_1 = c_p \ln\left(\frac{T_2}{T_1}\right)$$

$$u = c_v\, dT \qquad \ln(p_r) = \frac{\Phi}{R}$$

$$v_r = \frac{RT}{p_r}$$

	A/	B/	C/	D/	E/	F/
1	Problem 8.1	Reference		Point		
2						
3			T=	273	R=	0.287
4			pr=	1	Cp=	1.0047
5			ø=	2.42	Cv=	0.7176
6	T	h	pr	u	vr	ø
7						
8	273	+A8*$F$3	+D3	+A8*$F$4	+$F$2*A8/C8	+D4
9	300	+A9*$F$3	+$D$3*(@EXP((F9-$D$4)/$F$2))	+A9*$F$4	+$F$2*A9/C9	+$F$3*@LN(A9/$D$2)+$D$4
10	350	+A10*$F$3	+$D$3*(@EXP((F10-$D$4)/$F$2))	+A10*$F$4	+$F$2*A10/C10	+$F$3*@LN(A10/$D$2)+$D$4
11	400	+A11*$F$3	+$D$3*(@EXP((F11-$D$4)/$F$2))	+A11*$F$4	+$F$2*A11/C11	+$F$3*@LN(A11/$D$2)+$D$4
12	450	+A12*$F$3	+$D$3*(@EXP((F12-$D$4)/$F$2))	+A12*$F$4	+$F$2*A12/C12	+$F$3*@LN(A12/$D$2)+$D$4
13	500	+A13*$F$3	+$D$3*(@EXP((F13-$D$4)/$F$2))	+A13*$F$4	+$F$2*A13/C13	+$F$3*@LN(A13/$D$2)+$D$4
14	550	+A14*$F$3	+$D$3*(@EXP((F14-$D$4)/$F$2))	+A14*$F$4	+$F$2*A14/C14	+$F$3*@LN(A14/$D$2)+$D$4
15	600	+A15*$F$3	+$D$3*(@EXP((F15-$D$4)/$F$2))	+A15*$F$4	+$F$2*A15/C15	+$F$3*@LN(A15/$D$2)+$D$4
16	650	+A16*$F$3	+$D$3*(@EXP((F16-$D$4)/$F$2))	+A16*$F$4	+$F$2*A16/C16	+$F$3*@LN(A16/$D$2)+$D$4
17	700	+A17*$F$3	+$D$3*(@EXP((F17-$D$4)/$F$2))	+A17*$F$4	+$F$2*A17/C17	+$F$3*@LN(A17/$D$2)+$D$4
18	750	+A18*$F$3	+$D$3*(@EXP((F18-$D$4)/$F$2))	+A18*$F$4	+$F$2*A18/C18	+$F$3*@LN(A18/$D$2)+$D$4
19	800	+A19*$F$3	+$D$3*(@EXP((F19-$D$4)/$F$2))	+A19*$F$4	+$F$2*A19/C19	+$F$3*@LN(A19/$D$2)+$D$4
20	850	+A20*$F$3	+$D$3*(@EXP((F20-$D$4)/$F$2))	+A20*$F$4	+$F$2*A20/C20	+$F$3*@LN(A20/$D$2)+$D$4
21	900	+A21*$F$3	+$D$3*(@EXP((F21-$D$4)/$F$2))	+A21*$F$4	+$F$2*A21/C21	+$F$3*@LN(A21/$D$2)+$D$4
22	950	+A22*$F$3	+$D$3*(@EXP((F22-$D$4)/$F$2))	+A22*$F$4	+$F$2*A22/C22	+$F$3*@LN(A22/$D$2)+$D$4
23	1000	+A23*$F$3	+$D$3*(@EXP((F23-$D$4)/$F$2))	+A23*$F$4	+$F$2*A23/C23	+$F$3*@LN(A23/$D$2)+$D$4
24	1050	+A24*$F$3	+$D$3*(@EXP((F24-$D$4)/$F$2))	+A24*$F$4	+$F$2*A24/C24	+$F$3*@LN(A24/$D$2)+$D$4
25	1100	+A25*$F$3	+$D$3*(@EXP((F25-$D$4)/$F$2))	+A25*$F$4	+$F$2*A25/C25	+$F$3*@LN(A25/$D$2)+$D$4
26	1150	+A26*$F$3	+$D$3*(@EXP((F26-$D$4)/$F$2))	+A26*$F$4	+$F$2*A26/C26	+$F$3*@LN(A26/$D$2)+$D$4
27	1200	+A27*$F$3	+$D$3*(@EXP((F27-$D$4)/$F$2))	+A27*$F$4	+$F$2*A27/C27	+$F$3*@LN(A27/$D$2)+$D$4
28	1250	+A28*$F$3	+$D$3*(@EXP((F28-$D$4)/$F$2))	+A28*$F$4	+$F$2*A28/C28	+$F$3*@LN(A28/$D$2)+$D$4
29	1300	+A29*$F$3	+$D$3*(@EXP((F29-$D$4)/$F$2))	+A29*$F$4	+$F$2*A29/C29	+$F$3*@LN(A29/$D$2)+$D$4
30	1350	+A30*$F$3	+$D$3*(@EXP((F30-$D$4)/$F$2))	+A30*$F$4	+$F$2*A30/C30	+$F$3*@LN(A30/$D$2)+$D$4
31	1400	+A31*$F$3	+$D$3*(@EXP((F31-$D$4)/$F$2))	+A31*$F$4	+$F$2*A31/C31	+$F$3*@LN(A31/$D$2)+$D$4
32	1450	+A32*$F$3	+$D$3*(@EXP((F32-$D$4)/$F$2))	+A32*$F$4	+$F$2*A32/C32	+$F$3*@LN(A32/$D$2)+$D$4
33	1500	+A33*$F$3	+$D$3*(@EXP((F33-$D$4)/$F$2))	+A33*$F$4	+$F$2*A33/C33	+$F$3*@LN(A33/$D$2)+$D$4

This will produce the following output.

Problem 8.1	Reference Point			
	T=	273	R=	0.287
	pr=	1	Cp=	1.0047
	ø=	2.42	Cv=	0.7176

T	h	pr	u	vr	ø
273	274.2831	1	195.9048	78.351	2.42
300	301.41	1.391181	215.28	61.88985	2.514753
350	351.645	2.386404	251.16	42.09260	2.669629
400	401.88	3.808520	287.04	30.14293	2.803788
450	452.115	5.752091	322.92	22.45270	2.922124
500	502.35	8.317808	358.8	17.25214	3.027980
550	552.585	11.61213	394.68	13.59353	3.123738
600	602.82	15.74702	430.56	10.93540	3.211158
650	653.055	20.83963	466.44	8.951693	3.291577
700	703.29	27.01213	502.32	7.437399	3.366034
750	753.525	34.39149	538.2	6.258815	3.435351
800	803.76	43.10931	574.08	5.325995	3.500193
850	853.995	53.30165	609.96	4.576780	3.561102
900	904.23	65.10892	645.84	3.967197	3.618529
950	954.465	78.67572	681.72	3.465490	3.672851
1000	1004.7	94.15072	717.6	3.048303	3.724385
1050	1054.935	111.6865	753.48	2.698175	3.773404
1100	1105.17	131.4398	789.36	2.401859	3.820143
1150	1155.405	153.5707	825.24	2.149172	3.864804
1200	1205.64	178.2432	861.12	1.932190	3.907563
1250	1255.875	205.6251	897	1.744679	3.948577
1300	1306.11	235.8874	932.88	1.581686	3.987982
1350	1356.345	269.2047	968.76	1.439239	4.025900
1400	1406.58	305.7550	1004.64	1.314123	4.062439
1450	1456.815	345.7196	1040.52	1.203720	4.097695
1500	1507.05	389.2832	1076.4	1.105878	4.131756

Comment: A comparison with Table A.2 shows some significant differences. They can largely be explained by the use of constant values for specific heat since h, u, Φ, p_r and v_r are all affected by it.

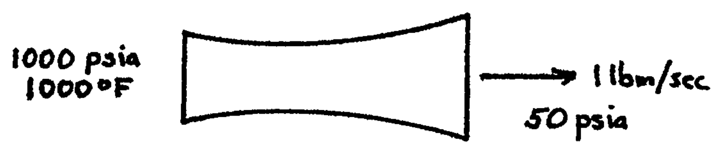
Problem C8.5

One lbm/sec of steam expands isentropically in a nozzle form 1000 psia and 1000°F to 50 psia. Modify STEAM.TK to compute the nozzle area as a function of pressure.

Given: Steam expanding isentropically in a nozzle.

Find: Nozzle area as function of pressure.

Sketch and Given Data:



Assumptions:
1) Steam is in equilibrium.
2) Change in potential energy is negligible.

Analysis: Load STEAM.TK into TK Solver. Enter the following equations into the Rule Sheet.

```
==================== RULE SHEET ====================
S Rule-------------------------------------------------
  mdot=A*V/v
  V=(2*1000*(ho-h))^.5
  s=so
```

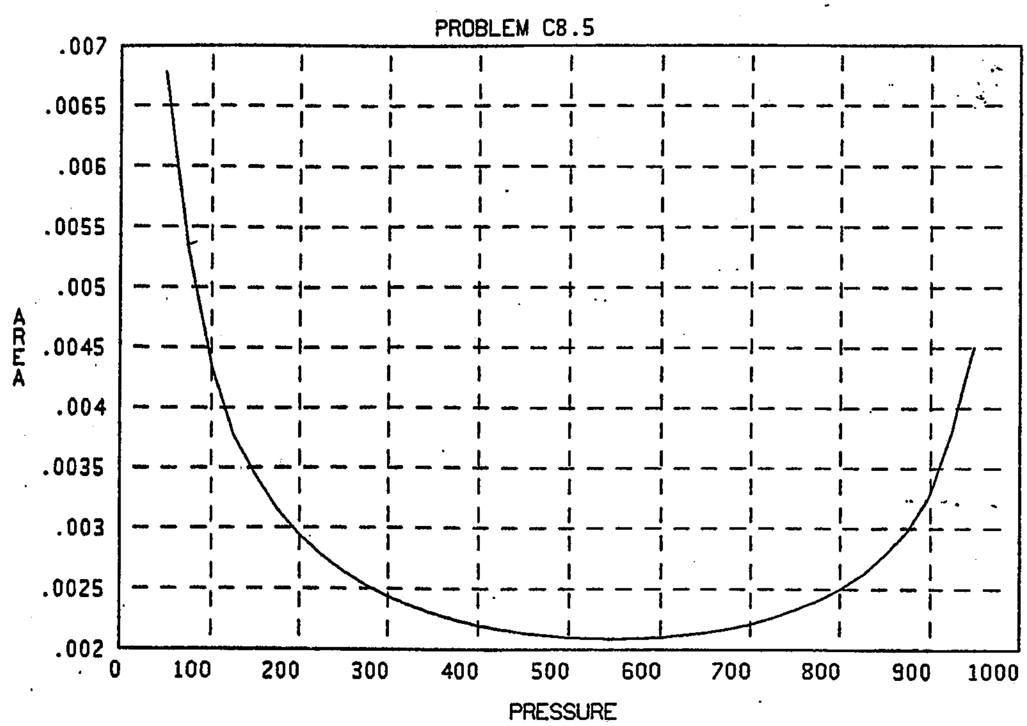
Enter SI units in the Variable Sheet for the new variables, and then change all units to English. Enter values for the inlet enthalpy and entropy. Use the List Solver for a range of pressures to compute the nozzle areas. The results are as follows.

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					ENGINEERING THERMODYNAMICS 4/E
					M. David Burghardt & James A. Harbach
					Single Point Steam Properties
L	100	P		psia	Pressure (kPa, MPa, psia)
		T	401.24	degF	Temperature (degK, degC, degR, degF)
		v	4.9453	ft3/lbm	Specific Volume (m3/kg, ft3/lbm)
		h	1228.1	BTU/lbm	Enthalpy (kJ/kg, BTU/lbm)
		s	1.6525	B/lbm-R	Entropy (kJ/kg-K, B/lbm-R)
		x	1		Quality
	1	mdot		lbm	Mass Flow
L		A	.004349	ft3	Area
		V	1137.1	m/s	Velocity
	1506	ho		BTU/lbm	Enthalpy at Inlet
	1.6525	so		B/lbm-R	Entropy at Inlet

Problem C8.5

P(psia)	A(ft3)
950	.0045085
900	.0032947
850	.0027838
800	.0024998
750	.0023239
700	.0022112
650	.0021406
600	.0021016
550	.0020889
500	.0021004
450	.0021362
400	.0021993
350	.0022955
300	.0024355
250	.002639
200	.0029443
150	.003436
100	.004349
50	.0067753



CHAPTER NINE

Problem 9.1

Determine the availability of a unit mass for each of the following assuming the system is at rest, at zero elevation and $T_o = 27°C$ and $p_o = 1$ atmosphere.

a. Dry saturated steam at 5 MPa.
b. Refrigerant 12 at 1 MPa and 90°C.
c. Air at 500 K and 1000 kPa.
d. Water as a saturated liquid at 100°C.
e. Water as a saturated liquid at 10°C.

Given: Various substances and T_o and p_o.

Find: The specific availability.

Assumptions: 1) The kinetic and potential energies are zero.

Analysis: The specific availability is

$$a = (u - u_o) + p_o\,(v - v_o) - T_o\,(s - s_o) + \frac{V^2}{2} + gz$$

Applying assumption (1) yields.

$$a = (u - u_o) + p_o\,(v - v_o) - T_o\,(s - s_o)$$

(a) Steam at 5 MPa. For steam at T_o and p_o is a saturated liquid at 27°C. From the steam tables.

$$u_o = 112.4 \text{ kJ/kg} \qquad s_o = 0.3908\ \frac{\text{kJ}}{\text{kg-K}} \qquad v_o = 0.001 \text{ m}^3\text{/kg}$$

$$u = 2597.3\ \frac{\text{kJ}}{\text{kg}} \qquad s = 5.9726\ \frac{\text{kJ}}{\text{kg-K}} \qquad v = 0.03945 \text{ m}^3\text{/kg}$$

$$a = (2597.3 - 112.4 \text{ kJ/kg}) + \left(101.3\ \frac{\text{kN}}{\text{m}^2}\right)(0.03945 - 0.001 \text{ m}^3\text{/kg})$$

$$- (300 \text{ K})(5.9726 - 0.3908 \text{ kJ/kg-K})$$

$\underline{a = 814.2 \text{ kJ/kg}}$

(b) R12 at 1 MPa and 90°C. R12 at T_o and p_o is a subcooled liquid with properties similar to those of a saturated liquid at T_o.

$u_o = 61.7$ kJ/kg $\quad s_o = 0.2307$ kJ/kg-K $\quad v_o = 0.00076$ m³/kg

$u = 218.0$ kJ/kg $\quad s = 0.7900$ kJ/kg-K $\quad v = 0.02225$ m³/kg

$$a = (218 - 61.7 \text{ kJ/kg}) + \left(101.3 \frac{\text{kN}}{\text{m}^2}\right)(0.02225 - 0.00076 \text{ m}^3\text{/kg})$$

$$- (300 \text{ K})(0.7900 - 0.2307 \text{ kJ/kg-K})$$

$a = -9.3$ kJ/kg

(c) Air at 500 K and 1000 kPa.

$$u - u_o = c_v(T - T_o) = \left(0.7176 \frac{\text{kJ}}{\text{kg-K}}\right)(500 - 300 \text{ K}) = 143.5 \text{ kJ/kg}$$

$$v = \frac{RT}{p} = \frac{(0.287 \text{ kJ/kg-K})(500 \text{ K})}{(1000 \text{ kN/m}^2)} = 143.5 \text{ kJ/kg}$$

$$v_o = \frac{RT_o}{p_o} = \frac{(0.287)(300)}{(101.3)} = 0.850 \text{ m}^3\text{/kg}$$

$$p_o(v - v_o) = \left(101.3 \frac{\text{kN}}{\text{m}^2}\right)(0.1435 - 0.850 \text{ m}^3\text{/kg}) = -71.6 \text{ kJ/kg}$$

$$s - s_o = c_p \ln\left(\frac{T}{T_o}\right) - R \ln\left(\frac{p}{p_o}\right) = \left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{500}{300}\right)$$

$$- \left(0.287 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{1000}{101.3}\right)$$

$s - s_o = -0.1439$ kJ/kg-K

$-T_o(s - s_o) = (300 \text{ K})(-0.1439 \text{ kJ/kg-K}) = +43.2$ kJ/kg

$a = (143.5) + (-71.6) + (43.2) =$ 115.1 kJ/kg

(d) Water as a saturated liquid at 10°C.

$a = 41.1$ kJ/kg $\quad s = 0.1459$ kJ/kg-K $\quad v = 0.001$ m³/kg

$a = (41.1 - 112.4) + (101.3)(0.001 - 0.001) - (300)(0.1459 - 0.3908)$

$a =$ 2.2 kJ/kg

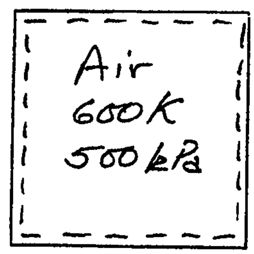
Problem 9.5

The availability of a tank filled with air at 600 K and 500 kPa is 8000 kJ. Determine the tank's volume if T_o = 300 K and p_o = 100 kPa.

Given: The availability of a tank of air is known as are the air's other properties.

Find: The volume of the tank.

Sketch and Given Data:



$\mathcal{A} = 8000$ kJ

$T_o = 300$ K

$P_o = 100$ kPa

Assumptions:
1) Air is an ideal gas.
2) The changes is kinetic and potential energies are zero.

Analysis: The availability is

$$A = m\left[(u - u_o) + p_o(v - v_o) - T_o(s - s_o) + \frac{v^2}{2} + gz\right]$$

Apply assumptions 1 and 2.

$$(u - u_o) = c_v(T - T_o) = (0.7176 \text{ kJ/kg-K})(600 - 300 \text{ K}) = 215.3 \text{ kJ/kg}$$

$$s - s_o = c_p \ln\left(\frac{T}{T_o}\right) - R \ln\left(\frac{p}{p_o}\right)$$

$$s - s_o = (1.0047 \text{ kJ/kg-K}) \ln\left(\frac{600}{300}\right) - \left(0.287 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{500}{100}\right)$$

$$s - s_o = 0.2345 \text{ kJ/kg-K}$$

$$v = \frac{RT}{p} = \frac{(0.287 \text{ kJ/kg-K})(600 \text{ K})}{(500 \text{ kN/m}^2)} = 0.344 \text{ m}^3\text{/kg}$$

$$v_o = \frac{RT_o}{p_o} = \frac{(0.287)(300)}{(100)} = 0.861 \text{ m}^3/\text{kg}$$

$$p_o(v - v_o) = (100 \text{ kN/m}^2)(0.344 - 0.861 \text{ m}^3/\text{kg}) = -51.7 \text{ kJ/kg}$$

$$-T_o(s - s_o) = -(300 \text{ K})(0.2345 \text{ kJ/kg-K}) = -70.4 \text{ kJ/kg}$$

$$8000 \text{ kJ} = (m \text{ kg})(215.3 - 51.7 - 70.4 + 0 + 0 \text{ kJ/kg})$$

$$m = 85.84 \text{ kg}$$

$$V = m\,v = (85.84 \text{ kg})\left(0.344 \frac{\text{m}^3}{\text{kg}}\right) = \underline{29.5 \text{ m}^3}$$

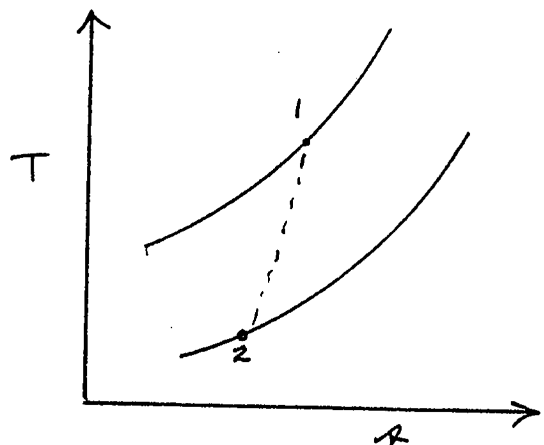
Problem 9.9

Air at initial conditions of 450°C and 300 kPa undergoes a process to a final state of 280 K and 80 kPa. T_o = 300 K and p_o = 100 kPa. Determine the availability per unit mass at the initial state and at the final state.

Given: A unit mass of air changes state.

Find: The specific availability at the initial and final states.

Sketch and Given Data:



$T_o = 300\,K$
$P_o = 100\,kPa$
$T_1 = 450°C$
$P_1 = 300\,kPa$
$T_2 = 280\,K$
$P_2 = 80\,kPa$

Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.

Analysis: The specific availability is

$$a = (u - u_o) + p_o(v - v_o) - T_o(s - s_o) + \frac{V^2}{2} + gz$$

Applying assumptions 2 eliminates the last two terms.

$$u_1 - u_o = c_v(T_1 - T_o) = \left(0.7176 \frac{kJ}{kg\text{-}K}\right)(723 - 300\ K) = 303.5 \frac{kJ}{kg}$$

$$s_1 - s_o = c_p \ln\left(\frac{T_1}{T_o}\right) - R \ln\left(\frac{p_1}{p_o}\right)$$

$$= \left(1.0047 \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{723}{300}\right) - \left(0.287 \frac{kJ}{kg\text{-}K}\right) \ln\left(\frac{300}{100}\right)$$

$s_1 - s_o$ = 0.5684 kJ/kg-K

$T_o(s_1 - s_o)$ = (300 K)(0.5684 kJ/kg-K) = 170.5 kJ/kg

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287 \text{ kJ/kg-K})(723 \text{ K})}{(300 \text{ kN/m}^2)} = 0.6917 \text{ m}^3\text{/kg}$$

$$v_o = \frac{RT_o}{p_o} = \frac{(0.287)(300)}{100} = 0.861 \text{ m}^3\text{/kg}$$

At the initial state, the specific availability a_1 is

$$a_1 = (303.5 \text{ kJ/kg}) + \left(100 \frac{\text{kN}}{\text{m}^2}\right)(0.6917 \text{ m}^3\text{/kg}) - (170.5 \text{ kJ/kg})$$

$$a_1 = \underline{116.1 \text{ kJ/kg}}$$

At the final state

$$u_2 - u_o = c_v(T_2 - T_o) = (0.7176)(280 - 300) = -14.4 \text{ kJ/kg}$$

$$s_2 - s_o = c_p \ln\left(\frac{T_2}{T_o}\right) - R \ln\left(\frac{p_2}{p_o}\right)$$

$$= (1.0047) \ln\left(\frac{280}{300}\right) - (0.287) \ln\left(\frac{80}{100}\right)$$

$$s_2 - s_o = -0.00527 \text{ kJ/kg}$$

$$T_o(s_2 - s_o) = (300)(-0.00527) = -1.581 \text{ kJ/kg}$$

$$v_2 = \frac{RT_2}{p_2} = \frac{(0.287)(280)}{(80)} = 1.0045 \text{ m}^3\text{/kg}$$

$$v_o = 0.861 \text{ m}^3\text{/kg}$$

$$p_o(v_2 - v_o) = (100)(1.0045 - 0.861) = 14.4 \text{ kJ/kg}$$

$$a_2 = -14.4 + 14.4 - 1.581 = \underline{-1.581 \text{ kJ/kg}}$$

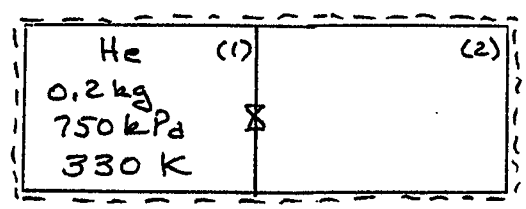
Problem 9.13

An adiabatic container has two compartments of equal volume, one containing 0.2 kg helium at 750 kPa and 330 K and the other completely evacuated. A valve connecting the two compartments is opened and the helium expands throughout both compartments. Determine the final temperature and pressure of the helium and the irreversibility. $T_o = 300$ K and $p_o = 100$ kPa.

Given: An adiabatic container has two compartments of the same volume. One holds helium and the other is empty. The partition is removed.

Find: The final helium T and p and the irreversibility.

Sketch and Given Data:



$V_2 = V_1$

$T_o = 300$ K

$P_o = 100$ kPa

Assumptions:
1) Helium is an ideal gas.
2) Neglect potential and kinetic energies.
3) The heat and work are zero.

Analysis: Determine the volume of compartment 1.

$$V_1 = \frac{m_1 RT_1}{p_1} = \frac{(0.2\ \text{kg})(2.077\ \text{kJ/kg-K})(330\ \text{K})}{(750\ \text{kN/m}^2)} = 0.1828\ \text{m}^3$$

Perform a first law analysis

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$0 = \Delta U \qquad U_{final} = U_{initial}$$

$$m\, c_v\, T_1 = m\, c_v\, T_3 \qquad \therefore \qquad T_3 = T_1 = \underline{330\ \text{K}}$$

The total volume, $V_3 = 2V_1 = 0.3656\ \text{m}^3$. The final pressure is

$$p = \frac{m\, RT_3}{V_3} = \frac{(0.2\ \text{kg})(2.077\ \text{kJ/kg-K})(330\ \text{K})}{(0.3656\ \text{m}^3)} = \underline{375\ \text{kPa}}$$

The entropy change is

$$\Delta S = m\, c_p \ln \left(\frac{T_2}{T_1}\right)^{\nearrow 0} - m\, R \ln \left(\frac{p_2}{p_1}\right) = - m\, R \ln \left(\frac{p_2}{p_1}\right)$$

$$\Delta S = -(0.2 \text{ kg})(2.077 \text{ kJ/kg-K}) \ln \left(\frac{375}{750}\right) = 0.288 \text{ kJ/K}$$

For the adiabatic case, $\Delta S = \Delta S_{prod}$.

$$I = T_o\, \Delta S_{prod} = (300 \text{ K})\left(0.288 \frac{\text{kJ}}{\text{K}}\right) = \underline{86.4 \text{ kJ}}$$

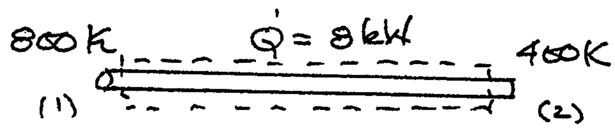
Problem 9.17

An insulated cylindrical rod, except for its ends, is connected to two constant temperature reservoirs; one maintained at 800 K and the other at 400 K. The heat transfer rate through the rod is 8 kW. Determine the rod's irreversibility rate. T_o = 300 K.

Given: A cylindrical rod is insulated except for its ends which are maintained at different constant temperature.

Find: The irreversibility rate.

Sketch and Given Data:



Assumptions: 1) The heat flow is steady, with the same numerical value at each end.

Analysis: Determine the heat's availability transfer rate (HAT) at each end.

$$(HAT)_1 = \left(1 - \frac{T_o}{T_1}\right) \dot{Q} = \left(1 - \frac{300}{800}\right)(8\ kW) = 5\ kW$$

$$(HAT)_2 = \left(1 - \frac{T_o}{T_2}\right) \dot{Q} = \left(1 - \frac{300}{400}\right)(-8\ kW) = -2\ kW$$

From Equation 9.15 where $\dot{W} = 0$ and $p_o(dV/dt) = 0$ an $dA/dt = 0$

$$\dot{I} = 5 - 2 = \underline{3\ kW}$$

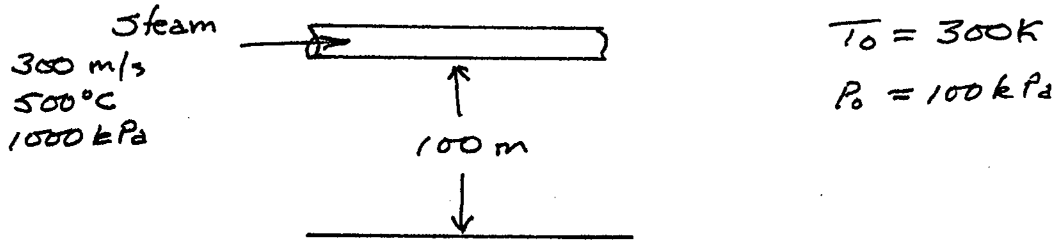
Problem 9.21

Steam flows at a velocity of 300 m/s, at a temperature of 500°C and a pressure of 1000 kPa and at an elevation of 100 m. Determine the specific flow availability if T_o = 300 K and p_o = 100 kPa and g = 9.8 m/s^2.

Given: Steam flows steadily at an elevation, a velocity and with state properties known.

Find: The specific flow availability.

Sketch and Given Data:



Assumptions: 1) Steam is a pure substance and the states are equilibrium ones.

Analysis: The specific flow availability is

$$\Psi_1 = (h_1 + \frac{V_1^2}{2} + gz_1) - (h_o + gz_o) - T_o(s_1 - s_o)$$

Locate the steam property values in the steam table, noting that at 300 K and 100 kPa the steam is a subcooled liquid.

h_1 = 3477.8 kJ/kg $\qquad$ s_1 = 7.7585 kJ/kg-K

h_o = 111.7 kJ/kg $\qquad$ s_o = 0.3887 kJ/kg-K

$$\Psi_1 = (3477.8 - 111.7 \text{ kJ/kg}) + \frac{(9.8 \text{ m/s}^2)(100 - 0 \text{ m})}{(1000 \text{ J/kJ})}$$

$$+ \frac{(300 \text{ m/s})_2}{(2)(1000 \text{ J/kJ})} - (300 \text{ K})(7.7585 - 0.3887 \text{ kJ/kg-K})$$

$$\Psi_1 = 1201.1 \text{ kJ/kg}$$

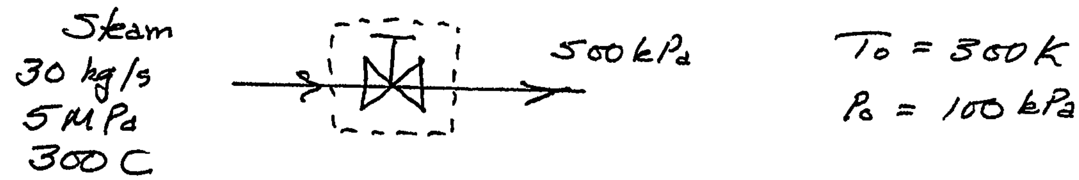
Problem 9.25

30 kg/s of steam flow through a throttling valve where the inlet conditions to the valve are 5 MPa and 300°C and the exit conditions are 500 kPa. T_o = 300 K and p_o = 100 kPa. Determine the specific flow availability change and the irreversibility rate across the valve.

Given: Steam flows steadily through a throttling valve where an adiabatic pressure drop occurs.

Find: The irreversibility rate and the change in specific flow availability across the valve.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.
3) Heat and work are zero.
4) The valve is a steady open system.

Analysis: Determine the steam exit state from the valve. For a throttling process $h_2 = h_1$. From the steam tables h_1 = 2925.2 kJ/kg s_1 = 6.2085 kJ/kg-K. Knowing that h_2 = 2925.2 kJ/kg and p_2 = 500 kPa, find from the tables that s_2 = 7.2021 kJ/kg-K. The irreversibility rate is

$$\dot{I} = \dot{m}\, T_o(s_2 - s_1) = (30 \text{ kg/s})(300 \text{ K})(7.2021 - 6.2085 \text{ kJ/kg-K})$$

$$\dot{I} = \underline{8942.4 \text{ kW}}$$

Solve Equation 9.22 for $(\Psi_1 - \Psi_2)$ noting that $\dot{Q}$ and $\dot{W}$ are zero.

$$\Psi_1 - \Psi_2 = i = \frac{(8942.4 \text{ kJ/s})}{(30 \text{ kg/s})} = \underline{298.1 \text{ kJ/kg}}$$

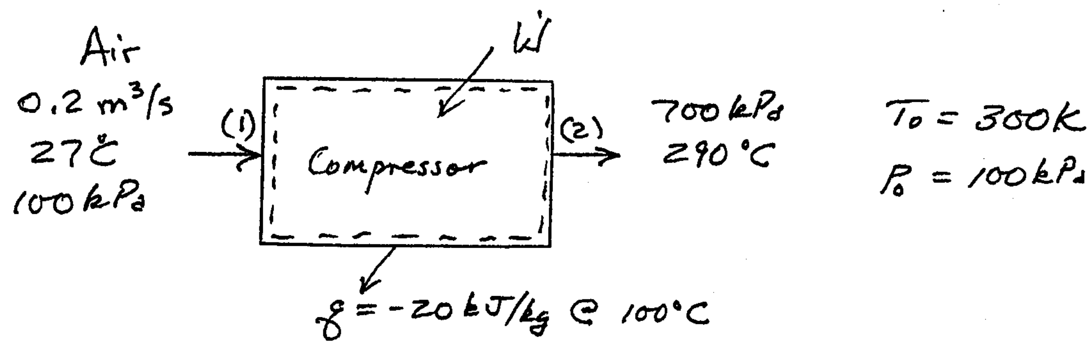
Problem 9.29

A compressor receives 0.2 m^3/s of air at 27°C and 100 kPa and compresses it to 700 kPa and 290°C. Heat loss per unit mass from the compressor surface at 100°C is 20 kJ/kg. Determine the change in the air's availability across the compressor and the availability transfer rate of the heat. T_o = 300 K and p_o = 100 kPa.

Given: A compressor compresses air between two states. Heat loss from the surface occurs.

Find: The air's availability change and the availability transfer rate of the heat.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.
3) The compressor is a steady, open system.

Analysis: Determine the mass flowrate of air

$$\dot{m} = \frac{p_1\dot{V}_1}{RT_1} = \frac{(100 \text{ kN/m}^2)(0.2 \text{ m}^3\text{/s})}{(0.287 \text{ kJ/kg-K})(300 \text{ K})} = 0.232 \text{ kg/s}$$

$$\dot{Q} = \dot{m}\, q = (0.232 \text{ kg/s})(-20 \text{ kJ/kg}) = -4.64 \text{ kW}$$

Apply assumption 2.

$$\dot{m}(\Psi_2 - \Psi_1) = \dot{m}(h_2 - h_1) - \dot{m}\, T_o(s_2 - s_1)$$

$$\dot{m}(h_2 - h_1) = \dot{m}\, c_p\, (T_2 - T_1)$$

$$\dot{m}(h_2 - h_1) = (0.232 \text{ kg/s})\left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right)(563 - 300 \text{ K}) = \underline{61.30 \text{ kW}}$$

$$\dot{m}\ T_o(s_2\ -\ s_1)\ =\ \dot{m}\ T_o\left[c_p\ \ln\left(\frac{T_2}{T_1}\right)\ -\ R\ \ln\left(\frac{p_2}{p_1}\right)\right]$$

$$\dot{m}\ T_o(s_2\ -\ s_1)\ =\ (0.232\ \text{kg/s})(300\ \text{K})\left[\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{563}{300}\right)\right.$$

$$\left. -\left(0.287\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{700}{100}\right)\right]$$

$$\dot{m}\ T_o(s_2\ -\ s_1)\ =\ 5.15\ \text{kW}$$

$$\dot{m}(\Psi_2\ -\ \Psi_1)\ =\ 61.30\ -\ 5.15\ =\ \underline{+56.15\ \text{kW}}$$

The heat's availability transfer rate (HAT) is

$$\text{HAT} = \left(1\ -\ \frac{T_o}{T_i}\right)\dot{Q}_i\ =\ \left(1\ -\ \frac{300}{373}\right)(-4.64\ \text{kW})\ =\ \underline{-0.91\ \text{kW}}$$

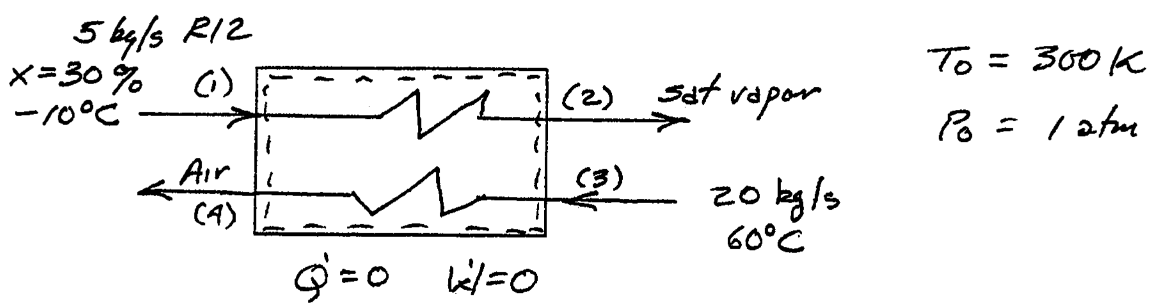
Problem 9.33

An evaporator, a counterflow heat exchanger, in a refrigeration system receives 5 kg/s of R12 at 30% quality and -10°C and evaporates it at constant pressure until it is a saturated vapor. 20 kg/s of air enter the evaporator at 60°C and 1 atmosphere and are cooled at constant pressure. T_o = 300 K and p_o = 1 atmosphere. Determine the availability changes of both the air and refrigerant and the irreversibility rate.

Given: An evaporator uses R12 as the cold source and air as the warm source. Both fluid states and flows are given across the heat exchanger.

Find: The availability change across the evaporator for each fluid and the irreversibility rate.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.
3) R12 is a pure substance and the states are equilibrium ones.
4) The heat and work are zero.
5) The heat exchanger is a steady, open system.

Analysis: The air exit conditions may be found from a first law analysis. Then find the change of availability for each substance. The first law is

$$\dot{Q} + \dot{m}_a(h + ke + pe)_3 + \dot{m}_{R12}(h + ke + pe)_1$$

$$= \dot{W} + \dot{m}_a(h + ke + pe)_4 + \dot{m}_{R12}(h + ke + pe)_2$$

Apply assumptions 2 and 4.

$$\dot{m}_a(h_3 - h_4) = \dot{m}_{R12}(h_2 - h_1)$$

From the R12 tables

$$h_1 = 26.86 + (0.30)(156.33) = 73.76 \text{ kJ/kg}$$

$$s_1 = 0.1079 + (0.30)(0.5940) = 0.2861 \text{ kJ/kg-K}$$

$$h_2 = 183.2 \text{ kJ/kg} \qquad s_2 = 0.7019 \text{ kJ/kg-K}$$

Substitute in first law expression.

$$(20 \text{ kg/s})(1.0047 \text{ kJ/kg-K})(333 - T_4 \text{ K}) = (5 \text{ kg/s})(183.2 - 73.76 \text{ kJ/kg})$$

$$T_4 = 305.8 \text{ K}$$

The specific flow availability for R12 applying assumption 2 is

$$\Psi_2 - \Psi_1 = (h_2 - h_1) - T_o(s_2 - s_1) = \left(183.2 - 73.76 \frac{\text{kJ}}{\text{kg}}\right)$$

$$- (300 \text{ K})\left(0.7019 - 0.2861 \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$\Psi_2 - \Psi_1 = -15.3 \text{ kJ/kg}$$

$$\dot{m}_{R12}(\Psi_2 - \Psi_1) = (5 \text{ kg/s})(-15.31 \text{ kJ/kg}) = \underline{-76.5 \text{ kW}}$$

The air availability change is

$$\Psi_4 - \Psi_3 = h_4 - h_3 - T_o(s_4 - s_3) = c_p(T_4 - T_3)$$

$$- T_o\left[c_p \ln\left(\frac{T_4}{T_3}\right) - R \cancel{\ln}^{0}\left(\frac{p_4}{p_3}\right)\right]$$

$$\Psi_4 - \Psi_3 = \left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right)(305.8 - 333 \text{ K})$$

$$- (300 \text{ K})\left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{305.8}{333}\right)$$

$$\Psi_4 - \Psi_3 = -1.64 \text{ kJ/kg}$$

$$\dot{m}_a(\Psi_4 - \Psi_3) = (20 \text{ kg/s})(-1.64 \text{ kJ/kg}) = \underline{-32.8 \text{ kJ/kg}} \text{ kW}$$

The irreversibility rate in the absence of heat and work is.

$$\dot{I} = T_o \, \Delta\dot{S}_{prod}$$

$$\dot{m}_{R12}(s_2 - s_1) = (5)(0.7019 - 0.2861) = 2.079 \text{ kW/K}$$

$$\dot{m}_a(s_4 - s_3) = (20)(1.0047) \ln \left(\frac{305.8}{333}\right) = -1.712 \text{ kW/K}$$

$$\Delta\dot{S}_{prod} = 2.079 - 1.712 = 0.367 \text{ kW/K}$$

$$\dot{I} = (300 \text{ K})(0.367 \text{ kW/K}) = \underline{110.1 \text{ kW}}$$

Comments

1) The availability changes of the R12 is negative because the R12 temperature is less than the surroundings.
2) When different substances flow through the same open system, you cannot add unit mass values of these substances with one another.

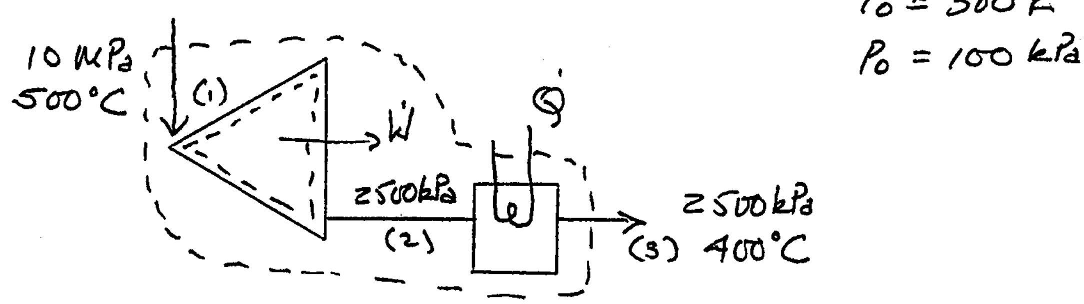
Problem 9.37

Referring to the previous problem another engineer suggests expanding the steam through an adiabatic turbine tot he desired pressure and then heating or cooling the steam to the desired temperature. Investigate the availability destruction in this scenario. What assumptions are necessary?

Given: Steam is reduced in pressure from one state to another using a turbine and a heat exchanger.

Find: The availability destruction per unit mass.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.
3) The turbine and heat exchanger form a steady, open system.

Analysis: Determine the enthalpy and entropy value at state 2. For the best situation, the flow through the turbine is irreversible adiabatic, or isentropic, and $s_2 = s_1$. In this situation where $s_2 = s_1 = 6.5983$ kJ/kg-K and $p_2 = 2500$ kPa, find from the steam tables that $h_2 = 2983.7$ kJ/kg and $T_2 = 289.2$°C. Thus, the steam would need heat added to raise its temperature to 400°C. The enthalpy and entropy values are:

$h_1 = 3376.5$ kJ/kg $\qquad s_1 = 6.5982$ kJ/kg-K

$h_2 = 2983.7$ kJ/kg $\qquad s_2 = s_1$ kJ/kg-K

$h_3 = 3240.2$ kJ/kg $\qquad s_3 = 7.0145$ kJ/kg-K

The heat added per unit mass at constant pressure is

$$q = (h_3 - h_2) = (3240.2 - 2983.7 \text{ kJ/kg}) = 256.5 \text{ kJ/kg}$$

Assume that the average temperature of heat addition is halfway between 289°C and 400°C or 345°C. From Equation 8.42

$$\Delta s_{prod} = (s_3 - s_1) - \frac{q}{T}$$

$$= (7.0145 - 6.5982 \text{ kJ/kg-K}) - \frac{(256.5 \text{ kJ/kg})}{(618 \text{ K})}$$

$$\Delta s_{prod} = 0.0013 \text{ kJ/kg-K}$$

$$i = T_o \, \Delta s_{prod} = (300 \text{ K})(0.0013 \text{ kJ/kg-K}) = 0.39 \text{ kJ/kg}$$

Comment: 1) The dramatic reduction in irreversibility is because heat is added in this problem. The availability of the added heat reduces the irreversibility.

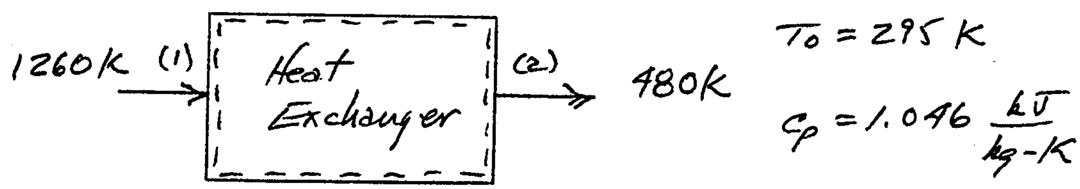
Problem 9.41

Determine the available energy per unit mass of furnace gas, c_p = 1.046 kJ/kg-K, when it is cooled from 1260 K to 480 K at constant pressure. The surroundings are at 295 K.

Given: Gas from a furnace is cooled at constant pressure between two temperatures.

Find: The available energy of the heat transferred.

Sketch and Given Data:



Assumptions:
1) The gas is an ideal gas.
2) Neglect potential and kinetic energies.
3) The work is zero.
4) The furnace is an open steady system.

Analysis: The first law for an open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3 and divide by $\dot{m}$.

$$q = h_2 - h_1 = c_p(T_2 - T_1)$$

The available energy is

$$(a_1e_1)_{1\text{-}2} = q - T_o(s_2 - s_1) = q - T_o\left[c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)^{\nearrow 0}\right]$$

$$(a_1e_1)_{1\text{-}2} = c_p(T_2 - T_1) - T_o\, c_p \ln\left(\frac{T_2}{T_1}\right)$$

$$(a_1e_1)_{1\text{-}2} = \left(1.046\ \frac{\text{kJ}}{\text{kg-K}}\right)(480 - 1260\ \text{K}) - (295\ \text{K})\left(1.046\ \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{480}{1260}\right)$$

$$(a_1e_1)_{1\text{-}2} = \underline{-518.1}\ \frac{\text{kJ}}{\text{kg}}$$

Problem 9.45

A constant-volume container holds air at 102 kPa and 300 K. A paddle wheel does work on the air until the temperature is 422 K. The air is now cooled by the surroundings (at 289 K) to its original state. Determine (a) the paddle work required (adiabatic) per kilogram; (b) the available portion of the heat removed per kilogram.

Given: Air in a constant volume tank receives paddle work adiabatically. The air is then cooled to the original state.

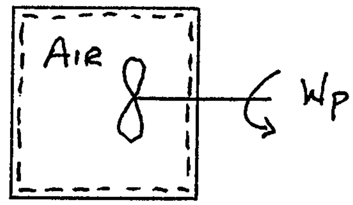
Find: The paddle work and the available energy of the heat rejected.

Sketch and Given Data:

$T_1 = 300\,K$

$P_1 = 102\,kPa$

$T_o = 289\,K$



$T_2 = 422\,K$

$T_3 = T_1$

Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.
3) The mechanical work is zero.
4) The heat is zero where paddle work is added.
5) The volume is constant.
6) Air forms the closed system.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W + W_p$$

Apply assumptions 2, 3 and 4 and divide by m.

$$0 = \Delta u + w_p \qquad w_p = u_1 - u_2 = c_v(T_1 - T_2)$$

a) $w_p = (0.7176\ \text{kJ/kg-K})(300 - 422\ \text{K}) = \underline{-87.5\ \text{kJ/kg}}$

The cooling of the air is at constant volume, hence

$$q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2) \text{ for an ideal gas}$$

The available portion of the heat is

$$(a_1e_1)_{2\text{-}3} = q_{2\text{-}3} - T_o(s_3 - s_2)$$

$$s_3 - s_2 = c_v \ln\left(\frac{T_3}{T_2}\right) + R \ln\left(\frac{v_3}{v_2}\right)^{\to 0} = c_v \ln\left(\frac{T_3}{T_2}\right)$$

$$(a_1e_1)_{2\text{-}3} = \left(0.7176\ \frac{\text{kJ}}{\text{kg-K}}\right)(300\ -\ 422\ \text{K})$$

$$-\ (289\ \text{K})\left(0.7176\ \frac{\text{kJ}}{\text{kg-K}}\right)\ \ln\left(\frac{300}{422}\right)$$

b) $(a_1e_1)_{2\text{-}3} = \underline{-16.8\ \text{kJ/kg}}$

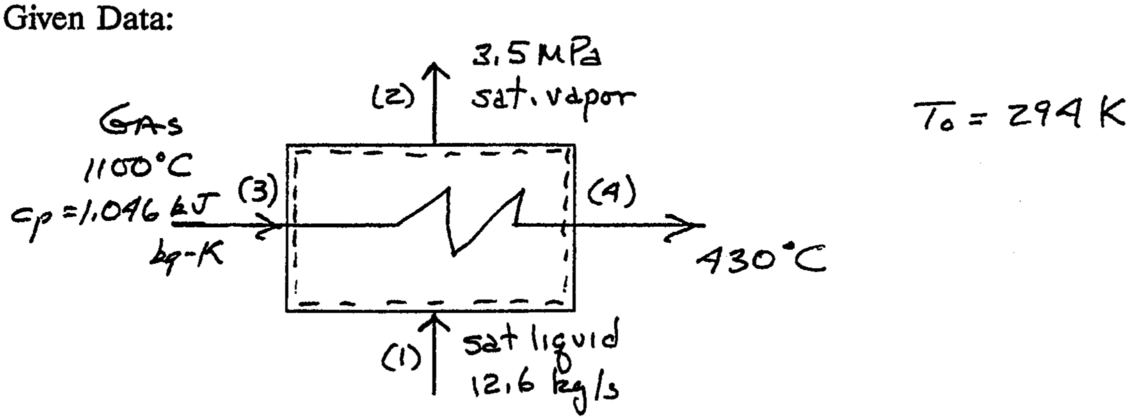
Problem 9.49

A boiler produces dry saturated steam at 3.5 MPa. The furnace gas enters the tube bank at a temperature of 1100°C, leaves at a temperature of 430°C, and has an average specific heat, c_p = 1.046 kJ/kg-K, over this temperature range. Neglecting heat losses from the boiler and for the water entering the boiler as a saturated liquid with a flowrate of 12.6 kg/s, determine for T_o = 21°C (a) the heat transfer, (b) the loss of available energy of the gas; (c) the gain of available energy of the steam; (d) the entropy production.

Given: Water enters a boiler with a given flowrate as a saturated liquid and leaves as a saturated vapor. It is boiled by combustion gases at known inlet and exit temperatures.

Find: The heat transfer to the water, the available energy changes of the gas and water and the entropy production.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.
3) Heat loss to surroundings is zero as in the work.
4) The boiler is a steady, open system.

Analysis: Determine the steam states from the steam tables.

$$h_1 = 1050.1 \text{ kJ/kg} \quad s_1 = 2.7240 \text{ kJ/kg-K}$$

$$h_2 = 2803.5 \text{ kJ/kg} \quad s_2 = 6.1239 \text{ kJ/kg-K}$$

From a first law for an open system, find the gas flowrate.

$$\dot{Q} + \dot{m}_g(h + ke + pe)_3 + \dot{m}_s(h + ke + pe)_1$$
$$= \dot{W} + \dot{m}_g(h + ke + pe)_4 + \dot{m}_s(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{m}_g = \frac{\dot{m}_s(h_2 - h_1)}{(h_3 - h_4)} = \frac{(12.6 \text{ kg/s})(2803.5 - 1050.1 \text{ kJ/kg})}{\left(1.046 \dfrac{\text{kJ}}{\text{kg-K}}\right)(1373 - 703) \text{ K}} = 31.5 \text{ kg/s}$$

Consider a control volume which only is on the steam side of the boiler. The first law is

$$\dot{Q} + \dot{m}_s(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumption 2 and that the work is zero.

a) $$\dot{Q} = \dot{m}(h_2 - h_1)$$

$$= (12.6 \text{ kg/s})\left(2803.5 - 1050.1 \frac{\text{kJ}}{\text{kg}}\right) = \underline{22\ 093} \text{ kW}$$

$$(\Delta A\dot{E})_{stm} = \dot{Q} - \dot{m}_s T_o(s_2 - s_1)$$

c) $$(A\dot{E})_{stm} = (22093 \text{ kW}) - (12.6 \text{ kg/s})(294 \text{ K})\left(6.1239 - 2.7240 \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$= \underline{9498 \text{ kW}}$$

$$(\Delta A\dot{E})_{gas} = \dot{Q} - \dot{m}_g T_o(s_4 - s_3)$$

$$s_4 - s_3 = c_p \ln\left(\frac{T_4}{T_3}\right) - \cancelto{0}{R \ln\left(\frac{p_4}{p_3}\right)} = \left(1.046 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{703}{1373}\right)$$

$$= -0.7002 \frac{\text{kJ}}{\text{kg-K}}$$

b) $$(A\dot{E})_{gas} = (-22093 \text{ kW}) - (31.5 \text{ kg/s})(294 \text{ K})\left(-0.7002 \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$= \underline{-15\ 608 \text{ kW}}$$

$$\Delta\dot{S}_{prod} = \sum \Delta\dot{S}_i = \dot{m}_g(s_4 - s_3) + \dot{m}_s(s_2 - s_1)$$

$$\Delta\dot{S}_{prod} = (31.5 \text{ kg/s})\left(-0.7002 \ \frac{\text{kJ}}{\text{kg-K}}\right)$$

$$+ \ (12.6 \text{ kg/s})(6.1239 - 2.7240 \text{ kJ/kg-K})$$

d) $\Delta\dot{S}_{prod} = 20.78 \text{ kW/K}$

Also, note that $(U\dot{E})_{net} = T_o \ \Delta\dot{S}_{prod}$

$$(A\dot{E})_{net} = -15608 + 9498 = -6110 \text{ kW}$$

$$(U\dot{E})_{net} = -(A\dot{E})_{net} = +6110 \text{ kW}$$

$$\Delta\dot{S}_{prod} = \frac{6110 \text{ k}\dot{W}}{294 \text{ K}} = 20.78 \ \frac{\text{kW}}{\text{K}}$$

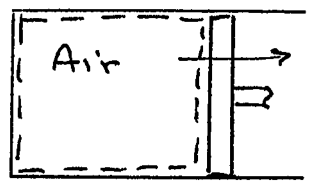
Problem 9.53

Air expands from 825 kPa and 500 K to 140 kPa and 500 K. Determine (a) the Gibbs function at the initial conditions; (b) the maximum work; (c) the entropy change.

Given: Air expands between two known states.

Find: The Gibbs function at state 1, the maximum work possibly done by the air between the states and the entropy change.

Sketch and Given Data:



$P_1 = 825$ kPa
$T_1 = 500$ K
$T_2 = T_1$
$P_2 = 140$ kPa

Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.

Analysis: The Gibbs function per unit mass is $g = h - Ts$. To evaluate g @ T_1, use the air tables to find the value of s_1 and h_1.

$$s_1 = \Phi_1 - R \ln\left(\frac{p_1}{p_0}\right) = (3.0328 \text{ kJ/kg-K}) - \left(0.287 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{825}{101.3}\right)$$

$$s_1 = 2.4309 \text{ kJ/kg-K}$$

a) $$g_1 = (503.02 \text{ kJ/kg}) - (500 \text{ K})\left(2.4309 \frac{\text{kJ}}{\text{kg-K}}\right) = \underline{-712.43}$$

$$s_2 = \Phi_2 - R \ln\left(\frac{p_2}{p_0}\right) = \left(3.0328 \frac{\text{kJ}}{\text{kg-K}}\right) - \left(0.287 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{140}{101.3}\right)$$

$$s_2 = 2.9400 \text{ kJ/kg-k}$$

c) $$(s_2 - s_1) = 2.9400 - 2.4309 = \underline{0.5091 \text{ kJ/kg}}$$

$$g_2 = (503.02) - (500)(2.9400) = -966.98 \text{ kJ/kg}$$

$$w_{max} = -(g_2 - g_1) = -(-966.98 - (-712.43)) = \underline{254.55} \frac{\text{kJ}}{\text{kg}}$$

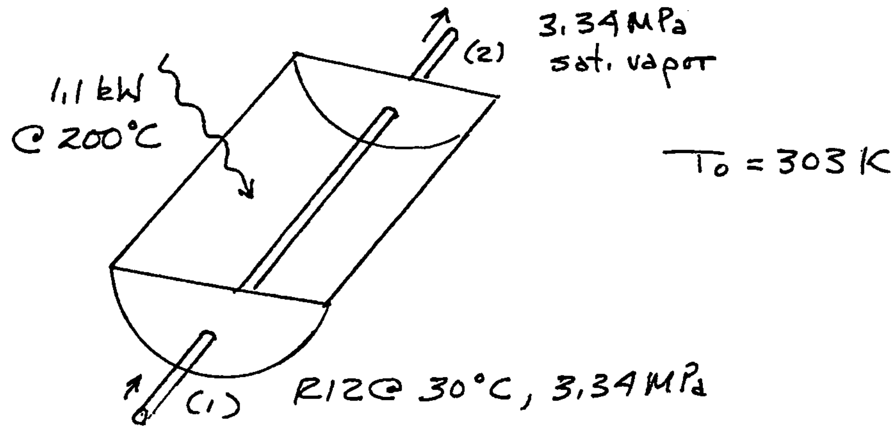
Problem 9.57

A parabolic collector receives 1.1 kW of solar radiation at 200°C. This energy is used to evaporate R12 from a subcooled liquid at 30°C and 3.34 MPa to a saturated vapor at 3.34 MPa. T_o = 30°C. Determine (a) refrigerant flowrate; (b) entropy production; (c) second-law efficiency.

Given: A parabolic collector is a heat exchanger, receiving solar energy and using this to evaporate R12 at constant pressure.

Find: The R12 flowrate, the entropy production and the second law efficiency.

Sketch and Given Data:



Assumptions:
1) The R12 is a pure substance and the states are equilibrium ones.
2) The heat is supplied at constant temperature.
3) Neglect potential and kinetic energies.
4) The collector is a steady, open system.
5) The work is zero.

Analysis: From the R12 tables, find that

$$h_1 = 64.7 \text{ kJ/kg} \qquad s_1 = 0.2403 \text{ kJ/kg-K}$$

$$h_2 = 209.6 \text{ kJ/kg} \qquad s_2 = 0.6435 \text{ kJ/kg-K}$$

The first law for a steady, open system from the R12 view is

$$\dot{Q} + \dot{m}_{R12}(h + ke + pe)_1 = \dot{W} + \dot{m}_{R12}(h + ke + pe)_2$$

Apply assumptions 3 and 5.

a) $$\dot{m}_{R12} = \frac{\dot{Q}}{(h_2 - h_1)} = \frac{(1.1 \text{ kW})}{(209.6 - 64.7 \text{ kJ/kg})} = \underline{0.00759 \text{ kg/s}}$$

The entropy change of the heat source is

$$\Delta \dot{S}_{source} = \frac{\dot{Q}}{T} = \frac{-1.1\ kW}{473\ K} = -0.002326\ \frac{kW}{K}$$

The entropy change of the R12 is

$$\Delta \dot{S}_{R12} = \dot{m}(s_2 - s_1) = (0.00759\ kg/s)(0.6435 - 0.2403\ kJ/kg\text{-}K)$$

$$\Delta \dot{S}_{R12} = 0.003060\ \frac{kW}{K}$$

The entropy production is

b) $$\Delta \dot{S}_{prod} = +0.003060 - 0.002326 = +0.000734\ \frac{kW}{K}$$

The change in availability of the R12 is

$$\dot{m}(\Psi_2 - \Psi_1) = \dot{m}(h_2 - h_1) - \dot{m}\ T_o(s_2 - s_1)$$

$$\dot{m}(\Psi_2 - \Psi_1) = 1.1\ kW - (303\ K)(0.003060\ \frac{kW}{K}) = +0.1728\ kW$$

The change in availability of the heat supplied is

$$\Delta \Psi_{source} = Q\left(1 - \frac{T_o}{T}\right) = (1.1)\left(1 - \frac{303}{473}\right) = -0.3953\ kW$$

c) $$\eta_2 = \frac{0.1728}{0.3953} = 0.437 \text{ or } \underline{43.7\%}$$

Problem 9.1*

Determine the availability of a unit mass for each of the following assuming the system is at rest, at zero elevation and T_o = 77°F and p_o = 1 atmosphere.

a. Dry saturated steam at 500 psia.
b Refrigerant 12 at 200 psia and 200°F.
c. Air at 900 R and 150 psia.
d. Water as a saturated liquid at 212°F.
e. Water as a saturated liquid at 40°F.

Given: Various substances and T_o and p_o.

Find: The specific availability.

Assumptions: 1) The kinetic and potential energies are zero.

Analysis: The specific availability is

$$a = (u - u_o) + p_o(v - v_o) - T_o\,(s - s_o) + \frac{V^2}{2} + gz$$

Applying assumption (1) yields

$$a = (u - u_o) + p_o\,(v - v_o) - T_o\,(s - s_o)$$

(a) Steam at 500 psia. Steam at T_o and p_o is a saturated liquid at 77°F. From the steam tables.

$$u_o = 44.7\ \frac{\text{Btu}}{\text{lbm}} \qquad s_o = 0.0867\ \text{Btu/lbm-R} \qquad v_o = 0.01607\ \text{ft}^3\text{/lbm}$$

$$u = 1119.4\ \text{Btu/lbm} \qquad s = 1.4641\ \frac{\text{Btu}}{\text{lbm-R}} \qquad v = 0.9285\ \text{ft}^3\text{/lbm}$$

$$a = (1119.4 - 44.7\ \text{Btu/lbm})$$

$$+\ \frac{(14.7\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(0.9285 - 0.01607\ \text{ft}^3/\text{lbm})}{(778.16\ \text{ft-lb}_f/\text{Btu})}$$

$$-\ (537\ \text{R})(1.4641 - 0.0867\ \text{Btu/lbm-R})$$

$$a = \underline{372.1\ \text{Btu/lbm}}$$

b) R12 at 200 psia and 200°F. R12 at T_o and p_o is a subcooled liquid with properties similar to those of a saturated liquid at T_o.

$$u = 93.4 \text{ Btu/lbm} \qquad s = 0.18311 \frac{\text{Btu}}{\text{lbm-R}} \qquad v = 0.2486 \text{ ft}^3\text{/lbm}$$

$$u_o = 25.5 \text{ Btu/lbm} \qquad s_o = 0.0536 \frac{\text{Btu}}{\text{lbm-R}} \qquad v_o = 0.0122 \text{ ft}^3\text{/lbm}$$

$$a = (93.4 - 25.5) + \frac{(14.7)(144)(0.2486 - 0.0122)}{(778.16)} - (537)(0.18311 - 0.0536)$$

a = <u>-1.0 Btu/lbm</u>

c) Air at 900 R and 150 psia

$$u - u_o = c_v(T - T_o) = \left(0.1714 \frac{\text{Btu}}{\text{lbm-R}}\right)(900 - 537 \text{ R})$$

$$= 62.2 \text{ Btu/lbm}$$

$$v = \frac{RT}{p} = \frac{(53.34 \text{ ft-lb}_f\text{/lbm-R})(900 \text{ R})}{(150 \text{ lb}_f\text{/in}^2)(144 \text{ in}^2\text{/ft}^2)} = 2.222 \text{ ft}^3\text{/lbm}$$

$$v_o = \frac{RT_o}{p_o} = \frac{(53.34)(537)}{(14.7)(144)} = 13.532 \text{ ft}^3\text{/lbm}$$

$$p_o(v - v_o) = \frac{(14.7 \text{ lb}_f\text{/in}^2)(144 \text{ in}^2\text{/ft}^2)(2.222 - 13.532 \text{ ft}^3\text{/lbm})}{(778.16 \text{ ft-lb}_f\text{/Btu})}$$

$$= -30.8 \frac{\text{Btu}}{\text{lbm}}$$

$$s - s_o = c_p \ln\left(\frac{T}{T_o}\right) - R \ln\left(\frac{p}{p_o}\right) = \left(0.24 \frac{\text{Btu}}{\text{lbm-R}}\right) \ln\left(\frac{900}{537}\right)$$

$$- \frac{(53.34 \text{ ft-lb}_f\text{/lbm-R}) \ln\left(\frac{150}{14.7}\right)}{(778.16 \text{ ft-lb}_f\text{/Btu})}$$

$$s - s_o = -0.0353 \text{ Btu/lbm-R}$$

$$T_o(s - s_o) = -(537\ R)(-0.0353\ Btu/lbm\text{-}R) = 18.9\ Btu/lbm$$

$$a = 62.2 - 30.8 + 18.9 = \underline{50.3\ Btu/lbm}$$

d) Water as a saturated liquid at 212°F. The "o" values are the same as part a.

$u = 180.4$ Btu/lbm $\qquad s = 0.3120 \dfrac{Btu}{lbm\text{-}R} \qquad v = 0.0167\ ft^3/lbm$

$$a = (180.4 - 44.7) + \frac{(14.7)(144)(0.0167 - 0.01607)}{(778.16)} - (537)(0.3120 - 0.0867)$$

$a = \underline{14.7\ Btu/lbm}$

e) Water as a saturated liquid at 40°F. The "o" values are the same as part a.

$u = 7.8$ Btu/lbm $\qquad s = 0.0152 \dfrac{Btu}{lbm\text{-}R} \qquad v = 0.01602\ ft^3/lbm$

$$a = (7.8 - 44.7) + \frac{(14.7)(144)(0.01602 - 0.01607)}{(778.16)} - (537)(0.0152 - 0.0867)$$

$a = \underline{1.5\ Btu/lbm}$

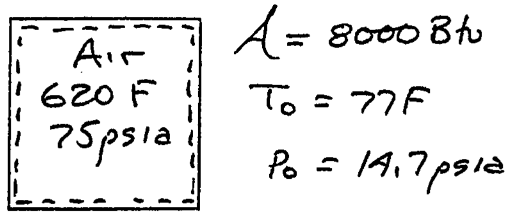
Problem 9.5*

The availability of a tank filled with air at 620°F and 75 psia is 8000 Btu. Determine the tanks volume if T_o = 77°F and p_o = 14.7 psia.

Given: The availability of a tank of air is known as are the air's other properties.

Find: The volume of the tank.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The changes in kinetic and potential energies are zero.

Analysis: The availability is

$$m\left[(u - u_o) + p_o(v - v_o) - T_o(s - s_o) + \frac{v^2}{2} + gz\right]$$

Apply assumptions 1 and 2

$$(u - u_o) = c_v(T - T_o)$$

$$= \left(0.1714 \frac{Btu}{lbm\text{-}R}\right)(1080 - 537\ R) = 93.1 \frac{Btu}{lbm}$$

$$s - s_o = c_p \ln\left(\frac{T}{T_o}\right) - R \ln\left(\frac{p}{p_o}\right)$$

$$s - s_o = (0.24 \text{ Btu/lbm-R}) \ln \left(\frac{1080}{537}\right) - \frac{\left(53.34 \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{\left(778.16 \dfrac{\text{ft-lb}_f}{\text{Btu}}\right)} \ln \left(\frac{75}{14.7}\right)$$

$$s - s_o = 0.056 \text{ Btu/lbm-R}$$

$$v = \frac{RT}{p} = \frac{(53.34 \text{ ft-lb}_f\text{/lbm-R})(1080 \text{ R})}{(75 \text{ lb}_f\text{/in}^2)(144 \text{ in}^2\text{/ft}^2)} = 5.334 \text{ ft}^3\text{/lbm}$$

$$v_o = \frac{RT_o}{p_o} = \frac{(53.34)(537)}{(14.7)(144)} = 13.532 \text{ ft}^3\text{/lbm}$$

$$p_o(v - v_o) = \frac{(14.7 \text{ lb}_f\text{/in}^2)(144 \text{ in}^2\text{/ft}^2)(5.334 - 13.532 \text{ ft}^3\text{/lbm})}{(778.16 \text{ ft-lb}_f\text{/Btu})}$$

$$p_o(v - v_o) = -22.3 \frac{\text{Btu}}{\text{lbm}}$$

$$-T_o(s - s_o) = -(537 \text{ R})(0.056 \text{ Btu/lbm-R}) = -30.1 \text{ Btu/lbm}$$

$$(8000 \text{ Btu}) = (m \text{ lbm})\left[93.1 - 22.3 - 30.1 + 0 + 0 \frac{\text{Btu}}{\text{lbm}}\right]$$

$$m = 196.6 \text{ lbm}$$

$$V = mv = (196.6 \text{ lbm})(5.334 \text{ ft}^3\text{/lbm}) = \underline{\underline{1048.7}} \text{ ft}^3$$

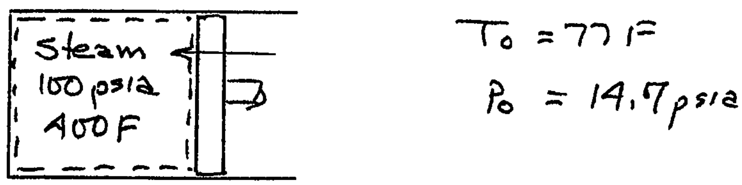
Problem 9.9*

A piston/cylinder contains steam at 100 psia and 400°F cools at constant pressure until the temperature is equal to that of the surroundings. Find, per unit mass, the heat, the work and the availability transfer with the heat and work. The surroundings are at T_o = 70°F and p_o = 1 47 psia.

Given: A unit mass of steam expands at constant pressure until $T_2 = T_o$.

Find: The heat, work and availability transfer.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.

Analysis: Determine the steam properties at the initial and final states. The final state is a subcooled liquid.

u_1 = 113.1 Btu/lbm h_1 = 1227.4 Btu/lbm s_1 = 1.6517 Btu/lbm-R

u_2 = 37.7 Btu/lbm v_1 = 4.937 ft³/lbm $s_2 = 0.0735 \dfrac{\text{Btu}}{\text{lbm-R}}$

h_2 = 37.7 Btu/lbm v_1 = 0.01605 ft³/lbm

For a constant pressure process.

$$q = \Delta h = (h_2 - h_1) = (37.7 - 1227.4) = -1189.7 \text{ Btu/lbm}$$

$$(u_2 - u_1) = (37.7 - 1136.1) = -1098.4 \text{ Btu/lbm}$$

The first law for a closed system subject to assumption 2 is

$$q = \Delta u + w$$

$$-1189.7 = -1098.4 + w$$

$$w = -91.3 \text{ Btu/lbm}$$

The availability transfer accompanying work (WAT) is

$$WAT = w - p_o(v_2 - v_1)$$

$$WAT = -91.3 \frac{\text{Btu}}{\text{lbm}} - \frac{(14.7 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)(0.01605 - 4.937 \text{ ft}^3/\text{lbm})}{\left(778.16 \frac{\text{ft-lb}_f}{\text{Btu}}\right)}$$

$$WAT = \underline{-77.9} \frac{\text{Btu}}{\text{lbm}}$$

The availability transfer accompanying heat (HAT) is

$$HAT = \int_1^2 \left(1 - \frac{T_o}{T}\right) \delta q$$

$$HAT = q - T_o(s_2 - s_1)$$

$$HAT = -1189.7 - (530)(0.0735 - 1.6517)$$

$$HAT = \underline{-353.2} \frac{\text{Btu}}{\text{lbm}}$$

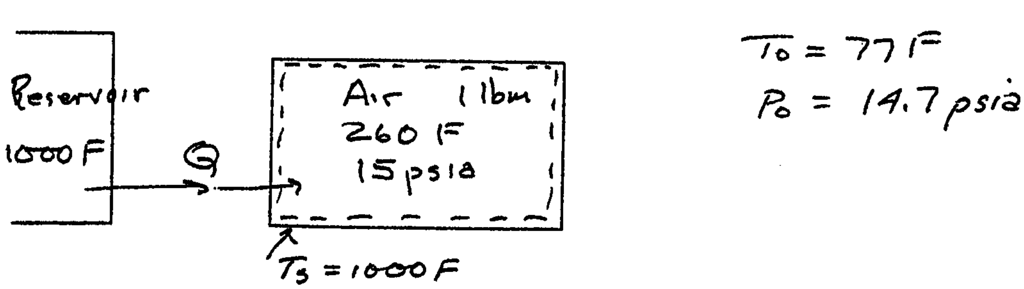
Problem 9.13*

A rigid tank contains 1 lbm air at 260°F and 15 psia and receives heat from a constant temperature reservoir at 1000°F until the air temperature increases to 620°F. The tank surface temperature during the heat addition process is 1000°F. Determine the heat transferred, its availability transfer and the irreversibility for the process. T_o = 77°F and p_o = 14.7 psia.

Given: A constant volume tank containing air receives heat from a constant temperature heat reservoir. The tank surface temperature is 1000°F during the heat transfer process. The final air temperature is 620°F.

Find: The heat transfer, the heat's availability transfer and the irreversibility.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.
3) The work is zero, the volume is constant.

Analysis: Perform a first law analysis to determine the heat transferred.

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = \Delta U = m\, c_v\, (T_2 - T_1)$$

$$= (1\ \text{lbm})\left(0.1714\ \frac{\text{Btu}}{\text{lbm-R}}\right)(1080 - 720\ \text{R})$$

$$Q = 61.7\ \text{Btu}$$

The heat's availability transfer (HAT) is

$$\text{HAT} = \left(1 - \frac{T_o}{T}\right) Q = \left(1 - \frac{537}{1460}\right)(61.7 \text{ Btu}) = 39 \text{ Btu}$$

The entropy change for the air is

$$\Delta S_{sys} = m\, c_v \ln\left(\frac{T_2}{T_1}\right) + m\, R \ln\left(\frac{V_2}{V_1}\right)$$

$$= (1 \text{ lbm})\left(0.1714 \frac{\text{Btu}}{\text{lbm-R}}\right) \ln\left(\frac{1080}{720}\right)$$

$$\Delta S_{sys} = 0.0695 \text{ Btu/R}$$

The entropy change of the source is

$$\Delta S_{source} = \frac{Q}{T} = \frac{-61.7 \text{ Btu}}{1460 \text{ R}} = -0.0423 \text{ Btu/R}$$

The entropy production is

$$\Delta S_{prod} = 0.0695 - 0.0423 = 0.0272 \text{ Btu/R}$$

$$I = T_o\, \Delta S_{prod} = (537 \text{ R})\left(0.272 \frac{\text{Btu}}{\text{R}}\right) = \underline{14.6 \text{ Btu}}$$

Problem 9.17*

An electric kiln uses wire as a heating element. A steady state condition occurs when the wire is at a temperature of 3000 R, the kiln walls at a temperature of 1500 R and the electrical power through the wire is 10 kW. T_o = 77°F.

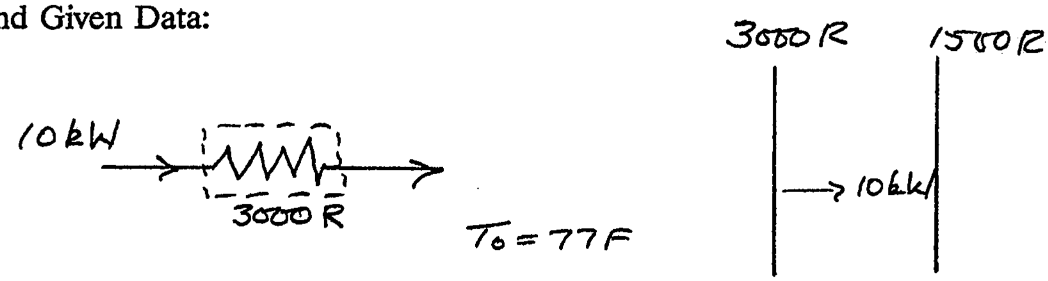
a) Considering the wire as the system, determine its irreversibility rate;

b) Considering the space between the wire and the kiln walls as the system, determine its irreversibility rate.

Given: The wire in an electric kiln radiates heat to the walls at another constant temperature. The power dissipated as heat is known.

Find: The irreversibility rate of wire; of the space between the wall and the wall that the heat passes through.

Sketch and Given Data:



Assumptions:
1) The temperatures are constant.
2) All the power is dissipated as heat.

Analysis: (a) The heat transfer availability rate (HAT) is

$$(\text{HAT}) = \left(1 - \frac{T_o}{T}\right)\dot{Q} = \left(1 - \frac{537}{3000}\right)(-10\text{ kW}) = -8.2\text{ kW}$$

The work availability transfer rate (WAT) is -10 kW as it is entering the system. The irreversibility rate is found from Equation 9.15.

$$\cancel{\frac{dA}{dt}} = \left(1 - \frac{T_o}{T}\right)\dot{Q} - \dot{W} + \cancel{p_o\frac{dV}{dt}} - \dot{I}$$

$$\dot{I} = -8.2\text{ kW} - (-10\text{ kW}) = \underline{1.8\text{ kW}}$$

b) The space between receives heat at 3000 R and transfers heat at 1500 R. There is no work transfer, hence $\dot{W} = 0$.

$$(HAT)_{in} = \left(1 - \frac{T_o}{T_1}\right)\dot{Q} = \left(1 - \frac{537}{3000}\right)(10\ kW) = 8.2\ kW$$

$$(HAT)_{out} = \left(1 - \frac{T_o}{T_2}\right)\dot{Q} = \left(1 - \frac{537}{1500}\right)(-10\ kW) = -6.4\ kW$$

From Equation 9.15

$$\frac{dA}{dt} = 8.2 - 6.4 - 0 + 0 - \dot{I}$$

$\dot{I}$ = <u>1.8 kW</u>

Comments: 1) Electrical energy is considered to have 100% availability. In case (a), of the 10 kW supplied, heat transfer irreversibilities reduced it by 1.8 kW. In case (b), irreversibilities reduced the availability of 10 kW of heat, not work, by 1.8 kW.

Problem 9.21*

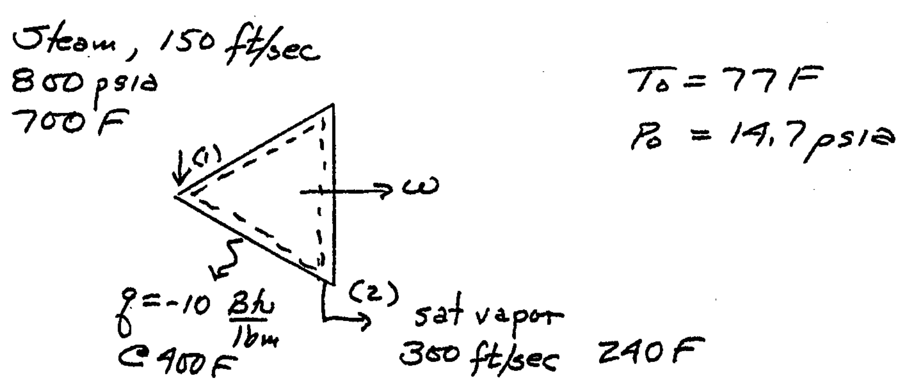
A steam turbine receives at 150 ft/sec, 800 psia and 700°F and it exits as a saturated vapor at 240°F with a velocity of 300 ft/sec. Heat transfer from the turbine casing is 10 Btu/lbm of steam and the casing is at a temperature of 400°F. Determine per unit mass of steam flowing through the turbine and for T_o = 77°F and p_o = 14.7 psia;

a) the work done by the steam;
b) the heat's availability transfer;
c) the irreversibility.

Given: Steam flow steadily through a turbine performing work. Heat is lost from the turbine casing.

Find: The work, the heat's availability transfer and the irreversibility per unit mass.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential energy.

Analysis: Perform a first law analysis to find the turbine work. For a steady open system.

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

For steam

h_1 = 1339.0 Btu/lbm $\quad$ s_1 = 1.5475 Btu/lbm-R

h_2 = 1160.7 Btu/lbm $\quad$ s_2 = 1.7139 Btu/lbm-R

Divide by $\dot{m}$, apply assumption 2 and solve for w.

$$w = q + (h_1 - h_2) + ke_1 - ke_2$$

$$w = (-10 \text{ Btu/lbm}) + (1339.0 - 1160.7 \text{ Btu/lbm})$$

$$+ \frac{(150^2 - 300^2 \text{ ft}^2/\text{sec}^2)}{(2)\left(32.174 \dfrac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)\left(778.16 \dfrac{\text{ft-lb}_f}{\text{Btu}}\right)}$$

$$w = 167.0 \frac{\text{Btu}}{\text{lbm}}$$

The heat's availability transfer (HAT) is

$$HAT = \left(1 - \frac{T_o}{T}\right) q = \left(1 - \frac{537}{860}\right)\left(-10 \frac{\text{Btu}}{\text{lbm}}\right) = -3.8 \text{ Btu/lbm}$$

The change in specific flow availability is

$$\Psi_1 - \Psi_2 = (h_1 - h_2) - T_o (s_1 - s_2) + \frac{V_1^2 - V_2^2}{2}$$

$$\Psi_1 - \Psi_2 = (1339.0 - 1160.7 \text{ Btu/lbm})$$

$$- (537 \text{ R})(1.5475 - 1.7139 \text{ Btu/lbm-R})$$

$$+ \frac{(150^2 - 300^2 \text{ ft}^2/\text{sec}^2)}{(2)\left(32.174 \dfrac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)\left(778.16 \dfrac{\text{ft-lb}_f}{\text{Btu}}\right)}$$

$$\Psi_1 - \Psi_2 = 266.3 \text{ Btu/lbm}$$

From Equation 9.22

$$i = \left(1 - \frac{T_o}{T}\right) q - w + (\Psi_1 - \Psi_2)$$

$$i = -3.8 - 167.0 + 266.3 = 95.5 \frac{\text{Btu}}{\text{lbm}}$$

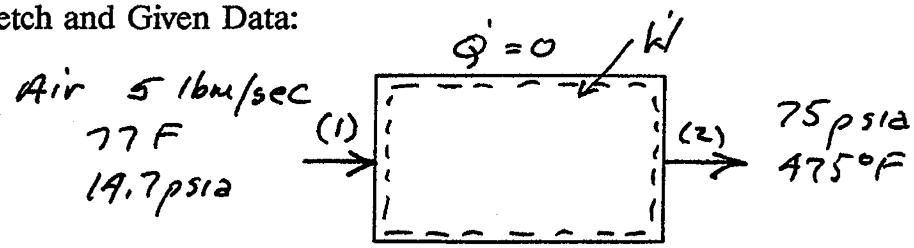
Problem 9.25*

5 lbm/sec of air enter an adiabatic compressor at 77°F and 14.7 psia and are compressed to 75 psia and 475°F. T_o = 77°F and p_o = 14.7 psia. Determine the power required and the change of availability of the air.

Given: Air flows through a compressor from state 1 to state 2. There is no heat loss.

Find: The power required and the change of the air's availability.

Sketch and Given Data:



T_o = 77 F
P_o = 14.7 psia

Assumptions:
1) Air is an ideal gas.
2) Neglect potential and kinetic energies.
3) The heat is zero.
4) The compressor is a steady, open system.

Analysis: Determine the power required from a first law analysis. For a steady, open system.

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{W} = \dot{m}(h_1 - h_2) = \dot{m}\, c_p(T_1 - T_2)$$

$$\dot{W} = (5 \text{ lbm/sec})\left(0.24 \frac{\text{Btu}}{\text{lbm-R}}\right)(537 - 935 \text{ R}) = -477.6 \text{ Btu/sec}$$

The change of availability in the absence of changes in kinetic and potential energies is

$$\dot{m}(\Psi_2 - \Psi_1) = \dot{m}(h_2 - h_1) - \dot{m}\, T_o(s_2 - s_1)$$

$$\dot{m}(h_2 - h_1) = +477.6 \text{ Btu/sec}$$

$$\dot{m}\, T_o(s_2 - s_1) = \dot{m}\, T_o \left[c_p \ln \left(\frac{T_2}{T_1}\right) - R \ln \left(\frac{p_2}{p_1}\right) \right]$$

$$\dot{m}\, T_o(s_2 - s_1) = (5 \text{ lbm/sec})(537 \text{ R}) \left[\left(0.24 \frac{\text{Btu}}{\text{lbm-R}}\right) \ln \left(\frac{935}{537}\right) - \frac{\left(53.34 \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{\left(778.16 \frac{\text{ft-lb}_f}{\text{Btu}}\right)} \ln \left(\frac{75}{14.7}\right) \right]$$

$$\dot{m}\, T_o(s_2 - s_1) = 57.4 \text{ Btu/sec}$$

$$\dot{m}(\Psi_2 - \Psi_1) = 477.6 - 57.4 = 420.2 \text{ Btu/sec}$$

Comments: 1) Not all the work supplied is converted into raising the air's availability, some of it is lost through irreversibilities. In this case, of the 477.6 Btu/sec supplied, the theoretical maximum that can be converted back into work is 420.2 Btu/sec.

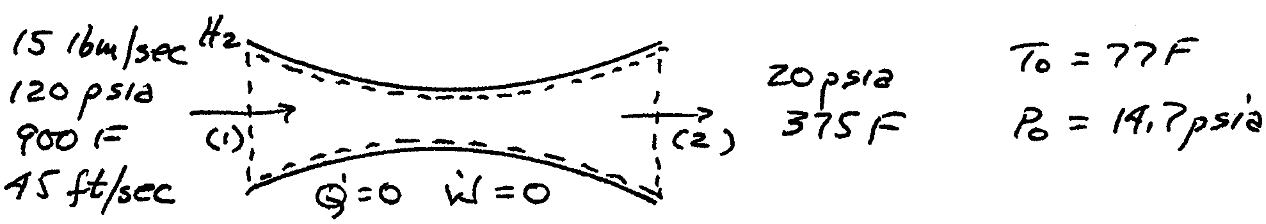
Problem 9.29*

Hydrogen enters an adiabatic nozzle with a flowrate of 15 lbm/sec, a temperature of 900°F, a pressure of 120 psia and a velocity of 45 ft/sec. It exits at 20 psia and 375°F. T_o = 77°F and p_o = 14.7 psia. Determine the gas's exit velocity and the change in availability.

Given: Hydrogen flows steadily through an adiabatic nozzle.

Find: The hydrogen's exit velocity and change of availability.

Sketch and Given Data:



Assumptions:
1) Hydrogen is an ideal gas.
2) Neglect changes in potential energy.
3) The heat and work are zero.
4) The nozzle is a steady, open system.

Analysis: Perform a first law analysis to find the exit velocity. For a steady, open system.

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3 and divide by $\dot{m}$

$$ke_2 = ke_1 + (h_1 - h_2) = \frac{v_1^2}{2\,g_c} + c_p\,(T_1 - T_2)$$

$$\frac{(v_2^2\ \mathrm{ft^2/sec^2})}{(2)\left(32.174\ \frac{\mathrm{lbm\text{-}ft}}{\mathrm{lb_f\text{-}sec^2}}\right)\left(778.16\ \frac{\mathrm{ft\text{-}lb_f}}{\mathrm{Btu}}\right)} = \frac{(45^2\ \mathrm{ft^2/sec^2})}{(2)\left(32.174\ \frac{\mathrm{lbm\text{-}ft}}{\mathrm{lb_f/sec^2}}\right)\left(778.16\ \frac{\mathrm{ft\text{-}lb_f}}{\mathrm{Btu}}\right)}$$

$$+ \left(3.419\ \frac{\mathrm{Btu}}{\mathrm{lbm\text{-}R}}\right)(1360 - 835\ \mathrm{R})$$

<u>v_2 = 9481 ft/sec</u>

The change of availability, neglecting potential energy, is

$$\Psi_2 - \Psi_1 = (h_2 - h_1) + \frac{(v_2^2 - v_1^2)}{2\, g_c} - T_o(s_2 - s_1)$$

The change of enthalpy and kinetic energy terms add out from the first law.

$$\Psi_2 - \Psi_1 = -T_o(s_2 - s_1) = T_o\left[c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)\right]$$

$$\Psi_2 - \Psi_1 = -(537\,R)\left[\left(3.419\ \frac{Btu}{lbm\text{-}R}\right) \ln\left(\frac{835}{1360}\right) - \frac{\left(766.54\ \frac{ft\text{-}lb_f}{lbm\text{-}R}\right)}{\left(778.16\ \frac{ft\text{-}lb_f}{Btu}\right)} \ln\left(\frac{20}{120}\right)\right]$$

$$\Psi_2 - \Psi_1 = -52.19\ \frac{Btu}{lbm}$$

$$\dot{m}(\Psi_2 - \Psi_1) = (15\ lbm/sec)\left(-52.19\ \frac{Btu}{lbm}\right) = \underline{-782.8}\ \frac{Btu}{sec}$$

Comment: 1) The hydrogen's availability decreases by 782.8 Btu/sec due to fluid flow irreversibilities.

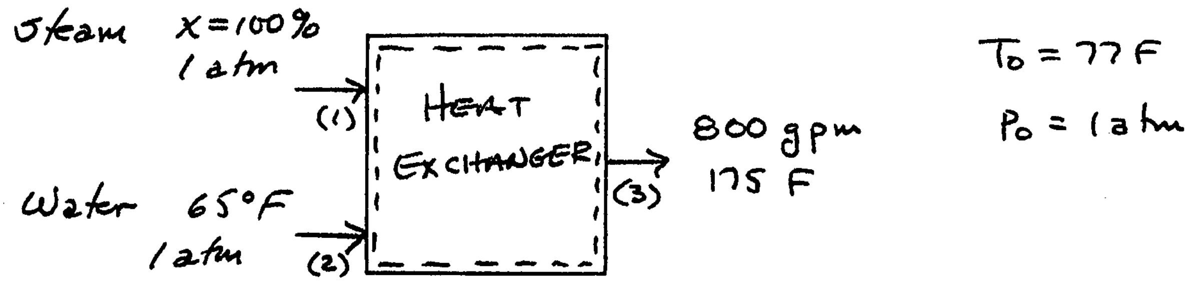
Problem 9.33*

A manufacturing process requires 800 gpm of water at 175°F and one atmosphere. This can be obtained by mixing dry saturated steam a one atmosphere with subcooled water at 65°F. Determine for T_o = 77°F and p_o = 1 atmosphere.
a) the water and steam flowrates;
b) the irreversibility of the process.

Given: Steam and water mix to form hot water.

Find: The steam and water flows and the irreversibility.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.
3) The heat and work are zero.
4) The heat exchanger is a steady, open system.

Analysis: Determine the enthalpy and entropy values for the steam and water, then perform a first law analysis

h_1 = 1150.5 Btu/lbm $\quad$ s_1 = 1.7563 Btu/lbm-R

h_2 = 32.7 Btu/lbm $\quad$ s_2 = 0.0639 Btu/lbm-R

h_3 = 143.4 Btu/lbm $\quad$ s_3 = 0.2552 Btu/lbm-R

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2 = \dot{W} + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 2 and 3.

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

For isothermal open system, $\dot{Q} = \dot{W} = -1464.4$ Btu/min (heat out). The heat availability transfer rate (HAT) is

$$HAT = \left(1 - \frac{T_o}{T_i}\right)\dot{Q}_i = \left(1 - \frac{537}{560}\right)(-1464.4) = \underline{-60.1 \text{ Btu/min}}$$

The work availability transfer rate (WAT) is

$$WAT = -\left(\dot{W} - p_o\frac{dV}{dt}\right) = -\dot{W} \quad \text{as} \quad \frac{dV}{dt} = 0$$

$$WAT = (-1464.4) = +1464.4 \text{ Btu/min}$$

The change in availability is

$$\dot{m}(\Psi_1 - \Psi_2) = \dot{m}(h_1 - h_2) - T_o(s_1 - s_2)$$

$$\dot{m}(s_1 - s_2) = \frac{-\dot{Q}}{T} = \frac{-(-1464.4)}{560} = 2.615 \text{ Btu/min-R}$$

$$h_1 - h_2 = c_p(T_1 - T_2) = 0$$

$$\dot{m}(\Psi_1 - \Psi_2) = -(537 \text{ R})(2.615 \text{ Btu/min-R}) = -1404.3 \text{ Btu/min}$$

From Equation 9.22

$$\dot{I} = HAT + WAT + \dot{m}(\Psi_1 - \Psi_2)$$

$$\dot{I} = -60.1 + 1464.4 - 1404.3 = 0$$

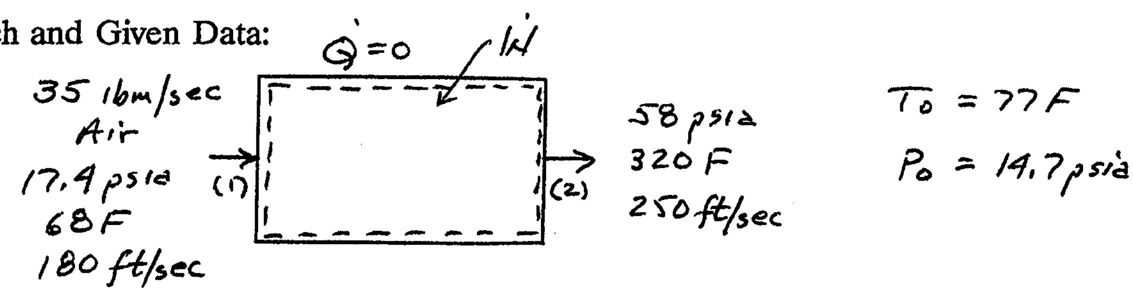
Problem 9.37*

35 lbm/sec of air enter an adiabatic compressor at 17.4 psia, 68°F and with a velocity of 180 ft/sec and exits at 58 psia, 320°F and with a velocity of 250 ft/sec. T_o = 77°F and p_o = 14.7 psia. Determine the power required, the change of availability and the second law efficiency.

Given: A compressor adiabatically compresses air between two states.

Find: The power required, the air's change of availability and the second law efficiency.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The change in potential energy is zero.
3) The heat flow is zero.
4) The compressor is a steady, open system.

Analysis: Perform a first law analysis to find the power. For a steady-state open system.

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{W} = \dot{m}\left[(h_1 - h_2) + ke_1 - ke_2\right] = \dot{m}\left[c_p(T_1 - T_2) + \frac{v_1^2 - v_2^2}{2\,g_c}\right]$$

$$\dot{W} = (35\ \text{lbm/sec})\left[\left(0.24\ \frac{\text{Btu}}{\text{lbm-R}}\right)(528 - 720\ \text{R}) + \frac{(180^2 - 250^2\ \text{ft}^2/\text{sec}^2)}{(2)\left(32.174\ \frac{\text{lbm-ft}}{\text{lb}_f\text{-sec}}\right)\left(778.16\ \frac{\text{ft-lb}_f}{\text{Btu}}\right)}\right]$$

$$\dot{W} = \underline{-2138} \ \frac{\text{Btu}}{\text{sec}}$$

The change of availability is

$$\dot{m}(\Psi_2 - \Psi_1) = \dot{m}\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} - T_o(s_2 - s_1)\right]$$

$$s_2 - s_1 = c_p \ln\left(\frac{T_2}{T_1}\right) - R \ln\left(\frac{p_2}{p_1}\right)$$

$$s_2 - s_1 = \left[(0.24 \text{ Btu/lbm-R}) \ln\left(\frac{780}{528}\right) - \frac{\left(53.34 \ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{(778.16 \text{ ft-lb}_f\text{/Btu})} \ln\left(\frac{58}{17.4}\right)\right]$$

$$s_2 - s_1 = 0.0111 \ \frac{\text{Btu}}{\text{lbm-R}}$$

$$\dot{m}\ T_o(s_2 - s_1) = (35 \text{ lbm/sec})(537 \text{ R})\left(0.0111 \ \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$\dot{m}\ T_o(s_2 - s_1) = 208.6 \ \frac{\text{Btu}}{\text{sec}}$$

$$\dot{m}(\Psi_2 - \Psi_1) = +2138 - 208.6 = 1929.4 \ \frac{\text{Btu}}{\text{sec}}$$

The second law efficiency is

$$\eta_{2c} = \frac{\dot{m}(\Psi_2 - \Psi_1)}{\dot{W}_{compr}} = \frac{1929.4}{2138} = 0.902 \quad \text{or} \quad 90.2\%$$

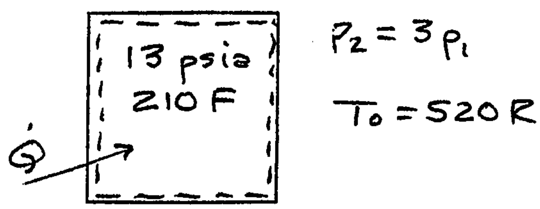
Problem 9.41*

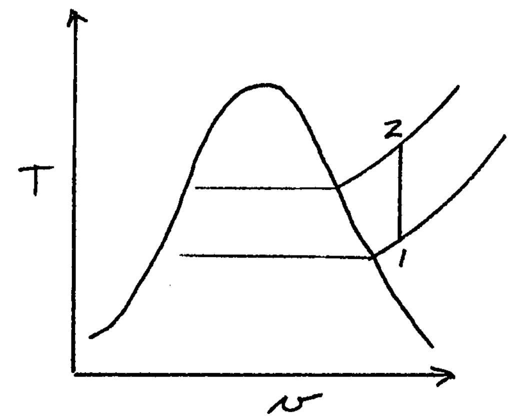
A tank contains water vapor at a pressure of 13 psia and a temperature of 210°F. Heat is added to the water vapor until the pressure is tripled. The lowest available temperature is 60°F. Find the available portion of the heat added.

Given: A tank contains a slightly superheated water vapor at known conditions. Heat is added and the pressure triples.

Find: The available energy of the heat added per unit mass.

Sketch and Given Data:





Assumptions:
1) Steam is a pure substance and the states are equilibrium ones.
2) Neglect potential and kinetic energies.
3) The volume is constant, work is zero.
4) The steam in the tank forms a closed system.

Analysis: The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3 and divide by the mass.

$$q = \Delta u = u_2 - u_1$$

From the steam tables.

$$u_1 = 1076.9 \frac{Btu}{lbm} \qquad s_1 = 1.7694 \frac{Btu}{lbm\text{-}R} \qquad v_1 = 30.26 \text{ ft}^3/\text{lbm}$$

The process from 1-2 is V = C, hence $v_2 = v_1$ and $p_2 = 39$ psia. From the steam tables.

$$u_2 = 1596.4 \frac{Btu}{lbm} \qquad s_2 = 2.1878 \frac{Btu}{lbm\text{-}R} \qquad T_2 = 1522°F$$

$$q_{1\text{-}2} = (1596.4 - 1076.9 \text{ Btu/lbm}) = 519.5 \text{ Btu/lbm}$$

$$(a_1e_1)_{1\text{-}2} = q_{1\text{-}2} - T_o(s_2 - s_1)$$

$$= \left(519.5 \frac{\text{Btu}}{\text{lbm}}\right) - (520 \text{ R})\left(2.1878 - 1.7694 \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$(a_1e_1)_{1\text{-}2} = \underline{301.9 \text{ Btu/lbm}}$$

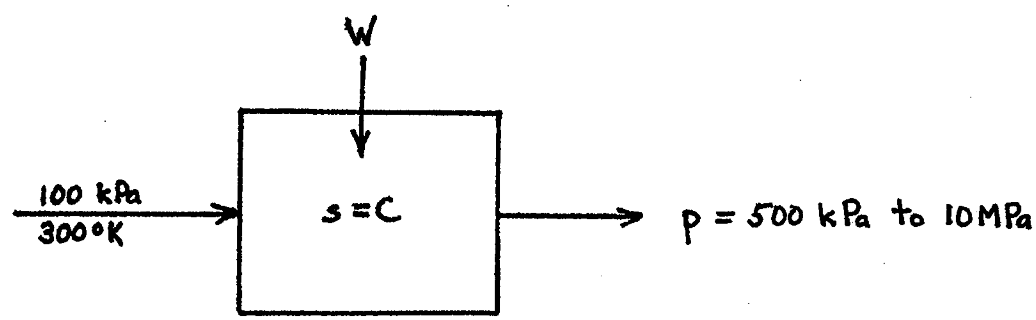
Problem C9.1

Air is compressed isentropically in a compressor from atmospheric conditions of 100 kPa and 300°K to various discharge pressures. Develop a computer model for the compressor to determine the change of availability of the air for discharge pressures of 500 kPa, 1 MPa, 5 MPa and 10 MPa. You may use the TK Solver model AIR.TK.

Given: Air compressed isentropically to various discharge pressures.

Find: Change in availability.

Sketch and Given Data:



Assumptions: 1) Change in kinetic and potential energy is negligible.

Analysis: Using AIR.TK, enter the inlet temperature and pressure, the discharge pressure, and zero for DELs. Since the process is isentropic, DELh is the change in availability. A List Solve produces the following results.

Problem C9.1

P2	T2	DELh
500	470.5	172.43
1000	570.97	276.31
5000	879.25	609.4
10000	1046.4	798.72

CHAPTER TEN

Problem 10.1

Derive an expression for the change of internal energy of a gas using the van der Waals equation of state.

Given: The van der Waals equation of state for a gas.

Find: The expression for the change of internal energy of the gas.

Assumptions: 1) The gas obeys van der Waals equation of state.

Analysis: The change of internal energy is deferred from Equation 10.29 as

$$du = c_v dT + \left[T\left(\frac{\partial p}{\partial T}\right)_v - p\right] dv$$

van der Waals Equation of State is:

$$p = \frac{\bar{R}T}{v-b} - \frac{a}{v^2}$$

$$\left(\frac{\partial p}{\partial T}\right)_v = \frac{\bar{R}}{v-b} - 0 = \frac{\bar{R}}{v-b}$$

$$du = c_v dT + \left[\frac{\bar{R}T}{v-b} - \frac{\bar{R}T}{v-b} + \frac{a}{v^2}\right] dv$$

$$du = c_v dT + \frac{a dv}{v^2}$$

Problem 10.5

Using the Maxwell relation in equations (10.22) and (10.11), develop the three remaining relations given in equation (10.23).

Given: Equations 10.22 and 10.11.

Find: Remaining relations in Equation 10.23.

Analysis: From Equation 10.22

$$\left(\frac{\partial T}{\partial v}\right)_s = -\left(\frac{\partial p}{\partial s}\right)_v \qquad \text{I}$$

The variables are *s, v, T.*

Equation 10.11 is

$$\left(\frac{\partial y}{\partial z}\right)_x\left(\frac{\partial z}{\partial x}\right)_y\left(\frac{\partial x}{\partial y}\right)_z = -1$$

Let p = y, v = z and s = x

$$\left(\frac{\partial p}{\partial v}\right)_s\left(\frac{\partial v}{\partial s}\right)_p\left(\frac{\partial s}{\partial p}\right)_v = -1$$

Substitute relationship I in

$$\left(\frac{\partial p}{\partial v}\right)_s\left(\frac{\partial v}{\partial s}\right)_p\left(\frac{\partial v}{\partial T}\right)_s = +1$$

$$\left(\frac{\partial p}{\partial T}\right)_s\left(\frac{\partial v}{\partial s}\right)_p = 1$$

$$\left(\frac{\partial v}{\partial s}\right)_p = \left(\frac{\partial T}{\partial p}\right)_s \qquad \text{II}$$

Use variables s, v, T.

$$\left(\frac{\partial s}{\partial v}\right)_T\left(\frac{\partial v}{\partial T}\right)_s\left(\frac{\partial T}{\partial s}\right)_v = -1$$

Substitute in relationship I

$$\left(\frac{\partial s}{\partial v}\right)_T \left(\frac{\partial s}{\partial p}\right)_v \left(\frac{\partial T}{\partial s}\right)_v = +1$$

$$\left(\frac{\partial s}{\partial v}\right)_T \left(\frac{\partial T}{\partial p}\right)_v = 1$$

$$\left(\frac{\partial s}{\partial v}\right)_T = \left(\frac{\partial p}{\partial T}\right)_v \qquad \text{III}$$

Use variables T, p, s

$$\left(\frac{\partial T}{\partial p}\right)_s \left(\frac{\partial p}{\partial s}\right)_T \left(\frac{\partial s}{\partial T}\right)_p = -1$$

From relationship II

$$\left(\frac{\partial v}{\partial s}\right)_p \left(\frac{\partial p}{\partial s}\right)_T \left(\frac{\partial s}{\partial T}\right)_p = -1$$

$$\left(\frac{\partial v}{\partial T}\right)_p \left(\frac{\partial p}{\partial s}\right)_T = -1$$

$$\left(\frac{\partial v}{\partial T}\right)_p = -\left(\frac{\partial s}{\partial p}\right)_T \qquad \text{IV}$$

Problem 10.9

Derive an expression for the change of entropy of a gas that obeys the van der Waals equation of state.

Given: A gas that obeys van der Waals equation of state.

Find: The expression for the change of entropy.

Assumptions: 1) The gas obeys van der Waals equation of state.

Analysis: The change of entropy may be found from Equation 10.36.

$$ds = c_v \frac{dT}{T} + \left(\frac{\partial p}{\partial T}\right)_v dv$$

van der Waals equation of state is:

$$p = \frac{RT}{v-b} - \frac{a}{v^2}$$

$$\left(\frac{\partial p}{\partial T}\right)_v = \frac{R}{(v-b)}$$

$$ds = c_v \frac{dT}{T} + \frac{R}{(v-b)} dv$$

Integrate assuming c_v and R are constant.

$$s_2 - s_1 = c_v \ln\left(\frac{T_2}{T_1}\right) + R \ln\left(\frac{v_2-b}{v_1-b}\right)$$

Problem 10.13

Compute the coefficient of thermal expansion for methane at 32°C and 1400 kPa using (a) the ideal-gas equation of state; (b) the van der Waals equation of state.

Given: Two gas equations of state and the expression for the coefficient of thermal expansion.

Find: The coefficient's value for methane.

Assumptions:

1) The gas obeys the appropriate equation of state.

2) The expression for α is available from problem 10.12.

Analysis: (a) For an ideal gas

$$\alpha = \frac{1}{T} = \frac{1}{305.15K} = \underline{0.00328\ K^{-1}}$$

(b) For a van der Waals gas, $p = \dfrac{RT}{v-b} - \dfrac{a}{v^2}$

$$\alpha = \frac{Rv^2(v-b)}{(RTv^3-2a(v-b)^2)}$$

For methane from Table 5.1

$a = 228.5\ (m^3/kgmol)^2$

$b = 0.0427\ (m^3/kgmol)$

$\bar{R} = 8.3143\ kJ/kgmol\cdot k \qquad T = 305.15k$

$p = 1400kPa$

Solve the van der Waals equation for v at this state. This is a trial and error solution or use TKSOLVER. The value for v is 1.761 $m^3/kgmol$.

$$\alpha = \frac{\left(8.3143\dfrac{kJ}{kgmol-K}\right)(1.761\ m^3/kgmol)^2\left(1.761-0.0427\dfrac{m^3}{kgmol}\right)}{A}$$

$$A = \left[\left(8.3143\frac{\text{kJ}}{\text{kgmol-K}}\right)(305.15\text{K})\left(1.761\frac{\text{m}^3}{\text{kgmol}}\right)^3 - \right.$$

$$\left.(2)(228.5\ \text{m}^6/\text{kgmol}^2)(1.761-0.0427\ \text{m}^3/\text{kgmol})^2\right]$$

α = $\underline{0.0035\ \text{K}^{-1}}$

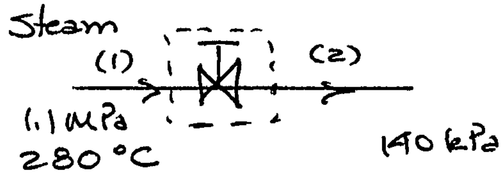
Problem 10.17

Determine the average Joule-Thomson coefficient for steam that is throttled from 1.1 MPa and 280°C to 140 kPa.

Given: Steam is throttled between 2 states.

Find: The average Joule-Thomson coefficient.

Sketch & Given Data:



Assumptions: 1) Steam is a pure substance and the states are equilibrium ones.

Analysis: The Joule-Thomson coefficient is deferred as

$$\mu = \left(\frac{\partial T}{\partial p}\right)_h$$

For a throttling process, h = C; let

$$\mu \approx \left(\frac{\Delta T}{\Delta p}\right)_h$$

For state 1 $p_2 = 1100$ kPa $T_1 = 280°C$ $h_1 = 3005.5$ kJ/kg

$h_2 = h_1$ $p_2 = 140$kPa $T_2 = 266.4°C$

$$\mu \approx \frac{(553-539.4\ K)}{(1100-140\ kPa)} = \underline{0.0142}\ K/kPa$$

Problem 10.21

The specific volume of steam at 350°C is 2.5 m^3/kg. Determine the pressure using the ideal gas equation of state, van der Waals equation of state and the Redlich-Kwong equation of state. Compare the results with that found from the steam tables.

Given: The specific volume of steam at a given temperature.

Find: The pressure using various equations of state and the steam tables.

Assumptions: 1) Steam obeys the appropriate equation of state.

Analysis: Ideal gas law

$$p = \frac{RT}{v} = \frac{(0.4615\ \text{kJ/kg-K})(623\text{K})}{(2.5\ \text{m}^3/\text{kg})} = \underline{115\ \text{kPa}}$$

Steam tables, superheat region, p = <u>114.8 kPa</u>

van der Waals

$$p = \frac{\overline{R}T}{\overline{v}-b} - \frac{a}{\overline{v}^2} \qquad b = \frac{v_c}{3} \qquad a = 27\ b^2\ p_c$$

$$v_c = 0.568 \frac{\text{m}^3}{\text{kgmol}} \qquad p_c = 22.09\ \text{MPa} \qquad T_c = 647.3\text{K}$$

$$a = \frac{27\overline{R}^2T_c^2}{64\ p_c} = \frac{(27)(8.3143)^2(647.3)^2}{(64)(22090)} = 553\ (\text{kPa})(\text{m}^6/\text{kgmol}^2)$$

$$b = \frac{RT_c}{8p_c} = \frac{(8.3143)(647.3)}{(8)(22090)} = 0.030\ \text{m}^3/\text{kgmol}$$

$$\overline{v} = Mv = \left(18.015 \frac{\text{kg}}{\text{kgmol}}\right)(2.5\ \text{m}^3/\text{kg}) = 45.04 \frac{\text{m}^3}{\text{kgmol}}$$

$$p = \frac{(8.3143\ \text{kJ/kgmol-K})(623\text{K})}{(45.04-0.030\ \text{m}^3/\text{kgmol})} - \frac{(553\ \text{kPa}(\text{m}^6/\text{kgmol}^2))}{(45.04\ \text{m}^3/\text{kgmol})^2}$$

$$p = \underline{114.8\ \text{kPa}}$$

Redlich-Kwong

$$p = \frac{\overline{R}T}{\overline{v}-b} - \frac{a}{T^{1/2}\overline{v}(\overline{v}+b)}$$

$$a = \frac{0.42748\ \overline{R}^2 T_c^{2.5}}{p_c} = \frac{(0.42748)\left(8.3143\frac{kJ}{kgmol-K}\right)(647.3K)^{2.5}}{(22090\ kN/m^2)}$$

$$a = 1715.2$$

$$b = 0.08664\ \frac{\overline{R}T_c}{p_c} = \frac{(0.08664)\left(8.3143\frac{kJ}{kgmol-K}\right)(647.3K)}{(22090\ kN/m^2)}$$

$$b = 0.021$$

$$p = \frac{(8.3143)(623K)}{(45.04-0.021)} - \frac{(1715.2)}{(623)^{0.5}(45.04)(45.04+0.021)}$$

$$p = \underline{115.0}\ kPa$$

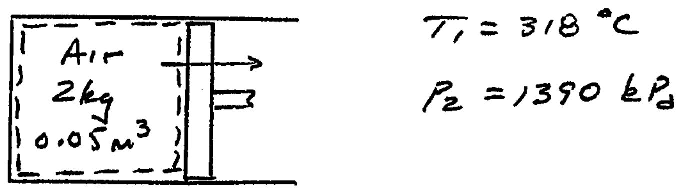
Problem 10.25

Two kilograms of air occupy a volume of 0.05 m^3 at a temperature of 318°C. The air expands isothermally until the pressure is 1390 kPa. Using van der Waals equation of state determine the initial pressure, the final volume and the work.

Given: Air expands isothermally from state 1 to state 2.

Find: The initial pressure and final volume using van der Waals equation of state and the work done.

Sketch & Given Data:



Assumptions:
1) The gas obeys van der Waals equation of state.
2) The process is isothermal.

Analysis: Using van der Waals equation of state find p_1 and V_2.

$$p = \frac{RT}{\bar{v}-b} - \frac{a}{\bar{v}^2} \qquad a = 135.8 \text{ kPa}(m^3/\text{kgmol})^2 \qquad b = 0.0364 \ m^3/\text{kgmol}$$

$$v_1 = \frac{V}{m} = \frac{0.05 \ m^3}{2 \text{ kg}} = 0.025 \ m^3/\text{kg}$$

$$\bar{v}_1 = Mv_1 = (28.97 \text{ kg/kgmol})(0.025 \ m^3/\text{kg}) = 0.7242 \ m^3/\text{kgmol}$$

$$p_1 = \frac{(8.3143 \text{ kJ/kgmol-K})(591\text{K})}{(0.7242-0.0364 \ m^3/\text{kgmol})} - \frac{(135.8 \text{ kPa}(m^6/\text{kgmol}^2))}{(0.7242 \ m^3/\text{kgmol})^2}$$

$$p_1 = 6885 \text{ kPa}$$

$$1390 = \frac{(8.3143)(591)}{(\bar{v}_2-0.0364)} - \frac{(135.8)}{(\bar{v}_2)^2}$$

Solve by trial and error

$$\overline{v_2} = 3.5442 \text{ m}^3\text{/kgmol} \qquad v_2 = \frac{\overline{v_2}}{M} = \frac{3.5442}{28.97} = \underline{0.122\text{m}^3\text{/kg}}$$

$$V_2 = mv_2 = (2)(0.122) = 0.244$$

The expression for isothermal work must be evaluated using van der Waals equation of state not the ideal gas law for T = C.

$$w = \int p dv = \int \left(\frac{\bar{R}T}{\bar{v}-h} - \frac{a}{\bar{v}^2} \right) dv$$

$$w = \bar{R}T \ln \left(\frac{\overline{v_2}-b}{\overline{v_1}-b} \right) - a \left(\frac{1}{\overline{v_2}} - \frac{1}{\overline{v_1}} \right)$$

$$w = (8.3143)(591) \ln \left(\frac{3.5442-0.0364}{0.7242-0.0364} \right) - (135.8) \left(\frac{1}{3.5442} - \frac{1}{0.7242} \right)$$

$$w = 8155 \text{kJ/kgmol}$$

$$W = \frac{(2 \text{ kg})(8155 \text{ kJ/kgmol})}{(28.97 \text{ kg/kgmol})} = \underline{563 \text{ kJ}}$$

Problem 10.29

The maximum density for liquid water at atmospheric pressure occurs at a temperature of 4°C. What can you determine about $\partial s/\partial p)_T$ at temperatures of 3°C, 4°C, and 5°C?

Given: The maximum density of water occurs at 4°C.

Find: What happens to $(\partial s/\partial p)_T$ at 3, 4 and 5 °C.

Analysis: From Maxwell's relations

$$\left(\frac{\partial s}{\partial p}\right)_T = -\left(\frac{\partial v}{\partial T}\right)_p = +\frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial T}\right)_p$$

At 4°C the maximum value of ρ occurs, before and after this point ρ is a lesser value. At 4°C, $(\partial\rho/\partial T)_p = 0$ as $\partial\rho$ is zero. At 3°C, $\partial\rho$ and ∂T are positive, hence $(\partial s/\partial p)_T$ is positive. At 5°C, $\partial\rho$ is negative and ∂T is positive, hence $(\partial\rho/\partial T)_p$ is negative as is $(\partial s/\partial p)_T$.

Problem 10.33

A gas's p-v-T behavior at certain states can create a compressibility factor of $Z = 1 - ApT^{-4}$ where A is a constant. Derive an expression for the difference in specific heats, $c_p - c_v$.

Given: A gas's compressibility factor.

Find: An expression for $c_p - c_v$.

Analysis:

$$c_p - c_v = -T\left(\frac{\partial v}{\partial T}\right)_p^2\left(\frac{\partial p}{\partial v}\right)_T$$

$$pv = ZRT$$

$$v = \frac{RT}{p}\left(1 - \frac{Ap}{T^4}\right) = \frac{RT}{p} - \frac{RA}{T^3} \qquad (1)$$

$$\left(\frac{\partial v}{\partial T}\right)_p = \frac{R}{p} + \frac{3AR}{T^4} = \frac{RT^4+3ARp}{pT^4}$$

$$\left(\frac{\partial v}{\partial T}\right)_p^2 = \frac{R^2T^8+6ARpT^4+9A^2R^2p^2}{p^2T^8}$$

Take the derivative with respect to v at constant temperature of (1)

$$1 = \frac{-RT\left(\frac{\partial p}{\partial v}\right)_T}{p^2} - 0$$

$$\left(\frac{\partial p}{\partial v}\right)_T = -\frac{p^2}{RT}$$

$$c_p - c_v = -T\left(\frac{-p^2}{RT}\right)\left(\frac{\partial v}{\partial T}\right)_p^2 = \left(\frac{p^2}{R}\right)\left(\frac{\partial v}{\partial T}\right)_p^2$$

$$c_p - c_v = \frac{p^2}{R}\left(\frac{R^2T^8+6ARpT^4+9A^2R^2p^2}{p^2T^8}\right)$$

$$c_p - c_v = R + \frac{6Ap}{T^4} + \frac{9A^2Rp^2}{T^8}$$

Problem *10.1

The equation of state for a gas is $p(v - b) = RT$ where b is an experimental constant. Find the expression for the coefficient of isothermal compressibility.

Given: A gas equation of state.

Find: The coefficient of isothermal compressibility.

Analysis: The coefficient of isothermal compressibility is

$$\beta_T = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_T$$

$$p(v-b) = RT$$

$$p\left(\frac{\partial v}{\partial p}\right)_T + v - b = 0$$

$$\left(\frac{\partial v}{\partial p}\right)_T = -\frac{(v-b)}{p} = \frac{-RT}{p^2}$$

$$\underline{\beta_T = \frac{+RT}{p^2 v}}$$

Problem *10.5

Determine the constant-volume and constant-pressure specific heats of steam at 350 psia and 500°F by means of equations (10.24) and (10.25).

Given: Equations 10.24 and 10.25 and the steam tables.

Find: c_p and c_v at 350 psia and 500°F.

Assumptions: 1) Steam is a pure substance and states are equilibrium ones.

Analysis: The expression for c_p and c_v are

$$c_v \equiv \left(\frac{\partial u}{\partial T}\right)_v \approx \left(\frac{\Delta u}{\Delta T}\right)_v$$

$$c_p \equiv \left(\frac{\partial h}{\partial T}\right)_p \approx \left(\frac{\Delta h}{\Delta T}\right)_p$$

From the tables at 350 psia and 500°F, $v = 1.4924 \, \frac{ft^3}{lbm}$

345 psia	355 psia
v = 1.4924	v = 1.4924
u = 1150.2 Btu/lbm	u = 1159.6 Btu/lbm
T = 489.6 F	T = 510.5 F

$$c_v \approx \left(\frac{1159.6-1150.2 \text{ Btu/lbm}}{970.5-949.6 \text{ R}}\right) = 0.450 \frac{\text{Btu}}{\text{lbm-R}}$$

350 psia	350 psia
495F	505F
$h = 1248.3 \frac{\text{Btu}}{\text{lbm}}$	$h = 1254.7 \frac{\text{Btu}}{\text{lbm-R}}$

$$c_p \approx \frac{(1254.7-1248.3 \text{ Btu/lbm})}{(965-955 \text{ R})} = 0.64 \frac{\text{Btu}}{\text{lbm-R}}$$

Problem *10.9

The specific volume of steam at 620°F is 1.50 ft^3/lbm. Determine the pressure using the ideal gas equation of state, van der Waals equation of state and the Redlich-Kwong equation of state. Compare the results with that found from the steam tables.

Given: The specific volume of steam at a given temperature.

Find: The pressure using the various equations of state and the steam tables.

Assumptions: 1) Steam obeys the appropriate equation of state.

Analysis: Ideal gas law

$$p = \frac{RT}{v} = \frac{(85.77\ \text{ft-lbf/lbm-R})(1080\text{R})}{(1.5\ \text{ft}^3/\text{lbm})(144\ \text{in}^2/\text{ft}^2)} = \underline{428\ \text{lbf/in}^2}$$

Steam tables, superheat region, $p = \underline{403\ \text{lbf/in}^2}$

van der Waals

$$p = \frac{\overline{R}T}{\overline{v}-b} - \frac{a}{\overline{v}^2}$$

$$v_c = 0.568 \frac{\text{m}^3}{\text{kgmol}}$$

$$p_c = 22.09\ \text{MPa}$$

$T = 620\text{F} = 1080\text{R} = 600\text{K}$

$$T_c = 647.3\text{K}$$

$$a = \frac{27\overline{R}^2T_c^2}{64\ p_c} = \frac{(27)(8.3143)^2(647.3)^2}{(64)(22090)} = 553\ (\text{kPa})(\text{m}^6/\text{kgmol}^2)$$

$$b = \frac{RT_c}{8p_c} = \frac{(8.3143)(647.3)}{(8)(22090)} = 0.030\ \text{m}^3/\text{kgmol}$$

$$v = (1.5\ \text{ft}^3/\text{lbm})(0.06243) = 0.0936\ \text{m}^3/\text{kg}$$

$$\overline{v} = Mv = \left(18.015 \frac{\text{kg}}{\text{kgmol}}\right)(0.0936\ \text{m}^3/\text{kg}) = 1.686\ \text{m}^3/\text{kg}$$

$$p = \frac{(8.3143\ \text{kJ/kgmol-K})(600\text{K})}{(1.686-0.030\ \text{m}^3/\text{kgmol})} - \frac{(553\ \text{kPa}(\text{m}^6/\text{kgmol}^2))}{(1.686\ \text{m}^3/\text{kgmol})^2}$$

$p = 2818\ \text{kPa} = \underline{408.7\ \text{lbf/in}^2}$

Redlich-Kwong

$$p = \frac{\overline{R}T}{\overline{v}-b} - \frac{a}{T^{1/2}\overline{v}(\overline{v}+b)}$$

$$a = \frac{0.42748\ \overline{R}^2 T_c^{2.5}}{p_c} = \frac{(0.42748)\left(8.3143\frac{\text{kJ}}{\text{kgmol-K}}\right)(647.3\text{k})^{2.5}}{(22090\text{kN/m}^2)}$$

$a = 1715.2$

$$b = 0.08664\frac{\overline{R}T_c}{p_c} = \frac{(0.08664)\left(8.3143\frac{\text{kJ}}{\text{kgmol-K}}\right)(647.3\text{k})}{(22090\ \text{kN/m}^2)}$$

$b = 0.021$

$$p = \frac{(8.3143)(600\text{K})}{(1.686-0.021)} - \frac{(1715.2)}{(600)^{0.5}(1.686)(1.686+0.021)}$$

$p = 2972\ \text{kPa} = \underline{431}\ \text{lbf/in}^2$

Problem C10.1

For steam from 25°C to 350°C, plot the inverse of the absolute temperature versus the natural log of the absolute pressure (1/T versus in p) using at least 20 data points.

Given: Saturated steam between 25°C and 350°C.

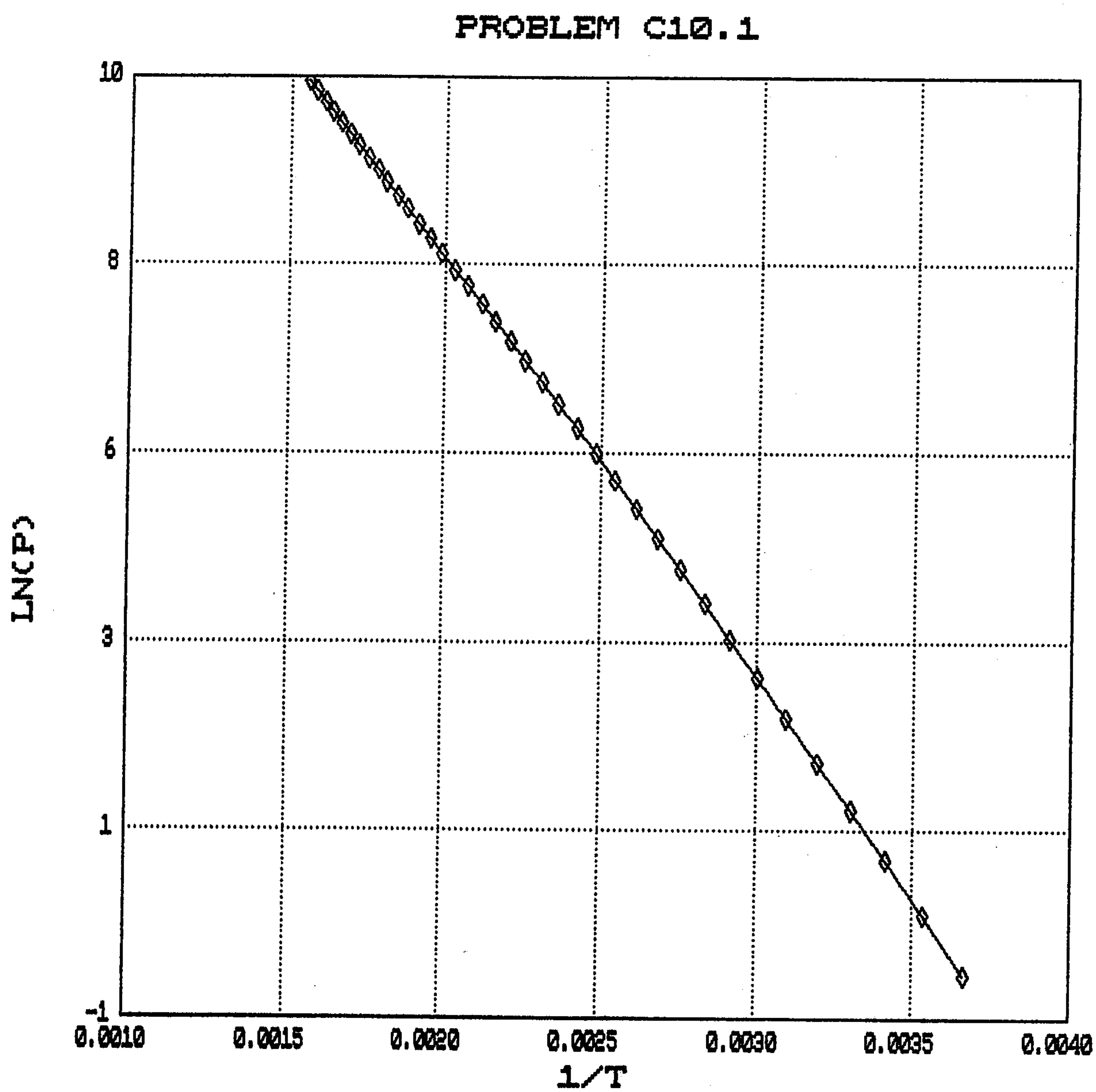
Find: Plot 1/T versus ln p.

Assumptions: 1) The steam is in equilibrium.

Analysis: Using a spreadsheet program, enter saturated pressure and temperature data for Appendix A.5. Enter formulas to convert temperature at degrees Kelvin, compute the inverse of the absolute temperature, and the natural log of the absolute pressure. Use the X-Y graph feature to plot 1/T versus ln p. See the graph which follows.

Comments:
1) Temperature must be converted to absolute.
2) The linear plot of 1/T versus ln p illustrates why equation 10.48 can be used to represent the relationship between saturated temperature and pressure.

	A	B	C	D	E
1	Problem C10.1				
2					
3	T (C)	T (K)	1/T	P	LN(P)
4					
5	0	+A5+273.15	1/B5	0.6106	@LN(D5)
6	+A5+10	+A6+273.15	1/B6	1.2287	@LN(D6)
7	+A6+10	+A7+273.15	1/B7	2.3414	@LN(D7)
8	+A7+10	+A8+273.15	1/B8	4.2505	@LN(D8)
9	+A8+10	+A9+273.15	1/B9	7.389	@LN(D9)
10	+A9+10	+A10+273.15	1/B10	12.355	@LN(D10)
11	+A10+10	+A11+273.15	1/B11	19.946	@LN(D11)
12	+A11+10	+A12+273.15	1/B12	31.196	@LN(D12)
13	+A12+10	+A13+273.15	1/B13	47.404	@LN(D13)
14	+A13+10	+A14+273.15	1/B14	70.169	@LN(D14)
15	+A14+10	+A15+273.15	1/B15	101.33	@LN(D15)
16	+A15+10	+A16+273.15	1/B16	143.38	@LN(D16)
17	+A16+10	+A17+273.15	1/B17	198.7	@LN(D17)
18	+A17+10	+A18+273.15	1/B18	270.34	@LN(D18)
19	+A18+10	+A19+273.15	1/B19	361.64	@LN(D19)
20	+A19+10	+A20+273.15	1/B20	476.3	@LN(D20)


PROBLEM C10.1
LN(P)
10
8
6
3
1
-1
0.0010
0.0015
0.0020
0.0025
0.0030
0.0035
0.0040
1/T

CHAPTER ELEVEN

Problem 11.1

A gaseous mixture has the following volumetric analysis: O_2, 30%; CO_2, 40%; N_2, 30%. Determine (a) the analysis on a mass basis; (b) the partial pressure of each component if the total pressure is 100 kPa and the temperature is 32°C; (c) the molecular weight of the mixture.

Given: The volumetric analysis of a gaseous mixture.

Find: The mass analysis of the mixture, the partial pressure of each component and the mixture molecular weight.

Assumptions: 1) Each component and the mixture behaves as an ideal gas.

Analysis: The mixture molecular weight is $M_{mix} = \sum yi\ Mi$

$$M_{mix} = (0.30)(32) + (0.40)(44.01) + (0.30)(28.016)$$

c) $M_{mix} = \underline{35.61}$ kg/kgmol

The partial pressure, p_i, is

$$p_i = y_i\ p_{total}$$

$$p_{o2} = (0.30)(100\text{ kPa}) = 30\text{ kPa}$$

b) $p_{co_2} = (0.40)(100\text{ kPa}) = 40\text{ kPa}$

$$p_{N_2} = (0.30)(100\text{ kPa}) = 30\text{ kPa}$$

The mass fractions are

$$x_i = \frac{y_i\ M_i}{M_{mix}} = \frac{(\text{kgmol})_i}{(\text{kgmol})_{mix}} \frac{(\text{kgmol})_{mix}}{(\text{kg})_{mix}} \frac{(\text{kg})_i}{(\text{kgmol})_i} = \frac{(\text{kg})_i}{(\text{kg})_{mix}}$$

a) $x_{o_2} = \dfrac{(0.30)(32)}{(35.61)} = 0.270$

$$x_{co_2} = \frac{(0.40)(44.01)}{(35.61)} = 0.494$$

$$x_{N_2} = \frac{(0.30)(28.016)}{(35.61)} = 0.236$$

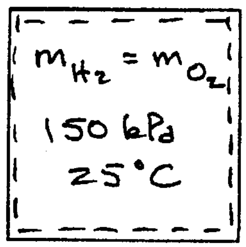
Problem 11.5

Equal masses of hydrogen and oxygen are mixed. The mixture is maintained at 150 kPa and 25°C. For each component determine the volumetric analysis and its partial pressure.

Given: Equal masses of H_2 and O_2 are maintained at 150 kPa and 25°C.

Find: The volumetric analysis and the component partial pressure.

Sketch and Given Data:



Assumptions: 1) Each component and the entire mixture behaves as an ideal gas.

Analysis: Determine the mass fractions of each where

$$x_i = m_i/m_{total}$$

$$x_{H_2} = m/2m = 0.5$$

$$x_{O_2} = 0.5$$

$$R_m = \sum x_i R_i = (0.5)(4.125) + (0.5)(0.2598) = 2.192 \frac{kJ}{kg\text{-}K}$$

$$M_m = \frac{\bar{R}}{R} = \frac{(8.3143 \text{ kJ/kgmol-K})}{(2.192 \text{ kJ/kg-K})} = 3.79 \text{ kg/kgmol}$$

$$y_i = \frac{x_i M_m}{M_i}$$

$$y_{H_2} = \frac{(0.5)(3.79)}{(2.016)} = \underline{0.94}$$

$$y_{O_2} = \frac{(0.5)(3.79)}{(32.0)} = \underline{0.06}$$

The partial pressure, $p_i = y_i \, P_{total}$

$$P_{H_2} = (0.94)(150 \text{ kPa}) = \underline{141 \text{ kPa}}$$

$$P_{O_2} = (0.06)(150 \text{ kPa}) = \underline{9 \text{ kPa}}$$

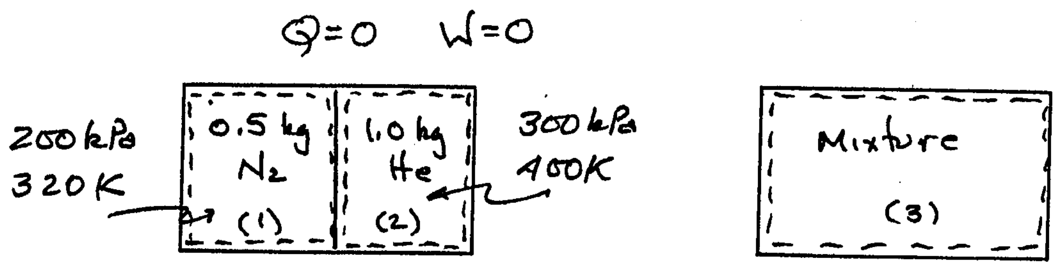
Problem 11.9

A rigid insulated tank, as shown in Figure 11.3, is divided into two sections by a membrane. One side contains 0.5 kg of nitrogen at 200 kPa and 320 K, and the other side contains 1.0 kg of helium at 300 kPa and 400 K. The membrane is removed. Determine (a) the mixture temperature and pressure; (b) the change of entropy for the system; (c) the change of internal energy of the system.

Given: An insulated tank has two compartments, each containing a gas. The membrane separating the compartments is removed.

Find: The mixture temperature and pressure, the system entropy change and the system internal energy change.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) Heat and work are zero.

Analysis: Determine the volume and mixture specific heat.

$$V_1 = \frac{m\,RT_1}{p_1} = \frac{(0.5\text{ kg})(0.2968\text{ kJ/kg-K})(320\text{ K})}{(200\text{ kN/m}^2)} = 0.237\text{ m}^3$$

$$V_2 = \frac{m\,RT_2}{p_2} = \frac{(1.0)(2.077)(400)}{(300)} = 2.769\text{ m}^3$$

$$V_3 = V_1 + V_2 = 0.237 + 2.769 = 3.006\text{ m}^3$$

$$c_{vm} = \sum x_i\,c_{vi} = (0.333)(0.7431) + (0.667)(3.1189) = 2.328\text{ kJ/kg-K}$$

The first law for the system is $Q = \Delta U + \Delta KE + \Delta PE + W$

Apply assumptions 2 and 3.

$$U_{final} = U_{initial} \qquad \text{therefore} \qquad \Delta U = 0.$$

$$U_3 = U_1 + U_2$$

$$M_m\, c_{vm}\, T_3 = m_1\, c_{v1}\, T_1 + m_2\, c_{v2}\, T_2$$

$$(1.5 \text{ kg})(2.328 \text{ kJ/kg-K})(T_3 \text{ K}) = (0.5)(0.7431)(320) + (1.0)(3.1189)(400)$$

$$T_3 = \underline{391.3 \text{ K}}$$

Each gas may be viewed as occupying the total volume by itself at its partial pressure.

$$p_{N_2} = \frac{m\ RT}{V} = \frac{(0.5)(0.2968)(391.3)}{3.006} = 19.3 \text{ kPa}$$

$$p_{He} = \frac{m\ RT}{V} = \frac{(1.0)(2.077)(391.3)}{3.006} = 270.4 \text{ kPa}$$

$$p_{total} = p_3 = 19.3 + 270.4 = \underline{289.7 \text{ kPa}}$$

Find the entropy change for component and add them together.

$$S_3 - S_1 = m\ c_v \ln\left(\frac{T_3}{T_1}\right) + m\ R \ln\left(\frac{V_3}{V_1}\right)$$

$$(S_3 - S_1)_{N_2} = (0.5 \text{ kg})(0.7431 \text{ kJ/kg-K}) \ln\left(\frac{391.3}{320}\right)$$

$$+ (0.5 \text{ kg})\left(0.2968 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{3.006}{0.237}\right)$$

$$(S_3 - S_1)_{N_2} = +0.4517 \text{ kJ/K}$$

$$(S_3 - S_2)_{He} = (1.0)(3.1189) \ln\left(\frac{391.3}{400}\right) + (1.0)(2.077) \ln\left(\frac{3.006}{2.769}\right)$$

$$(S_3 - S_2)_{He} = 0.1020 \text{ kJ/K}$$

$$(\Delta S)_{total} = 0.4517 + 0.1020 = \underline{0.5537} \text{ kJ/K}$$

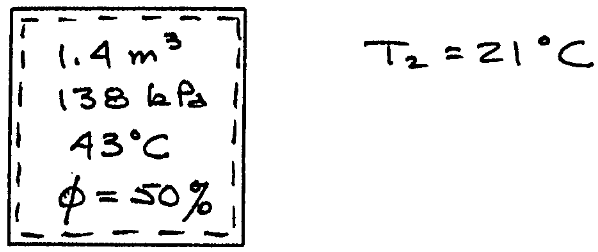
Problem 11.13

An air-water vapor mixture at 138 kPa, 43°C, and 50% relative humidity is contained in a 1.4 m^3. The tank is cooled to 21°C. Determine (a) the mass of water condensed; (b) the partial pressure of water vapor initially; (c) the final mixture pressure; (d) the heat transferred.

Given: An air-water vapor mixture is contained in a tank. The tank is cooled.

Find: The water condensed, the vapor's initial pressure, the final mixture pressure and the heat transferred.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The work is zero.
4) Neglect the volume of the liquid at state 2.

Analysis: Determine the partial pressure of the initial water vapor.

$$p_g = p_{sat} \text{ @ } 43°C = 8.655 \text{ kPa}$$

b) $$p_v = \Phi\, p_g = (0.5)(8.655) = 4.3 \text{ kPa}$$

$$p_{air} = 138 - 4.3 = 133.7 \text{ kPa}$$

$$\omega_1 = 0.622\,\frac{p_v}{p_a} = \frac{(0.622)(4.3)}{(133.7)} = 0.0200\,\frac{\text{kg vapor}}{\text{kg air}}$$

Determine ω_2. Note that the dew point is 30.2°C. Hence at state 2, $p_{v_2} = p_g = p_{sat}$ @ 21°C = 2.5 kPa.

Find the mass of air initially

$$m_a = \frac{pV}{RT} = \frac{(133.7\ kN/m^2)(1.4\ m^3)}{(0.287\ kJ/kg\text{-}K)(316\ K)} = 2.064\ kg$$

At state 2

$$p_{a_2} = \frac{m_a\ RT_2}{V} = \frac{(2.064)(0.287)(294\ K)}{(1.4)} = 124.4\ kPa$$

c) $p_{mix} = 124.4 + 2.5 = \underline{126.9\ kPa}$

$$\omega_2 = \frac{0.622\ p_{v_2}}{p_{a_2}} = \frac{(0.622)(2.5)}{(124.4)} = 0.0125\ \frac{kg\ vapor}{kg\ air}$$

$$m_{leq} = m_a(\omega_1 - \omega_2) = (2.064\ kg\ air)\left(0.020 - 0.0125\ \frac{kg\ vap}{kg\ air}\right)$$

a) $m_{leq} = \underline{0.0155\ kg}$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$Q = U_{final} - U_{initial} = m_a\ c_{va}\ (T_2 - T_1) + m_{v_2}\ u_{g_2} - m_{v_1}\ u_{g_1}$$

$$m_{v_2} = m_a\ \omega_2 = (2.064)(0.0125) = 0.0258\ kg$$

$$m_{v_1} = m_a\ \omega_1 = (2.064)(0.020) = 0.0413\ kg$$

$$u_{g_1} = 2434.4\ kJ/kg \qquad u_{g_2} = 2404.6\ kJ/kg$$

$$Q = (2.064\ kg)\left(0.7176\ \frac{kJ}{kg\text{-}K}\right)(294 - 316\ K)$$

$$+ (0.0258\ kg)(2404.6\ kJ/kg) - (0.0413\ kg)(2434.4\ kJ/kg)$$

d) $Q = \underline{-71.1\ kJ}$

Problem 11.17

A gas mixture has components with the following mass fractions; 50% CO_2, 20% CO, 30% He. The mixture temperature and pressure are 50°C and 150 kPa. Determine the mole fractions, the partial pressure of each component and the mixture gas constant.

Given: The mass analysis of a gas mixture.

Find: The molar analysis of the mixture, the component partial pressure and the mixture gas constant.

Assumptions: 1) Each component and the entire mixture behaves as an ideal gas.

Analysis: The mixture molecular weight is required before determining the molar analysis. Note that $M_m = \bar{R}/R_m$.

$$R_m = \sum x_i R_i = (0.5)(0.1889) + (0.20)(0.2968) + (0.30)(2.077)$$

$$R_m = \underline{0.777} \text{ kJ/kg-K}$$

$$M_m = \frac{(8.3143 \text{ kJ/kgmol-K})}{(0.777 \text{ kJ/kg-K})} = 10.7 \text{ kg/kgmol}$$

$$y_i = \frac{(x_i)(M_m)}{M_i}$$

$$y_{CO_2} = \frac{(0.5)(10.7)}{(44.01)} = 0.122$$

$$y_{CO} = \frac{(0.2)(0.7)}{(28.01)} = 0.076$$

$$y_{He} = \frac{(0.3)(10.7)}{(4.003)} = \frac{0.802}{1.000}$$

The partial pressure, p_i, is $p_i = y_i \, p_{total}$

$$p_{CO_2} = (0.122)(150) = 18.3 \text{ kPa}$$

$$p_{CO} = (0.076)(150) = 11.4 \text{ kPa}$$

$$p_{He} = (0.802)(150) = \frac{120.3}{150.0 \text{ kPa}}$$

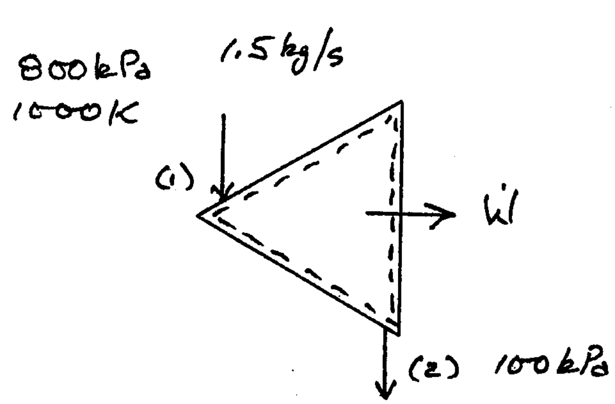
Problem 11.21

A turbine receives 1.5 kg/s of a gas mixture at 800 kPa and 1000 K and expands it to a pressure of 100 kPa isentropically. The mixture molal analysis is 60%F nitrogen, 20% carbon dioxide and 20% water vapor. Determine the exit temperature and the power developed.

Given: A known gas mixture expands isentropically through a turbine. The inlet and exit states are given.

Find: The exit temperature and turbine power.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero and s = c.

Analysis: Determine the mass fraction analysis and the specific heats, c_p, and c_v.

$$M_m = \sum y_i M_i = (0.60)(28.016) + (0.20)(44.01) + (0.20)(18.016)$$

$$M_m = 29.21 \text{ kg/kgmol}$$

$$x_i = \frac{y_i M_i}{M_m}$$

$$x_{N_2} = \frac{(0.6)(28.016)}{(29.21)} = 0.576 \qquad x_{CO_2} = \frac{(0.2)(44.01)}{(29.21)} = 0.302$$

$$x_{H_2O} = \frac{(0.2)(18.016)}{(29.21)} = 0.122$$

$$c_{pm} = \sum x_i\, c_{pi} = (0.576)(1.0399) + (0.302)(0.844) + (0.122)(1.8646)$$

$$c_{pm} = 1.081 \text{ kJ/kg-K}$$

$$c_{vm} = \sum x_i\, c_{vi} = (0.575)(0.7431) + (0.302)(0.6552) + (0.122)(1.4033)$$

$$c_{vm} = 0.796 \text{ kJ/kg-K}$$

$$k = c_{pm}/c_{vm} = \frac{1.081}{0.796} = 1.358$$

For an isentropic process for an ideal gas.

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (1000\text{ K})\left(\frac{100}{800}\right)^{\frac{0.358}{1.358}} = \underline{578°K}$$

The first law for an open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{W} = \dot{m}(h_1 - h_2) = \dot{m}\, c_{pm}(T_1 - T_2)$$

$$\dot{W} = (1.5\text{ kg/s})(1.081\text{ kJ/kg-K})(1000 - 578\text{ K}) = \underline{684.2}\text{ kW}$$

The power may also be found from

$$\dot{W} = \frac{k}{k-1}\, \dot{m}\, RT_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}\right]$$

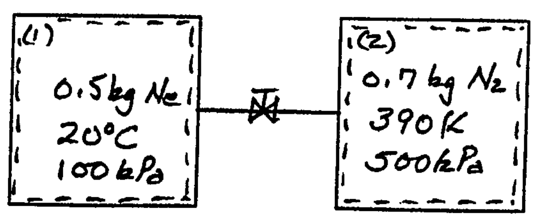
Problem 11.25

0.5 kilograms of neon at 20°C and 100 kPa is contained in an adiabatic tank. Another adiabatic tank contains 0.7 kilograms of nitrogen at 390 K and 500 kPa. A valve connecting the tanks is opened and the gases achieve equilibrium. Determine each tank's volume, the final mixture pressure, the entropy production.

Given: Two adiabatic tanks containing different gases are interconnected.

Find: The tank volumes, the final pressure and the entropy product.

Sketch and Given Data:



$$x_1 = \frac{0.5}{1.2} = 0.417$$

$$x_2 = \frac{0.7}{1.2} = 0.583$$

Assumptions:

1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) Heat and work are zero.
4) The tanks form a closed system.

Analysis: Determine the volume from the ideal gas law.

$$V_1 = \frac{m_1 R_1 T_1}{p_1} = \frac{(0.5\ \text{kg})(0.4120\ \text{kJ/kg-K})(293\ \text{K})}{(100\ \text{kN/m}^2)} = \underline{0.604\ \text{m}^3}$$

$$V_2 = \frac{m_2 R_2 T_2}{p_2} = \frac{(0.7)(0.2968)(390)}{(500)} = \underline{0.162\ \text{m}^3}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$\Delta U = 0 \qquad U_{final} = U_{initial} = U_3 = U_1 + U_2$$

Determine the mixture specific heat and gas constant.

$$c_{vm} = \sum x_i\, c_{vi} = (0.417)(0.6179) + (0.583)(0.7431) = 0.6909 \text{ kJ/kg-K}$$

$$R_m = \sum x_i\, R_i = (0.417)(0.4120) + (0.583)(0.2968) = 0.345 \text{ kJ/kg-K}$$

From $V_3 = U_1 + U_2$ and the ideal gas equation of state for internal energy

$$m_3\, c_{vm}\, T_3 = m_1\, c_{v1}\, T_1 + m_2\, c_{v2}\, T_2$$

$$(1.2 \text{ kg})(0.6909 \text{ kJ/kg-K})(T_3 \text{ K}) = (0.5)(0.6179)(293) + (0.7)(0.7431)(390 \text{ K})$$

$$T_3 = \underline{353.9 \text{ K}}$$

$$p_3 = \frac{m_3\, R_3\, T_3}{V_3} = \frac{(1.2\text{kg})(0.345\text{kJ/kg-K})(353.9 \text{ K})}{(0.766 \text{ m}^3)}$$

$$= \underline{191.3 \text{ kPa}}$$

$$(\Delta S)_{Ne} = m_1\, c_{v_1} \ln\left(\frac{T_3}{T_1}\right) + m_1\, R_1 \ln\left(\frac{V_3}{V_1}\right)$$

$$(\Delta S)_{Ne} = (0.5 \text{ kg})(0.6179 \text{ kJ/kg-K}) \ln\left(\frac{353.9}{293}\right) + (0.5 \text{ kg})\left(0.412 \frac{\text{kJ}}{\text{kg-K}}\right) \ln\left(\frac{0.766}{0.604}\right)$$

$$(\Delta S)_{Ne} = 0.107 \text{ kJ/K}$$

$$(\Delta S)_{N_2} = m_2\, c_{v_2} \ln\left(\frac{T_3}{T_2}\right) + m_2\, R_2 \ln\left(\frac{V_3}{V_2}\right)$$

$$(\Delta S)_{N_2} = (0.7)(0.7431) \ln\left(\frac{353.9}{390}\right) + (0.7)(0.2968) \ln\left(\frac{0.766}{0.162}\right)$$

$$(\Delta S)_{N_2} = 0.272 \text{ kJ/K}$$

$$(\Delta S)_{prod} = \sum \Delta S_i = 0.107 + 0.272 = \underline{0.379} \text{ kJ/K}$$

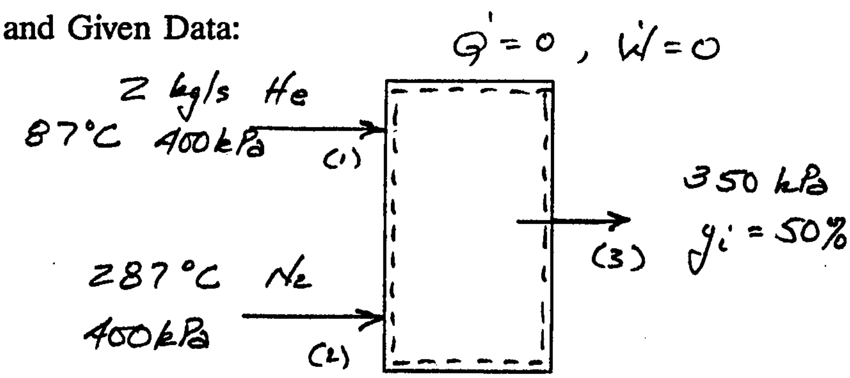
Problem 11.29

2 kg/s Helium flows steadily into an adiabatic mixing chamber at 87°C and 400 kPa and mixes with nitrogen entering at 287°C and 400 kPa. The mixture leaves at 350 kPa and with a molar analysis of 50% helium and 50% nitrogen. Determine the temperature of the mixture leaving the chamber and the rate of entropy production.

Given: Helium flows steadily into a mixing chamber and mixes adiabatically with nitrogen. The molar analysis of the exit stream is specified.

Find: The final mixture temperature and the rate of entropy production.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) Heat and work are zero.

Analysis: Determine mixture properties leaving the chamber.

$$M_m = \sum y_i M_i = (0.5)(4.003) + (0.5)(28.016) = 16.01 \text{ kg/kgmol}$$

$$R_m = \bar{R}/M_m = \frac{(8.3143 \text{ kJ/kgmol-K})}{(16.01 \text{ kg/kgmol})} = 0.519 \text{ kJ/kg-K}$$

$$x_i = \frac{y_i M_i}{M_m}$$

$$x_{He} = \frac{(0.5)(4.003)}{16.01} = 0.125$$

$$x_{N_2} = \frac{(0.5)(28.016)}{(16.01)} = 0.875$$

$$c_{pm} = \sum x_i \, c_{pi} = (0.125)(5.1954) + (0.875)(1.0399) = 1.5593 \ \frac{kJ}{kg-K}$$

The mass flowrate at state 3 is

$$x_{He} = \frac{\dot{m}_1}{\dot{m}_3} = \frac{2 \ kg/s}{\dot{m}_3} = 0.125$$

$$\dot{m}_3 = 16 \ kg/s \quad \therefore \quad \dot{m}_2 = \dot{m}_{N_2} = 14 \ kg/s$$

Perform a first law on the chamber

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2 = \dot{W} + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 2 and 3 and divide by $\dot{m}_3$.

$$x_1 \, c_{p1} \, T_1 + x_2 \, c_p \, T_2 = c_{pm} \, T_3$$

$$(0.125)(5.1954)(360) + (0.875)(1.0399)(560) = (1.5593)(T_3)$$

$$T_3 = 476.7 \ K = 203.7°C$$

$$(p_3)_{He} = (y_{He})(p_{total}) = (0.5)(350 \ kPa) = 175 \ kPa$$

$$(p_3)_{N_2} = (0.5)(350) = 175 \ kPa$$

$$(\Delta s)_{He} = c_p \ln\left(\frac{T_3}{T_1}\right) - R \ln\left(\frac{p_3}{p_1}\right)$$

$$(\Delta s)_{He} = (5.1954 \ kJ/kg-K) \ln\left(\frac{476.7}{360}\right)$$

$$- (2.077 \ kJ/kg-K) \ln\left(\frac{175}{400}\right)$$

$$(\Delta s)_{He} = 3.176 \ kJ/kg\text{-}K$$

$$\dot{m}(\Delta s)_{He} = (\Delta \dot{S})_{He} = (2 \ kg/s)(3.176 \ kJ/kg\text{-}K) = 6.352 \ kW/K$$

$$(\Delta s)_{N_2} = c_p \ln\left(\frac{T_3}{T_2}\right) - R \ln\left(\frac{p_3}{p_2}\right)$$

$$(\Delta s)_{N_2} = (1.0399)\ \ln\left(\frac{476.7}{560}\right) - (0.2968)\ \ln\left(\frac{175}{400}\right)$$

$$(\Delta s)_{N_2} = 0.0779 \text{ kJ/kg-K}$$

$$\dot{m}(\Delta s)_{N_2} = (\Delta\dot{S})_{N_2} = (14 \text{ kg/s})\left(0.0779\ \frac{\text{kJ}}{\text{kg-K}}\right) = 1.091\ \frac{\text{kW}}{\text{k}}$$

$$\Delta\dot{S}_{prod} = \sum_i \Delta S_i = 1.091 + 6.352 = \underline{7.443}\ \frac{\text{kW}}{\text{K}}$$

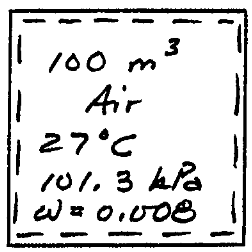
Problem 11.33

A 100 m³ tank contains atmospheric air at 27°C and with a humidity ratio of 0.008 kg vapor/kg air. What mass of water must be removed to lower the relative humidity to 25%?

Given: A tank contains air at a known humidity ratio.

Find: The mass of water vapor which must be removed to lower the relative humidity to 25%.

Sketch and Given Data:



$\phi_2 = 25\%$

Assumptions: 1) Each component and the entire mixture behaves as an ideal gas.

Analysis: Determine the humidity ratio when $\Phi = 25\%$

$$\Phi = \frac{\omega\, p_a}{(0.622)(p_g)} \qquad p_g = p_{sat} \text{ @ } 27°C = 3.57 \text{ kPa}$$

$$p_a = 101.3 - 3.57 = 97.73 \text{ kPa}$$

$$0.25 = \frac{(\omega_2)(97.73)}{(0.622)(3.57)}$$

$$\omega_2 = 0.0057 \text{ kg vapor/kg air}$$

$$m_a = \frac{p_a\, V}{R_a\, T} = \frac{(97.73 \text{ kN/m}^2)(100 \text{ m}^3)}{(0.287 \text{ kJ/kg-K})(300 \text{ K})} = 113.5 \text{ kg}$$

$$m_{water} = m_a(\omega_1 - \omega_2) = (113.5 \text{ kg air})\left(0.008 - 0.0057 \frac{\text{kg vap}}{\text{kg air}}\right)$$

$$m_{water} = \underline{0.261 \text{ kg}}$$

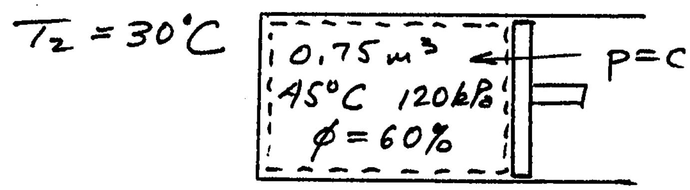
Problem 11.37

A piston/cylinder with an initial volume of 0.75 m³ contains air at 45°C, 120 kPa and 60% relative humidity. The system is cooled at constant total pressure until the air temperature is 30°C. What is the system work and heat transfer?

Given: An air-water vapor mixture is cooled at constant pressure to a final temperature.

Find: The system work and heat transfer.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.

Analysis: Determine the system properties at state 1.

$$p_g \text{ @ } 45°C = 9.6 \text{ kPa} \qquad h_{g_1} = 2583.4 \text{ kJ/kg}$$

$$u_{g_1} = 2437.0 \text{ kJ/kg}$$

$$\Phi = 0.6 = \frac{p_v}{p_g}$$

$$p_{v_1} = (0.6)(9.6) = 5.8 \text{ kPa}$$

$$p_{a_1} = 120 - 5.8 = 114.2 \text{ kPa}$$

$$\omega_1 = \frac{(0.622)p_v}{p_a} = \frac{(0.622)(5.8)}{(114.2)} = 0.0316 \frac{\text{kg vap}}{\text{kg air}}$$

At state 2, p_{sat} @ 30°C = 4.25 kPa $\qquad h_{g_2} = 2556.6$

$$u_{g_2} = 2416.9$$

Since $p_{g_2} < p_{v_1}$, condensation occurred and the air's relative humidity is 100%, $p_{v_2} = p_{g_2} = 4.25$ kPa

$$p_{a_2} = 120 - 4.25 = 115.75 \text{ kPa}$$

$$\omega_2 = \frac{(0.622)(4.25)}{(115.75)} = 0.0228 \text{ kg vap/kg air}$$

The mass of air remains constant and equal to the value at state 1.

$$m_a = \frac{p_{a_1} V_1}{R_a T_1} = \frac{(114.2 \text{ kN/m}^2)(0.75 \text{ m}^3)}{(0.287 \text{ kJ/kg-K})(318 \text{ K})} = 0.938 \text{ kg air}$$

$$m_{v_1} = m_a\omega_1 = (0.938 \text{ kg air})\left(0.0316 \frac{\text{kg vap}}{\text{kg air}}\right) = 0.03 \text{ kg vapor}$$

$$m_{v_2} = m_a\omega_2 = (0.938)(0.0228) = 0.021 \text{ kg vap}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumption 2

$$Q = \Delta U + W$$

and for p = c

$$Q = \Delta H = H_2 - H_1$$

$$H_2 - H_1 = m_a(h_2 - h_1) + m_{v_2} h_2 - m_{v_1} h_1 + m_l(h_{f_2} - h_{f_1})$$

Neglect the last term as being small compared to other terms per Example 11.5.

$$H_2 - H_1 = m_a\, c_p(T_2 - T_1) + m_{v_2} h_{g_2} - m_{v_1} h_{g_1}$$

$$H_2 - H_1 = (0.938\ \text{kg})\left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right)(303 - 318\ \text{K})$$

$$+ (0.021\ \text{kg})\left(2556.6\ \frac{\text{kJ}}{\text{kg}}\right) - (0.03\ \text{kg})(2583.4\ \text{kJ/kg})$$

$$H_2 - H_1 = -37.9\ \text{kJ}$$

$$Q = \underline{-37.9\ \text{kJ}}$$

$$U_2 - U_1 = m_a(u_2 - u_1) + m_{v_2}\, u_{g_2} - m_{v_2}\, u_{g_1}$$

$$U_2 - U_1 = m_a\, c_v(T_2 - T_1) + m_{v_2}\, u_{g_2} - m_{v_2}\, u_{g_1}$$

$$U_2 - U_1 = (0.938)(0.7176)(303 - 318) + (0.021)(2416.9) - (0.03)(2437.0)$$

$$U_2 - U_1 = \underline{-32.5\ \text{kJ}}$$

$$W = Q - \Delta U = -37.9 - (-32.5) = \underline{-5.4\ \text{kJ}}$$

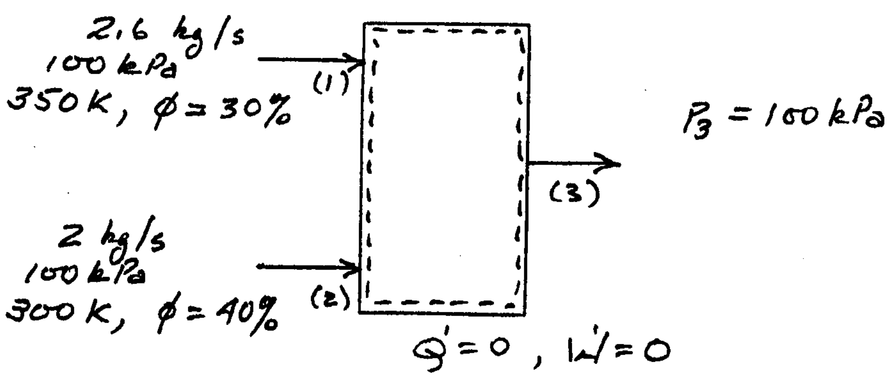
Problem 11.41

2.6 kg/s of air at 100 kPa, 350 K and 30% relative humidity enter a heat exchanger and is mixed with another stream of air with of a flowrate of 2.0 kg/s, a pressure of 100 kPa, a temperature of 300 K and a relative humidity of 40%. Determine the temperature of the exiting mixture.

Given: Two streams of humid air mix in a heat exchanger with one stream leaving.

Find: The temperature of the exiting air.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) Heat and work are zero.

Analysis: Determine the enthalpies of the entering streams where $h = h_a + \omega h_g$

For stream 1, $p_{g_1} = p_{sat}$ @ 350 K = 41.9 kPa

h_{g_1} = 2638.7 kJ/kg

$$p_{v_1} = \Phi_1 p_{g_1} = (0.3)(41.9) = 12.57 \text{ kPa}$$

$$p_a = 100 - 12.57 = 87.43 \text{ kPa}$$

$$\omega_1 = \frac{0.622\, p_{v_1}}{p_{a_1}} = \frac{(0.622)(12.57)}{(87.43)} = 0.0894 \text{ kg vap/kg air}$$

$$h_1 = c_p T_1 + \omega_1 h_{g_1}$$

$$= \left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right)(350 \text{ K}) + \left(0.0894 \frac{\text{kg vap}}{\text{kg air}}\right)\left(2638.7 \frac{\text{kJ}}{\text{kg vap}}\right)$$

$h_1 = 587.5$ kJ/kg air

For stream 2, $p_{g_2} = p_{sat}$ @ 300 K = 3.57 kPa $\qquad h_{g_2} = 2551.1 \frac{kJ}{kg}$

$$p_{v_2} = \Phi_2 \, p_{g_2} = (0.4)(3.57) = 1.4 \text{ kPa}$$

$$p_a = 100 - 1.4 = 98.6 \text{ kPa}$$

$$\omega_2 = \frac{(0.622)(1.4)}{(98.6)} = 0.0088 \text{ kg vap/kg air}$$

$$h_2 = (1.0047)(300) + (0.0088)(2551.1) = 323.9 \text{ kJ/kg air}$$

Find the air and water mass flowrates

$$\dot{m}_{a_1} + \dot{m}_{v_1} = 2.6 \text{ kg/s}$$

$$\dot{m}_{a_1}(1 + \omega_1) = 2.6$$

$$\dot{m}_{a_1}(1.0894) = 2.6 \qquad \dot{m}_{a_1} = 2.386 \text{ kg air/sec}$$

$$\dot{m}_{v_1} = 0.214 \text{ kg vap/sec}$$

$$\dot{m}_{a_2}(1 + \omega_2) = 2.0$$

$$\dot{m}_{a_2}(1.0088) = 2.0 \qquad \dot{m}_{a_2} = 1.982 \text{ kg air/sec}$$

$$\dot{m}_{v_2} = 0.018 \text{ kg vap/sec}$$

$$\dot{m}_{a_3} = \dot{m}_{a_1} + \dot{m}_{a_2} = 2.386 + 1.982 = 4.368 \text{ kg air/sec}$$

$$\dot{m}_{v_3} = \dot{m}_{v_1} + \dot{m}_{v_2} = 0.214 + 0.018 = 0.232 \text{ kg vap/sec}$$

$$\omega_3 = \frac{\dot{m}_{v_3}}{\dot{m}_{a_3}} = \frac{0.232}{4.368} = 0.0531 \text{ kg vap/kg air}$$

$$h_3 = c_p T_3 + \omega_3 h_{g_3}$$

The first law for a steady, open system is

$$\dot{Q} + \dot{m}_1(h + ke + pe)_1 + \dot{m}_2(h + ke + pe)_2 = \dot{W} + \dot{m}_3(h + ke + pe)_3$$

Apply assumptions 2 and 3

$$\dot{m}_1\, h_1 + \dot{m}_2\, h_2 = \dot{m}_3\, h_3$$

$$\dot{m}_{a_1}\, h_1 + \dot{m}_{a_2}\, h_2 = \dot{m}_{a_3} h_3$$

$$(2.386\ \text{kg/s})\left(587.5\ \frac{\text{kJ}}{\text{kg}}\right) + (1.982\ \text{kg/s})(323.9\ \text{kJ/kg}) =$$

$$(4.368)\left[(1.0047\ \text{kJ/kg-K})(T_3\ \text{K}) + (0.0531\ \text{kg vap/kg air})\left(h_{g_3}\ \frac{\text{kJ}}{\text{kg vap}}\right)\right]$$

This requires a trial and error solution. Assume a value of T_3, find h_{g_3} and determine if the equation balances. For the value of $\underline{T_3 = 328\ \text{K}}$ the equation essentially balances.

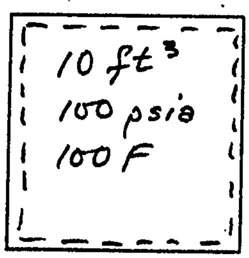
Problem *11.1

A 10-ft^3 tank contains a gas mixture at 100 psia and 100°F. The composition is 40% oxygen and 60% methane on a mass basis. It is desired to have a mixture at 50% oxygen and 50% methane at the same temperature and pressure. How much mixture must be removed and how much oxygen added to achieve this?

Given: A tank contains a mixture of two gases of specified composition. The mixture temperature and pressure remain constant and the final concentration is specified.

Find: The mixture removed and oxygen added to achieve the final result.

Sketch and Given Data:



$x_{O_2} = 40\%$ $\quad$ $x_{CH_4} = 60\%$

$T_2 = T_1$ $\quad$ $P_2 = P_1$ $\quad$ $x_2 = 50\%$

Assumptions: 1) Each component and the entire mixture behaves as an ideal gas.

Analysis: Determine the mixture gas constant.

$$R_m = \sum x_i R_i = (0.40)(48.29) + (0.60)(96.33) = 77.11 \frac{\text{ft-lb}_f}{\text{lbm-R}}$$

$$m_m = \frac{p_1 V_1}{R_m T_1} = \frac{(100 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)(10 \text{ ft}^3)}{\left(77.11 \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(560 \text{ R})} = 3.335 \text{ lbm}$$

The mass of oxygen is $m_{O_2} = (0.4)(3.335) = 1.334$ lbm.

The mixture gas constant at state 2 is

$$R_m = \sum x_i R_i = (0.5)(48.29) + (0.5)(96.33) = 72.31 \frac{\text{ft-lb}_f}{\text{lbm-R}}.$$

$$m_m = \frac{p_2 V_2}{R_m T_2} = \frac{(100)(144)(10)}{(72.31)(560)} = 3.556 \text{ lbm}$$

The mass of oxygen is

$$m_{O_2} = (0.5)(3.556) = 1.778 \text{ lbm}$$

There are (0.6)(3.335) = 2.001 lbm of CH_4 present. This must be reduced to 1.778 lbm by removing mixture. The mixture withdrawn is

$$m_{\substack{mix \\ out}} = \frac{2.001 - 1.778}{0.6} = \underline{0.372 \text{ lbm}}$$

The oxygen withdrawn is

$$(m_{O_2})_{out} = (0.4)(0.372) = 0.149 \text{ lbm}$$

The oxygen remaining is

$$(m_{O_2})_{left} = 1.334 - 0.1488 = 1.185 \text{ lbm}$$

The oxygen added is

$$(m_{O_2})_{add} = 1.778 - 1.185 = \underline{0.593 \text{ lbm}}$$

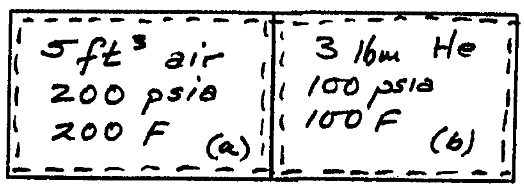
Problem *11.5

Referring to Figure 11.4, let gas a be 5 ft^3 of air at 200 psia and 200°F and gas b be 3 lbm of helium at 100 psia and 100°F. Determine (a) the final mixture temperature and pressure: (b) the entropy production.

Given: A tank has two compartments with gases at known states. The partition between them is removed.

Find: The mixture temperature and pressure and the entropy production.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) Heat and work are zero.

Analysis: Determine the mass of air

$$m = \frac{pV}{RT} = \frac{(200\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(5\ \text{ft}^3)}{\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(660\ \text{R})} = 4.09\ \text{lbm}$$

The mixture mass fractions are

$$x_{air} = \frac{4.09}{7.09} = 0.577 \qquad x_{He} = \frac{3.0}{7.09} = 0.423$$

$$R_m = \sum x_i R_i = (0.577)(53.34) + (0.423)(386) = 194.1\ \frac{\text{ft-lb}_f}{\text{lbm-R}}$$

$$c_{vm} = \sum x_i c_{vi} = (0.577)(0.1714) + (0.423)(0.745) = 0.4140\ \frac{\text{Btu}}{\text{lbm-R}}$$

The first law for a closed system is

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3.

$$\Delta U = 0 \qquad\qquad U_1 = U_2$$

$$m_a\, c_{va}\, T_a + m_b\, c_{vb}\, T_b = m_m\, c_{vm}\, T_m$$

$$(4.09 \text{ lbm})\left(0.1714\ \frac{\text{Btu}}{\text{lbm-R}}\right)(660 \text{ R})$$

$$+ (3 \text{ lbm})\left(0.745\ \frac{\text{Btu}}{\text{lbm-R}}\right)(560 \text{ R})$$

$$= (7.09 \text{ lbm})\left(0.4140\ \frac{\text{Btu}}{\text{lbm-R}}\right)(T_m)$$

$$T_m = \underline{584 \text{ R}}$$

Determine the volume occupied by helium initially.

$$V_b = \frac{m_b\, R_b\, T_b}{p_b} = \frac{(3)(386)(560)}{(100)(144)} = 45.0 \text{ ft}^3$$

$$V_{total} = 45.0 + 5 = 50.0 \text{ ft}^3$$

$$p_m = \frac{m_m\, R_m\, T_m}{V_m} = \frac{(7.09)(194.1)(584)}{(50.0)(144)} = \underline{111.6 \text{ psia}}$$

The entropy production is found from determining the entropy change of each component.

$$(\Delta S)_{air} = m\, c_v \ln\left(\frac{T_m}{T_a}\right) + m\, R \ln\left(\frac{V_m}{V_a}\right)$$

$$(\Delta S)_{air} = (4.09\ \text{lbm})\left(0.1714\frac{\text{Btu}}{\text{lbm-R}}\right)\ \ln\left(\frac{584}{660}\right)$$

$$+\ \frac{(4.09\ \text{lbm})\left(53.34\ \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{(778.16\ \text{ft-lb}_f/\text{Btu})}\ \ln\left(\frac{50.0}{5}\right)$$

$$(\Delta S)_{air} = 0.560\ \frac{\text{Btu}}{\text{R}}$$

$$(\Delta S)_{He} = m\ c_v\ \ln\left(\frac{T_m}{T_b}\right) + m\ R\ \ln\left(\frac{V_m}{V_b}\right)$$

$$(\Delta S)_{He} = (3)(0.745)\ \ln\left(\frac{584}{560}\right) + \frac{(3)(386)}{(778.16)}\ \ln\left(\frac{50}{45}\right)$$

$$(\Delta S)_{He} = 0.0251\ \frac{\text{Btu}}{\text{R}}$$

$$\Delta S_{prod} = 0.251 + 0.560 = \underline{0.811}\ \frac{\text{Btu}}{\text{R}}$$

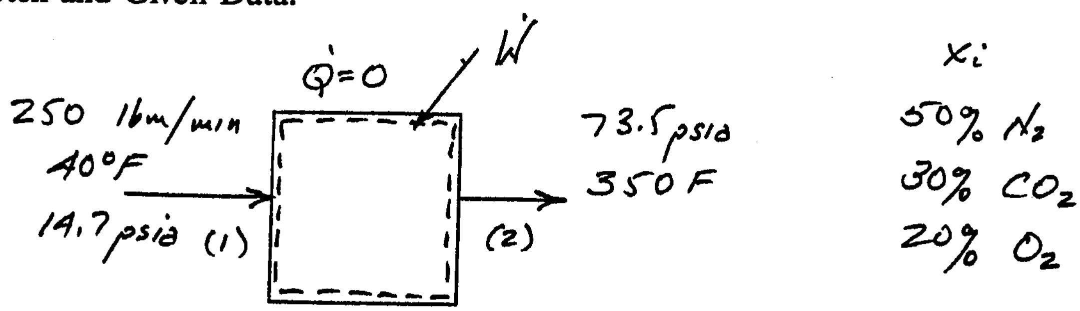
Problem 11.9*

An adiabatic compressor receives 250 lbm/min of a gas mixture and compresses it from 40°F and 14.7 psia to 73.5 psia and 350°F. The mixture's mass fraction analysis is 50% nitrogen, 30% carbon dioxide, and 20% oxygen. Determine the power required and the entropy production.

Given: A known gas mixture is compressed adiabatically from state 1 to state 2.

Find: The power required and the entropy production.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.

Analysis: Determine the mixture specific heat and gas constant.

$$c_{pm} = \sum x_i\, c_{pi} = (0.5)(0.2484) + (0.3)(0.2016) + (0.2)(0.2194)$$

$$c_{pm} = 0.2286 \text{ Btu/lbm-R}$$

$$R_m = \sum x_i\, R_i = (0.5)(55.16) + (0.3)(35.11) + (0.2)(48.29)$$

$$R_m = 47.37\ \frac{\text{ft-lb}_f}{\text{lbm-R}}$$

The first law for a steady, open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3.

$$\dot{W} = \dot{m}(h_1 - h_2) = \dot{m}\, c_{pm}\, (T_1 - T_2)$$

$$\dot{W} = (250 \text{ lbm/min})(0.2286 \text{ Btu/lbm-R})(500 - 810 \text{ R})$$

$$= -17{,}716.5 \frac{\text{Btu}}{\text{min}} = \underline{-417.8 \text{ hp}}$$

The entropy production is (Equation 8.43a)

$$\Delta\dot{S}_{prod} = \dot{m}(s_2 - s_1)$$

$$(s_2 - s_1) = c_{pm} \ln\left(\frac{T_2}{T_1}\right) - R_m \ln\left(\frac{p_2}{p_1}\right)$$

$$(s_2 - s_1) = (0.2286 \text{ Btu/lbm-R}) \ln\left(\frac{810}{500}\right)$$

$$- \frac{\left(47.37 \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{\left(778.16 \dfrac{\text{ft-lb}_f}{\text{Btu}}\right)} \ln\left(\frac{73.5}{14.7}\right)$$

$$(s_2 - s_1) = 0.0123 \frac{\text{Btu}}{\text{lbm-R}}$$

$$\Delta\dot{S}_{prod} = (250 \text{ lbm/min})(0.0123 \text{ Btu/lbm-R}) = \underline{3.075} \frac{\text{Btu}}{\text{min-R}}$$

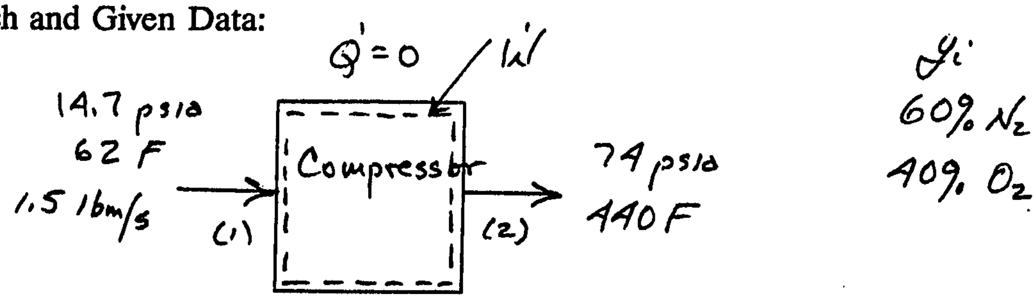
Problem *11.13

1.5 lbm/s of a gas mixture with a molar analysis of 60% nitrogen and 40% oxygen enters an adiabatic compressor at 14.7 psia and 62°F. The discharge pressure and temperature are 74 psia and 440°F. Determine the second law efficiency, the power and the entropy production.

Given: A gas mixture is steadily and adiabatically compressed between two states. The compressor second law efficiency is given.

Find: The exit temperature, the power and the entropy production.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The heat is zero.
4) T_o = 290 K

Analysis: Determine the mixture on a mass basis.

$$M_m = \sum y_i M_i = (0.6)(28.016) + (0.4)(32.0) = 29.61 \text{ lbm/pmol}$$

$$x_i = \frac{y_i M_i}{M_m}$$

$$x_{N_2} = \frac{(0.6)(28.016)}{(29.61)} = 0.568 \qquad x_{O_2} = \frac{(0.4)(32)}{(29.61)} = 0.432$$

$$c_{pm} = \sum x_i c_{pi} = (0.568)(0.2484) + (0.432)(0.2194)$$

$$= 0.2359 \frac{\text{Btu}}{\text{lbm-R}}$$

$$R_m = \sum x_i R_i = (0.568)(55.16) + (0.432)(48.29)$$

$$= 52.19 \frac{\text{ft-lb}_f}{\text{lbm-R}}$$

The second law efficiency is $\eta_2 = (\Psi_2 - \Psi_1)/w_{source}$

$$\Psi_2 - \Psi_1 = (h_2 - h_1) - T_o(s_2 - s_1)$$

$$(h_2 - h_1) = c_{p_m}(T_2 - T_1) = (0.2359 \text{ Btu/lbm-R})(900 - 522 \text{ R})$$

$$= 89.17 \frac{\text{Btu}}{\text{lbm}}$$

$$(s_2 - s_1) = c_{p_m} \ln\left(\frac{T_2}{T_1}\right) - R_m \ln\left(\frac{p_2}{p_1}\right)$$

$$= \left(0.2359 \frac{\text{Btu}}{\text{lbm-R}}\right) \ln\left(\frac{900}{522}\right)$$

$$- \frac{(52.19 \text{ ft-lb}_f/\text{lbm-R})}{\left(778.16 \frac{\text{ft-lb}_f}{\text{Btu}}\right)} \ln\left(\frac{74}{14.7}\right)$$

$$(s_2 - s_1) = 0.0201 \text{ Btu/lbm-R}$$

$$T_o(s_2 - s_1) = (522 \text{ R})(0.0201 \text{ Btu/lbm-R}) = 10.5 \text{ Btu/lbm}$$

$$\Psi_2 - \Psi_1 = (89.17) - (10.50) = 78.67 \text{ Btu/lbm}$$

The first law for an open system is

$$\dot{Q} + \dot{m}(h + ke + pe)_1 = \dot{W} + \dot{m}(h + ke + pe)_2$$

Apply assumptions 2 and 3 and divide by $\dot{m}$.

$$w = (h_1 - h_2) = -89.17\ \frac{\text{Btu}}{\text{lbm}}$$

$$\eta_2 = \frac{78.67}{89.17} = 0.88$$

$$\dot{W} = \dot{m}(h_1 - h_2) = (1.5\ \text{lbm/sec})\left(-89.17\ \frac{\text{Btu}}{\text{lbm}}\right) = \underline{133.75}\ \frac{\text{Btu}}{\text{sec}}$$

$$= \underline{189.3\ \text{hp}}$$

$$\Delta\dot{S}_{prod} = \dot{m}(s_2 - s_1) = (1.5\ \text{lbm/sec})(0.0201\ \text{Btu/lbm-R})$$

$$= \underline{0.03}\ \frac{\text{Btu}}{\text{sec-R}}$$

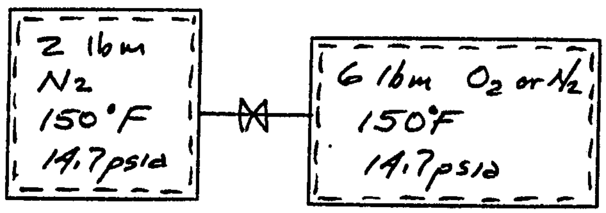
Problem *11.17

Two lbm of nitrogen at 150°F and 14.7 psia mix adiabatically with (a) six lbm of oxygen, (b) six lbm of nitrogen both of which are at the same initial conditions as the two lbm of nitrogen. Determine the entropy production.

Given: 2 lbm of nitrogen at a given state which mixes adiabatically with: (a) 6 lbm of oxygen at the same state: (b) 6 lbm of nitrogen at the same state.

Find: The entropy production.

Sketch and Given Data:



Assumptions: 1) Each component and the entire mixture behaves as an ideal gas.

Analysis: (a) Determine the moles of oxygen and nitrogen in the mixture.

$$n_{N_2} = \left(\frac{2 \text{ lbm}}{28.016 \text{ lbm/pmol}}\right) = 0.0714 \text{ moles}$$

$$n_{O_2} = \frac{6}{32} = 0.1875 \text{ moles}$$

$$y_{N_2} = \frac{n_{N_2}}{n_{total}} = \frac{0.0714}{0.2589} = 0.276$$

$$y_{O_2} = \frac{n_{O_2}}{n_{total}} = \frac{0.1875}{0.2589} = 0.724$$

From Equation 11.13

$$S_2 - S_1 = -\bar{R} \sum_i n_i \ln (y_i)$$

$$(S_2 - S_1) = -\left(\frac{1545\ \dfrac{\text{ft-lb}_f}{\text{pmol-R}}}{(778.16\ \text{ft-lb}_f/\text{Btu})}\right)\Big[(0.0714\ \text{moles})\ \ln\ (0.276) + (0.1875\ \text{moles})\ \ln\ (0.724)\Big]$$

$$(S_2 - S_1) = +0.3027\ \frac{\text{Btu}}{\text{R}}$$

$$\Delta S_{prod} = (S_2 - S_1) = \underline{+0.3027}\ \frac{\text{Btu}}{\text{R}}$$

Case (b) $\Delta S_{prod} = 0$ as there is no distinguishability between the subsystems.

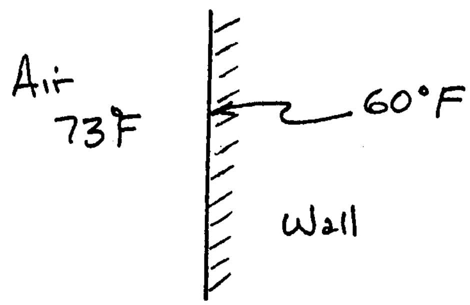
Problem 11.21*

The temperature of the inside surface of a room's exterior wall is 60°F, while the temperature of the air in the room is 73°F. What is the maximum relative humidity the air in the room can have before condensation occurs?

Given: The temperature of a cool surface and the air surrounding it.

Find: The maximum relative humidity before condensation occurs.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) The atmospheric pressure is 14.7 psia.

Analysis: When the dew point of the mixture is 15°C any further increase in relative humidity will cause condensation. From the steam tables

$$p_{sat} \ @ \ 60°F = 0.257 \text{ psia} \qquad p_{sat} \ @ \ 73°F = 0.403 \text{ psia}$$

$$\Phi = \frac{p_v}{p_g} = \frac{0.257}{0.403} = 0.637 \quad \text{or} \quad 63.7\%$$

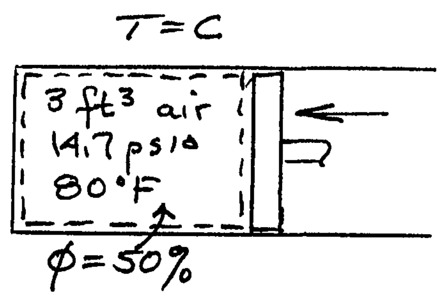
Problem 11.25*

3 ft³ of air at 14.7 psia and 80°F with a relative humidity of 50% are compressed isothermally until condensation of water occurs. At what pressure does the condensation first occur?

Given: Air is compressed isothermally until the dew point is reached.

Find: The total pressure at which condensation occurs.

Sketch and Given Data:



Assumptions:
1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.

Analysis: Determine the humidity ratio at state 1. As the compression occurs, p_a increases while p_g remains constant. From the expression for relative humidity when Φ = 100% condensation first occurs.

At 80°F, $p_g = 0.508$ psia

$$\Phi = 0.5 = \frac{p_v}{p_g} \qquad \therefore \qquad p_v = (0.5)(0.508) = 0.254 \text{ psia}$$

$$p_a = 14.7 - 0.254 = 14.446 \text{ psia}$$

$$\omega_1 = (0.622)\left(\frac{0.254}{14.446}\right) = 0.0109 \text{ lbm vapor/lbm air}$$

The expression for Φ is

$$\Phi = \frac{\omega\, p_a}{(0.622)\, p_g} \qquad \omega_2 = \omega_1$$

$$\Phi_2 = 1.0 = \frac{(0.0109)(p_a)}{(0.622)(0.508)}$$

$$p_a = 29.0 \text{ psia}$$

$$p_t = p_a + p_v = 29.0 + 0.254 = \underline{29.254 \text{ psia}}$$

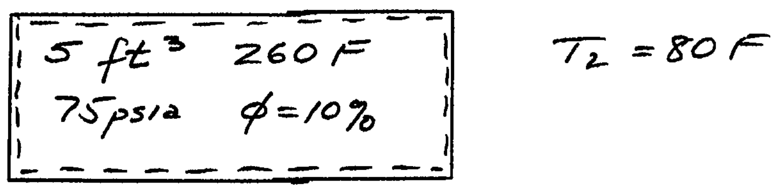
Problem 11.29*

A 5 ft^3 tank contains air at 260°F, 75 psia and with 10% relative humidity. The air is cooled until the temperature is 80°F. Determine the final pressure, the heat transferred and the change of entropy.

Given: A tank contains an air-water vapor mixture at known conditions. The mixture is cooled to a final temperature.

Find: The final pressure, the heat transfer and the entropy change.

Sketch and Given Data:



Assumptions:

1) Each component and the entire mixture behaves as an ideal gas.
2) Neglect changes in kinetic and potential energies.
3) The work is zero as $\mathbf{V}$ = c.

Analysis: Determine the humidity ratios at the initial and final states.

$$p_{g_1} \text{ @ } 260°F = 35.5 \text{ psia} \qquad u_{g_1} = 1090.5 \frac{Btu}{lbm}$$

$$s_{g_1} = 1.6861 \frac{Btu}{lbm\text{-}R}$$

$$p_{v_1} = \Phi_1 \, p_{g_1} = (0.1)(35.5) = 3.55 \text{ psia}$$

$$p_{a_1} = 75 - 3.55 = 71.45 \text{ psia}$$

$$\omega_1 = \frac{0.622 \, p_{v_1}}{p_{a_1}} = \frac{(0.622)(3.55)}{(71.45)} = 0.0309 \frac{lbm \ vap}{lbm \ air}$$

$$m_a = \frac{p_{a_1} V_1}{R_a T_1} = \frac{(71.45 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)(5 \text{ ft}^3)}{\left(53.34 \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)(720 \text{ R})} = 1.34 \text{ lbm air}$$

$$m_{v_1} = \omega_1 m_a = (0.0309)(1.34) = 0.0414 \text{ lbm vapor}$$

At 80°F, $p_{v_2} = p_{g_2} = 0.51$ psia $\qquad u_{g_2} = 1037.1 \dfrac{\text{Btu}}{\text{lbm}}$

$$s_{g_2} = 2.0355 \frac{\text{Btu}}{\text{lbm-R}}$$

$$s_{f_2} = 0.0923 \frac{\text{Btu}}{\text{lbm-R}}$$

For V = C, T/p = c and

$$p_2 = p_1\left(\frac{T_2}{T_1}\right) = (75)\left(\frac{540}{720}\right) = \underline{56.25 \text{ psia}}$$

$$p_{a_2} = 56.25 - 0.51 = 55.74 \text{ psia}$$

$$\omega_2 = \frac{(0.622)(0.51)}{(55.74)} = 0.0057 \text{ lbm vap/lbm air}$$

$$m_{v_2} = m_a\, \omega_2 = (1.34)(0.0057) = 0.0076 \text{ lbm vapor}$$

$$m_l = m_{v_1} - m_{v_2} = 0.0414 - 0.0076 = 0.0338 \text{ lbm}$$

The heat transferred is found from the first law

$$Q = \Delta U + \Delta KE + \Delta PE + W$$

Apply assumptions 2 and 3

$$Q = \Delta U$$

$$U_2 - U_1 = m_a\, c_v\, (T_2 - T_1) + m_{v_2} u_{g_2} - m_{v_1} u_{g_1} + m_l u_{f_2}$$

Neglect $m_l\, u_{f_2}$ as being very small per Example 11.5.

$$U_2 - U_1 = (1.34\ \text{lbm})\left(0.1714\ \frac{\text{Btu}}{\text{lbm-R}}\right)(540\ -\ 720\ \text{R})$$

$$+\ (0.0076\ \text{lbm})\left(1037.1\ \frac{\text{Btu}}{\text{lbm}}\right) - (0.0414\ \text{lbm})(1090.5\ \text{Btu/lbm})$$

$$U_2 - U_1 = -78.61\ \text{Btu}$$

$$Q = \Delta U = -78.61\ \text{Btu}$$

The entropy change is

$$\Delta S = \Delta S_{air} + \Delta S_{H_2O}$$

$$\Delta S_{air} = m_a\, c_p\, \ln\left(\frac{T_2}{T_1}\right) - m_a\, R\, \ln\left(\frac{p_{a_2}}{p_{a_1}}\right)$$

$$\Delta S_{air} = (1.34\ \text{lbm})(0.24\text{Btu/lbm-R})\ \ln\left(\frac{540}{720}\right)$$

$$-\ \frac{(1.34\ \text{lbm})\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{(778.16\ \text{ft-lb}_f/\text{Btu})}\ \ln\left(\frac{55.74}{71.45}\right)$$

$$\Delta S_{air} = -0.0697\ \text{Btu/R}$$

$$\Delta S_{H_2O} = m_{v_2}\, s_{g_2} - m_{v_1}\, s_{g_1} + m_l\, s_{f_2}$$

$$\Delta S_{H_2O} = (0.0076\ \text{lbm})(2.0355\ \text{Btu/lbm-R})$$

$$-\ (0.0414\ \text{lbm})\left(1.6861\ \frac{\text{Btu}}{\text{lbm-R}}\right) + (0.0338\ \text{lbm})\left(0.0923\ \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$\Delta S_{H_2O} = -0.0512\ \text{Btu/R}$$

$$\Delta S = -0.0697 - 0.0512 = -0.1209\ \frac{\text{Btu}}{\text{R}}$$

Problem C11.1

The reading from a sling psychrometer are 90°F dry bulb temperature and 70°F wet bulb temperature. Use PSYCHRO.TK to determine the relative humidity.

Given: Sling psychrometer readings of 90°F dry bulb and 70°F wet bulb.

Find: Relative humidity.

Assumptions: 1) Air-water mixture is in equilibrium.

Analysis: Enter the dry bulb and wet bulb temperatures into PSYCHRO.TK and solve.

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					ENGINEERING THERMODYNAMICS 4/E
					M. David Burghardt & James A. Harbach
					****Psychrometric Chart Model****
	90	DB		degF	Dry Bulb Temperature
	70	WB		degF	Wet Bulb Temperature
		DP	59.705	degF	Dew Point Temperature
		RH	36.358	%	Relative Humidity
		W	.011031	lbm/lbm	Humidity Ratio
		h	33.748	BTU/lbm	Total Enthalpy
		V	14.109	ft3/lbm	Specific Volume of Dry Air
		Pdb	.70434	psia	H2O Partial Pressure @ Dry Bulb Temp.
		Pdp	.25608	psia	H2O Partial Pressure @ Dew Point
	14.696	Pb		psia	Barometric Pressure

CHAPTER TWELVE

Problem 12.1

A fuel mixture of 50% C_7H_{16} and 50%C_8H_{18} is oxidized with 20% excess air. Determine (a) the mass of air required for 50 kg of fuel; (b) the volumetric analysis of products of combustion.

Given: Fuel mixture of 50%C_7H_{16} and C_8H_{18} burned with 20% excess air.

Find: Mass of air required for combustion of 50 kg fuel and volumetric analysis of products.

Assumptions:
1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Writing the reaction for 100% theoretical air and 100 total moles of fuel.

$$50\ C_7H_{16} + 50\ C_8H_{18} + a\ 0_2 + 3.76\ a\ N_2 \rightarrow b\ CO_2 + c\ H_{20}$$

$b = 750 \qquad c = 850 \qquad a = 1175$

Writing the equation for 120% theoretical air.

$$50\ C_7H_{16} + 50\ C_8H_{18} + (1.2)(1175)O_2 + (3.76)(1.2)(1175)\ N_2 \rightarrow$$

$$750\ CO_2 + 850\ H_2O + (3.76)(1.2)(1175)\ N_2 + (.2)(1175)\ O_2$$

$$r_{a/f} = \frac{(1410+5301.6 \text{ mol air})(28.97 \text{ kg/kgmol air})}{[(50)(100)+(50)(114) \text{ kg fuel}]}$$

$= 18.2$ kg air/kg fuel

(a) (50 kg fuel)(18.2 kg air/kg fuel) = 910 kg air

(b) Total moles of product = 750 + 850 + 5301.6 + 235 = 7136.6 mol

$$CO_2 = \frac{750}{7136.6} = 0.105 \qquad H_{20} = \frac{850}{7136.6} = 0.119$$

$$N_2 = \frac{5301.6}{7136.6} = 0.743 \qquad O_2 = \frac{235}{7136.6} = 0.033$$

Problem 12.5

With 110% theoretical air, 1 kgmol of methane is completely oxidized. The products of combustion are cooled and completely dried at atmospheric pressure. Determine (a) the partial pressure of oxygen in the products; (b) the mass in kg of water removed.

Given: Methane oxidized with 110% theoretical air and cooled.

Find: Partial pressure of oxygen and water condensed.

Assumptions:

1) Oxidation is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) Atmospheric pressure is 101.325 kPa.

Analysis: Writing the balanced reaction equation for 100% theoretical air.

$$CH_4 + a\,O_2 + 3.76a\,N_2 \rightarrow b\,CO_2 + c\,H_2O + 3.76\,aN_2$$

$b = 1 \qquad c = 2 \qquad a = 2$

Writing the equation for 110% theoretical air.

$$CH_4 + (1.1)(2)O_2 + (1.1)(3.76)(2)N_2 \rightarrow CO_2 + 2\,H_2O + 8.272\,N_2 + (.1)(2)\,O_2$$

Moles of product (without H_2O) = 1 + 8.272 + .2 = 9.472

(a) $O_2{:}\dfrac{0.2\text{ mol}}{9.472\text{ mol}} = 0.021 \qquad P_{O_2} = (0.021)(101.325\text{ kPa}) = 2.13\text{ kPa}$

(b) 2 moles of H_2O are condensed.

2 mol H_2O = 36 kg

Problem 12.9

The ultimate analysis of a coal sample is 77% C, 3.5% H_2, 1.8% N_2, 4.5% O_2, 0.7% S, 6.5% ash, and 6.0% H_2O. Determine the reaction equation for 120% theoretical air.

Given: Coal with known ultimate analysis is burned in 120% theoretical air.

Find: Reaction air.

Assumptions:
1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Determine the mole fractions of the coal's constituents on an ashless basis. See example 12.3.

	x_i	M_i	x_i/M_i	y_i
C	0.8235	12	0.06863	0.7354
H_2	0.0374	2	0.01870	0.2004
N_2	0.0193	28	0.00069	0.0074
O_2	0.0481	32	0.00150	0.0161
S	0.0075	32	0.00023	0.0025
H_2O	0.0642	18	0.00357	0.0382
	1.0000		0.09332	1.0000

Writing the reaction equation for 100% theoretical air.

$$0.7354C + 0.2004\,H_2 + (0.0161 + a)\,O_2 + (0.0074 + 3.76a)\,N_2$$

$$+ 0.0025S + 0.0382\,H_2O \rightarrow 0.7354\,CO_2 + (0.2004 + 0.0382)\,H_2O$$

$$+ 0.0025\,SO_2 + (0.0074 + 3.76a)\,N_2$$

$$O_2 \text{ balance: } 0.0161 + a = 0.7354 + \frac{(0.2004 + 0.0382)}{2} + 0.0025$$

$$a = 0.8411$$

Writing the reaction equation for 120% theoretical air, i.e.

$$a = (1.2)(0.8411) = 1.0093$$

$$0.7354C + 0.2004\,H_2 + 1.0254\,O_2 + 3.8024\,N_2 + 0.0025S$$
$$+ 0.0382\,H_2O \rightarrow 0.7354\,CO_2 + 0.2386\,H_2O + 0.0025\,SO_2$$
$$+ 3.8024\,N_2 + 0.1682\,O_2$$

Problem 12.13

An adiabatic container has a mixture of oxygen and carbon monoxide in it. Determine whether there is sufficient oxygen for complete combustion if the mixture is 33% O_2 and 67%CO on (a) a mole basis; (b) a mass basis.

Given: Container with 33% O_2 and 67% CO.

Find: If there is sufficient oxygen for complete combustion.

Assumptions: 1) The only product after complete combustion is CO_2.

Analysis: Writing the balanced reaction equation.

$$CO + \frac{1}{2}O_2 \rightarrow CO_2$$

$$\frac{\text{mol } O_2}{\text{mol CO}} = \frac{\frac{1}{2}}{1} = 0.5$$

(a) Actual ratio is $\frac{.33}{.67} = 0.493$ (not quite!)

$$\frac{\text{kg } O_2}{\text{kg CO}} = \frac{16 \text{ kg}}{28 \text{ kg}} = 0.571$$

(b) Actual ratio is $\frac{.33}{.67} = .493$ (No!)

Problem 12.17

Determine the heating value at 25°C and 1 atm of the municipal waste described in Problem 12.16.

Given: Garbage of known ultimate analysis.

Find: Heating value at 25°C and 1 atm.

Assumptions:

1) The products and reactants behave as ideal gases.

2) The nitrogen can be neglected since it appears as a product and reactant and will cancel.

3) The enthalpy of the SO_2 will be neglected.

Analysis: From the definition of heating value.

$$\bar{h}_{RP} = (H_p - H_R)$$

Using balanced equation from problem 12.16 and the enthalpy data from Appendix C.1.

$$H_R = 0 \text{ (all are elements)}$$

For H_2O as a vapor.

$$H_p = (0.7073)(-393\ 757)+(0.2636)(-241\ 971)$$

$$= -342\ 288 \text{ kJ/kgmol}$$

$$\bar{h}_{RP} = \frac{(-342\ 288-0 \text{ kJ/kgmol fuel})}{(9.92 \text{ kg/kgmol})}$$

$$= -34\ 505 \text{ kJ/kg (ashless)}$$

$$= -32\ 469 \text{ kJ/kg (with ash)}$$

Problem 12.21

A residual fuel with a mass analysis of 90%C, 8%H_2, and 2%S is burned with air at 40°C and 50% relative humidity. In addition steam atomization is used, requiring 0.05 kg steam/kg fuel. Determine the dew point of the products.

Given: Residual fuel oil with known ultimate analysis is burned with air at 40°C and 50%RH. Atomizing steam at 0.05 kg/kg air is also supplied.

Find: Dew point.

Assumptions:

1) Combustion is complete with 100% theoretical air; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) The pressure of the products is 101.325 kPa.

Analysis: Writing the reaction equation for 100% theoretical dry air based on 100 kg of fuel.

$$\frac{90}{12}C + \frac{8}{2}H_2 + \frac{2}{32}S + aO_2 + 3.76aN_2 \rightarrow 75\ CO_2$$

$$+ 4\ H_2O + 0.0625\ SO_2 + 3.76aN_2$$

$$O_2\ \text{Balance:}\ a=7.5+\frac{4}{2}+0.0625=9.5625$$

From Appendix B.4(a), at 40°C and 50%RH, the humidity ratio is 0.0235 kg water/kg dry air. The moles of water in the products due to the air humidity is.

$$\frac{[(9.5625)(32)+(3.76)(9.5625)(28)\text{kg air}]\left(0.0235\frac{\text{kg water}}{\text{kg air}}\right)}{(18\ \text{kg/kgmol})}=1.714\ \text{kgmol}$$

Determining the moles of atomizing steam supplied.

$$\frac{(100\ \text{kg fuel})\left(\frac{0.05\ \text{kg water}}{\text{kg fuel}}\right)}{18\ \text{kg/kgmol}}=0.278\ \text{kgmol}$$

$$\text{mol\% } H_2O = \frac{4+1.174+0.278}{7.5+4+0.0625+35.955+1.714+0.278} = 0.121$$

(101.325 kPa)(0.121) = 12.3 kPa

From Table A.6, dew point = 50°C.

Problem 12.25

A fuel C_xH_y burns with air. The products have the following molal analysis on a dry basis: 11%CO_2, 0.5%CO, 2%CH_4, 1.5%H_2, 6%O_2, and 79%N_2. Determine (a) the percentage of excess air; (b) the fuel composition.

Given: A fuel of unknown carbon-hydrogen ratio burns in air producing a given product molal analysis.

Find: Percentage of excess air and fuel composition.

Assumptions:

1) The molal ratio of nitrogen to oxygen for air is 3.76.

2) The products behave like an ideal gas.

Analysis: Writing the reaction equation for 100 moles of dry products.

$$C_xH_y + aO_2 + 3.76aN_2 \rightarrow 11CO_2 + 0.5CO + 2CH_4$$

$$+ 1.5H_2 + 6\,O_2 + 79N_2 + b\,H_2O$$

C balance: $x = 11 + 0.5 + 2 = 13.5$

N_2 balance: $3.76a = 79 \quad a = 21.0$

O_2 balance: $21 = 11 + \frac{0.5}{2} + 6 + \frac{b}{2} \qquad b = 7.5$

H balance: $y = 8 + 3 + 15 = 26$

(b) The fuel is thus $C_{13.5}H_{26}$

Writing the reaction equation for 100% theoretical air.

$$C_{13.5}H_{26} + aO_2 + 3.76aN_2 \rightarrow 13.5\,CO_2 + 13\,H_2O + 3.76aN_2$$

O_2 balance: $a = 13.5 + \frac{13}{2} = 20$

$$\%\text{ theoretical air} = \frac{\text{actual moles } O_2}{\text{theoretical moles } O_2} = \frac{21}{20} = 1.05$$

105% theoretical air = 5% excess air.

Comment: 1. Despite the addition of 5% excess air, the combustion is incomplete as evidenced by the CO, CH_4 and H_2 in the products. This indicates inadequate mixing of the fuel and air.

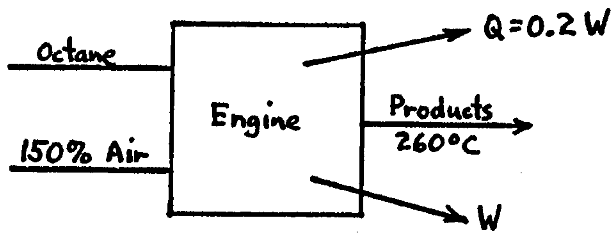
Problem 12.29

An internal-combustion engine uses liquid octane for fuel and 150% theoretical air at 25°C and 100 kPa. The products of combustion leave the engine at 260°C. The heat loss is equal to 20% of the work. Determine (a) the work/kgmol; (b) the dew point; (c) the kg/s of fuel required to produce 400kW.

Given: Internal-combustion engine operating on liquid octane and 150% theoretical air. Exhaust is 260°C and heat loss is 20% of work.

Find: Work, dew point, and fuel flow.

Sketch and Given Data:



Assumptions:

1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) The pressure of the products is 101.325 kPa.

Analysis: Writing the reaction equation, using solution from Problem 12.27.

$$C_8H_{18} + 18.75\ O_2 + 70.5N_2 \rightarrow 8\ CO_2 + 9\ H_2O + 6.25\ O_2 + 70.5\ N_2$$

From Appendix C.1 and C.2,

$$H_R = -250\ 102 \text{ kJ/kgmol fuel}$$

From Appendix C.2, product enthalpy is.

$$H_p = (8)(-393\ 757 + 9833) + (9)(-241\ 971 + 8101) + (6.25)(7130) + (70.25)(6895)$$

$$H_p = -4\ 647\ 286 \text{ kJ/kgmol fuel}$$

First law for the engine.

$$H_R = H_p + W + Q$$

$$-250\ 102 \text{ kg/kgmol} = -4\ 647\ 286 + W + 0.2W$$

(a) $W = 3\ 664\ 320 \text{ kJ/kgmol fuel}$

(b) $P_{H_2O} = (101.325 \text{ kPa})\left(\dfrac{9 \text{ mol } H_2O}{93.5 \text{ mol products}}\right) = 9.8 \text{ kPa}$

From Appendix A.6, dew point = 45.5°C

(c) $\dot{m}f = \dfrac{400\text{kw}}{\left(\dfrac{3\ 664\ 320 \text{ kJ/kgmol}}{114.23 \text{ kg/kgmol}}\right)} = 0.0125 \text{ kg/s}$

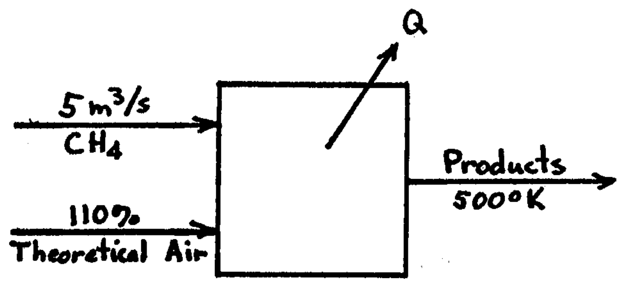
Problem 12.33

Five m^3/s of methane gas enters a furnace at 25°C and 1 atm and burns with 110% theoretical air at the same temperature and pressure. The products leave at 500°K. Determine (a) the air's volumetric flow rate; (b) the heat transfer to the surroundings.

Given: Methane burns with 110% theoretical air with the products leaving the furnace at 500°K.

Find: The air's volumetric flow rate and the heat transfer to the surroundings.

Sketch and Given Data:



Assumptions:

1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) Work is zero and kinetic and potential energies can be neglected.

Analysis: Writing the balanced reaction equation for 100% theoretical air.

$$CH_4 + aO_2 + 3.76aN_2 \rightarrow CO_2 + 2\,H_2O + 3.76aN_2$$

$$O_2 \text{ balance: } a = 1 + \frac{2}{2} = 2$$

(a) Since volume ratio is mole ratio.

$$\frac{5\ m^3/s\ CH_4}{\dot{V}\ Air} = \frac{1\ mol\ CH_4}{2\ mol\ Air} \qquad \dot{V}_{air} = 10\ m^3/s$$

Heat transfer per mole of fuel is.

$$Q = H_p - H_R = \sum_P n_j \bar{h}_j - \sum_R n_i \bar{h}_i$$

H_p = (1)(-393 757 + 8314) + (2)(-241 971 + 6920) + (.2)(6088)

+ (8.272)(5912)

H_p = -805 423 kJ/kgmol fuel

H_R = (1)(-74 871) + 0 + 0 = -74 917 kJ/kgmol fuel

Q = -805 423 - (-74 917) = -730 506 kJ/kgmol fuel

Find fuel flow rate in (kgmol/s) using ideal gas law.

$$p\dot{V} = \dot{n}\bar{R}T$$

$$\dot{n} = \frac{p\dot{V}}{\bar{R}T} = \frac{(101.325\ \text{kPa})(5\ \text{m}^3/\text{s})}{(8.3143\ \text{kJ/kgmol-K})(298°\text{K})} = 0.2045\ \text{kgmol/s}$$

$$\dot{Q} = (-730\ 506\ \text{kJ/kgmol})(0.2045\ \text{kgmol/s}) = -149\ 388\ \text{kW}$$

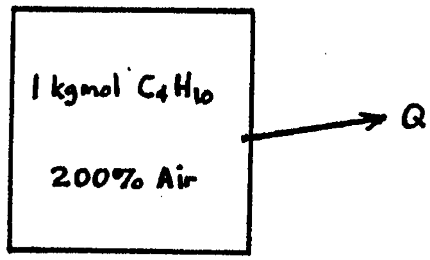
Problem 12.37

A tank contains 1 kgmol of butane and 200% theoretical air at 25°C and 1 atm. Combustion occurs, and heat is transferred from the tank until the products' temperature is 800°K. Determine (a) the heat transfer from the tank; (b) the final pressure of the products in the tank.

Given: The products of combustion of butane and 200% theoretical air are cooled to 800°K.

Find: Heat transfer and final pressure.

Sketch and Given Data:



Assumptions:

1) Combustion is complete; no CO is formed.
2) The products behave like an ideal gas.
3) The molal ratio of nitrogen to oxygen for air is 3.76.
4) The work is zero and kinetic and potential energies can be neglected.

Analysis: Writing the balanced equation for 100% theoretical air.

$$C_4H_{10} + aO_2 + 3.76aN_2 \rightarrow 4\ CO_2 + 5\ H_2O + 3.76aN_2$$

$$O_2 \text{ balance: } a = 4 + \frac{5}{2} = 6.5$$

The first law equation for the constant volume system is.

$$Q = U_P - U_R = \sum_P n_j\bar{u}_j - \sum_R n_i\bar{u}_i$$

where $\bar{u} = \bar{h} - \bar{R}T$

For 200% theoretical air.

$$U_R = (1)[-126\ 223-(8.3143)(298)]+(13.0)[0-(8.3143)(298)]$$
$$+(48.88)[0-(8.3143)(298)]$$
$$= -282\ 018 \text{ kJ/kgmol fuel}$$

$$U_p = (4)[-393\ 757+22\ 815-(8.3143)(800)]$$
$$+(5)[-241\ 971+17\ 991-(8.3143)(800)]$$
$$+(6.5)[15\ 841-(8.3143)(800)]+(48.88)[15\ 046-(8.3143)(800)]$$
$$= -2\ 193\ 466 \text{ kj/kgmol fuel}$$

(a) $Q = -2\ 193\ 466 - (-282\ 018) = -1\ 911\ 448$ kJ/kgmol

(b) $$P_2 = P_1\left(\frac{\text{moles products}}{\text{moles reactants}}\right)\left(\frac{\text{T products}}{\text{T reactants}}\right)$$
$$= 101.325 \text{ kPa}\left(\frac{64.38 \text{ kgmol}}{62.88 \text{ kgmol}}\right)\left(\frac{800°K}{298°K}\right)$$
$$= 278.5 \text{ kPa}$$

Problem 12.41

Determine the adiabatic flame temperature of butane with 100% oxygen if all reactants are at 25°C and 1 atm.

Given: Butane burned in 100% oxygen.

Find: Adiabatic flame temperature.

Assumptions:
1) The products and reactants behave like ideal gases.
2) Combustion is complete; no CO is formed.
3) The heat transfer is zero.
4) No work is done and the changes in kinetic and potential energies may be neglected.
5) No dissociation occurs.

Analysis: The balanced reaction equation is:

$$C_4H_{10} + 6.5\ CO_2 \rightarrow 4\ CO_2 + 5\ H_2O$$

From Appendix C.1.

$$\bar{h}^\circ_f = -126\ 223\ \text{kJ/kgmol}$$

using the TK Solver model COMBUST.TK, cancelling the rules for equilibrium constants and moles of N_2, and entering the data above, zero for x, y and z (no dissociation), zero for moles of N_2, and solving.

$$T_P = 5597°K$$

Comments:
1. See Example 12.11 for hand solution method.
2. The adiabatic flame temperature is significantly higher than for combustion in air because the heat of combustion is absorbed by less mass.

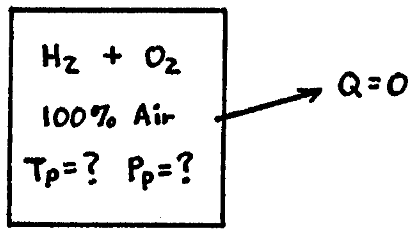
Problem 12.45

Equal moles of hydrogen and carbon monoxide are mixed with theoretical air in an insulated rigid vessel at standard temperature and pressure. The mixture is ignited by a spark. Complete oxidation occurs. Determine (a) the maximum temperature; (b) the maximum pressure.

Given: Hydrogen and carbon monoxide burned in theoretical air in insulated rigid vessel.

Find: Maximum temperature and pressure.

Sketch and Given Data:



Assumptions:

1) The products and reactants behave like ideal gases.
2) Combustion is complete.
3) The molal ratio of nitrogen to oxygen for air is 3.76.
4) No work is done and the changes in kinetic and potential energies may be neglected.
5) No dissociation occurs.

Analysis: Writing the balanced reaction equation.

$$H_2 + CO + O_2 + 3.76N_2 \rightarrow CO_2 + H_2O + 3.76N_2$$

First law; Q = W = 0.

$$U_P = U_R; \quad U = H - \bar{R}T$$

Solving for the reactant internal energies.

$$U_R = 1[0 - (8.3143)(298)] + 1[-110\ 596 + 0 - (8.3143)(298)]$$
$$+ 1[0 - (8.3143)(298)] + 3.76[0 - (8.3143)(298)]$$

$$U_R = -127\ 345 \text{ kJ}$$

The product internal energies are.

$$U_P = 1[-393\ 757+(\bar{h}^\circ-\bar{h}^\circ_{298})_{CO_2}-8.3143T_P]$$
$$+1[-241\ 971+(\bar{h}^\circ-\bar{h}^\circ_{298})_{H_2O}-8.3143T_P]$$
$$+3.76[0+(\bar{h}^\circ-\bar{h}^\circ_{298})_{N_2}-8.3143T_P]$$

(a) Solving by trial-and-error.

$$T_P = 3115°K$$

Solving for the volume based on initial conditions.

$$V=\frac{nRT}{P}=\frac{(6.76)(8.3143)(298)}{(101.325)}=165.3 \text{ m}^3$$

(b) Solving for the final (maximum) pressure.

$$p=\frac{nRT}{V}=\frac{(5.76)(8.3143)(3115)}{(165.3)}=902.5 \text{ kPa}$$

Comments: 1. With some modifications, COMBUST.TK could be used to solve this problem.

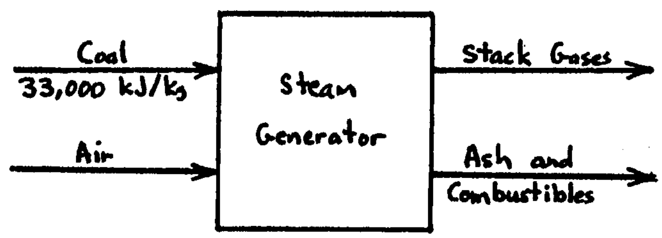
Problem 12.49

A coal-fired steam generating plant was operated for a year with an average flue gas analysis of 13%CO_2, 0%CO, 6.25%O_2, and 10% combustible matter to the ash pit. An attempt to improve efficiency was made, and the second-year average was 15%CO_2, 0.1%CO, and 3.9%O_2, and 16% combustible matter to the ash pit. Coal with a 7% ash content and a heating value of 33000 kJ/kg, dry, was used. At the end of the second year it was found that the efficiency had remained the same, but the cost of operation had increased. Why?

Given: Adjustments made to operation of steam generator burning coal.

Find: Why did cost of operation increase despite no change in efficiency.

Sketch and Given Data:



Assumptions:
1) Steam production each year was the same.
2) Steam outlet and feedwater inlet conditions are the same.

Analysis: Using ORSAT.TK, the excess air for each year is.

Year 1: 41% Year 2: 21.7%

It appears that the improvement due to reduced excess air in Year 2 has been counteracted by losses due to incomplete combustion (CO) and additional combustible matter discharged with the ash. From equation 12.34.

$$\eta_{sg} = \frac{\dot{m}_{stm}\Delta h_{stm}}{\dot{m}_f\, h_{RP}}$$

For constant efficiency, heating value, steam flow, and steam and feedwater conditions, the fuel flow must be same. The greater volume of refuse to be disposed of is one explanation for the increased cost of operation.

Problem 12.53

Compute the adiabatic flame temperature of gaseous methane, ethane, and octane for steady combustion in 100% theoretical air. Compare the resultant temperatures.

Given: Methane, ethane and octane burned in 100% theoretical air.

Find: Adiabatic flame temperature.

Assumptions:
1) The molal ratio of nitrogen to oxygen for air is 3.76.
2) No work is done and the changes in kinetic and potential energies are negligible.
3) Combustion is complete; no dissociation occurs.
4) Temperature of reactants is 298°K.

Analysis: Writing the balanced reaction equation for methane.

$$CH_4 + aO_2 + 3.76aN_2 \rightarrow b\ CO_2 + c\ H_2O + 3.76\ aN_2$$

C balance: $b = 1$
H balance: $c = 2$
O_2 balance: $a = 1 + \left(\frac{1}{2}\right)(2) = 2$

Using Appendices C.1 and C.2, writing $H_R = H_p$ for 1 kgmol fuel.

$$[-74917 + 0 + 0]\ \text{kJ/kgmol} = [-393\,757 + \Delta h(T_p)]$$

$$+ 2[-241971 + \Delta h(T_p)] + 7.52\,[\Delta h(T_p)]\ \text{kJ/kgmol}$$

Solving trial-and-error or using COMBUST.TK.

$$T_p = 2329°K$$

Writing the balanced reaction equation for ethane.

$$C_2H_6 + 3.5\ O_2 + (3.5)(3.76)N_2 \rightarrow 2CO_2 + 3\ H_2O + 13.16N_2$$

Using Appendices C.1 and C.2, writing $H_R = H_p$ for 1 kgmol fuel.

$$[-84\,718 + 0 + 0]\ \text{kJ/kgmol} = 2[-393\,757 + \Delta h(T_p)]$$

$$+ 3[-241\,971 + \Delta h(T_p)] + 13.16\,[\Delta h(T_p)]\ \text{kJ/kgmol}$$

Solving trial-and-error or using COMBUST.TK.

$$T_p = 2382°K$$

Writing the balanced reaction equation for octane.

$$C_8H_{18} + 12.5\ O_2 + (12.5)(3.76)N_2 \rightarrow 8\ CO_2 + 9H_2O + 47N_2$$

Using Appendices C.1 and C.2, writing $H_p = H_R$ for 1 kgmol fuel.

$$[-208\ 581 + 0 + 0]\text{kJ/kmol} = 8[-393\ 757 + \Delta h(T_p)]$$

$$+ 9[-241\ 971 + \Delta h(T_p)] + 47[\Delta h(T_p)]\ \text{kJ/kgmol}$$

Solving trial-and-error or using COMBUST.TK.

$$T_p = 2411°K$$

Problem 12.57

Calculate the percentage of dissociation of oxygen, $O_2 \rightarrow 2O$, at 4000°K and 1 atm pressure.

Given: Dissociation of oxygen at 4000°K and 1 atm.

Find: Percentage of dissociation.

Assumptions: 1) Reactants and products behave like ideal gases.

Analysis: The reaction equation is.

$$O_2 \leftrightarrow 2O$$

If x is fraction dissociated at 4000°K.

$$(1\text{-}x)\, O_2 \leftrightarrow 2xO$$

Total moles at equilibrium = (1-x) + 2x = 1 + x

From Appendix C.4, lnK = 0.783 (K = 2.188)

Partial pressures are thus.

$$P_{O_2} = \frac{(1-x)}{(1+x)} \qquad P_O = \frac{2x}{(1+x)}$$

Therefore.

$$K = \frac{\left(\frac{2x}{1+x}\right)^2}{\left(\frac{1-x}{1+x}\right)} = 2.188$$

Solving for x.

x = .595 (59.5% dissociation)

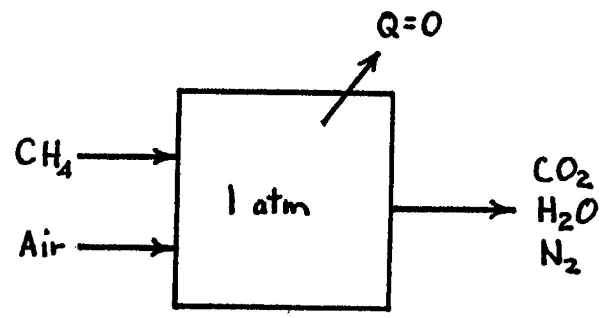
Problem 12.61

Methane enters an adiabatic reactor at 25°C and 1 atm and reacts with air also entering at 25°C and 1 atm. The products leave at 1 atm. Determine the entropy production in kJ/K per kgmol of methane entering.

Given: Adiabatic combustion of methane with air.

Find: Entropy production per kgmol.

Sketch and Given Data:



Assumptions:

1) The combustion is complete.
2) 100% theoretical air is supplied.
3) No work is done and the changes in kinetic and potential energies are negligible.
4) The molal ratio of nitrogen to oxygen for air is 3.76.

Analysis: From Problem 12.53, the balanced reaction equation and adiabatic flame temperature are.

$$CH_4 + 2O_2 + 7.52N_2 \rightarrow CO_2 + 2H_2O + 7.52N_2$$

$$T_p = 2329°K$$

Calculating the entropy production using data from Appendices C.1 and C.2, interpolating as necessary.

$$\Delta S = \sum_P n_j(\bar{s})_j - \sum_R n_j(\bar{s})_j$$

$$\Delta S = [(1)(318.56 + (2)(272.6) + (7.52)(257.59)]$$

$$- [(1)(186.27) + (2)(205.142) + (7.52)(191.611)]$$

$$\Delta S = 763.4 \text{ kJ/kgmol}$$

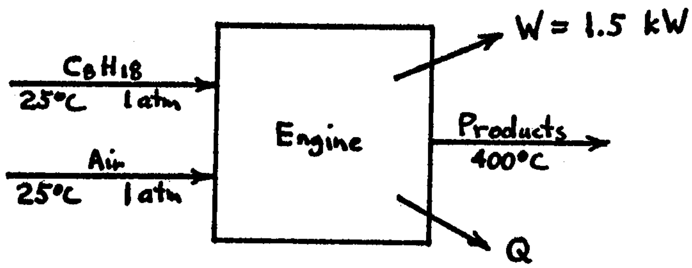
Problem 12.65

A small internal-combustion engine uses liquid octane as the fuel, which enters at 25°C and 1 atm, as does the air. The mass flow rate of the fuel is 0.86 kg/h, the engine develops 1.5 kW, and the products leave at 400°C. The dry molal analysis of the products is 11.4% CO_2, 2.9% CO, 1.6% O_2, and 84.1% N_2. Determine the heat transfer from the engine in kW.

Given: Engine burning 0.86 kg/hr of C_8H_{18} develops 1.5 kw. Products are at 400°C and the dry molal analysis is given.

Find: Heat transfer.

Sketch and Given Data:



Assumptions:

1) The products and reactants behave like ideal gases.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The changes in potential and kinetic energies are negligible.

Analysis: Writing the balanced reaction equation for 100 moles of dry products.

$$aC_8H_{18} + b\,O_2 + 3.76\,b\,N_2 \rightarrow 11.4\,CO_2 + 2.9\,CO$$

$$+ 1.6\,O_2 + 84.1\,N_2 + cH_2O$$

C balance: $8a = 11.4 + 2.9 \qquad a = 1.7875$

N_2 balance: $3.76b = 84.1 \quad b = 22.37$

O_2 balance: $22.37 = 11.4 + \frac{2.9}{2} + 1.6 + \frac{c}{2}$

$$c = 15.84$$

Writing the balanced reaction equation for 1 mole fuel.

$$C_8H_{18} + 12.51\ O_2 + 47.1\ N_2 \rightarrow 6.378\ CO_2 + 1.622\ CO$$

$$+ 0.895\ O_2 + 47.1\ N_2 + 8.862\ H_2O$$

The first law equation for the engine is.

$$\bar{n}_f H_R = \bar{n}_p H_p + W + Q$$

$$H_R = (1)(-250\ 102) + 0 + 0 = -250\ 102 \text{ kJ/kgmol fuel}$$

$$H_p = (6.378)(-393\ 757 + 16\ 543) + (1.622)(-110\ 596 + 11\ 189)$$

$$+ (0.895)(11\ 623) + (47.1)(11\ 115)$$

$$+ (8.862)(-241\ 971 + 13\ 189)$$

$$H_p = -4\ 060\ 656 \text{ kJ/kgmol}$$

$$\bar{n}_f = \frac{(0.86 \text{ kg/h})}{(114.23 \text{ kg/kgmol})(3600 \text{ s/h})} = 2.0913\times10^{-6} \text{ kgmol/s}$$

$$(2.0913 \times 10^{-6})(-250\ 102) = (2.0913 \times 10^{-6})(-4\ 060\ 656) + 1.5 + Q$$

$$Q = 6.47 \text{ kW}$$

Problem 12.69

One kgmol of carbon dioxide dissociates into a mixture of carbon dioxide, carbon monoxide, and oxygen at 2800°K. Determine the equilibrium composition if the mixture pressure is (a) 1 atm; (b) 20 atm.

Given: CO_2 dissociating into CO and O_2 at 2800°K at 1 atm and 20 atm.

Find: Mixture equilibrium composition.

Assumptions: 1) The reactants and products behave like ideal gases.

Analysis: From Appendix C.4, the $\ln(K_p)$ at 2800°K for the reaction $CO_2 \rightarrow CO + 1/2\ O_2$ is -1.900 (K_p = 0.1496). The dissociation reaction is.

$$(1-x)CO_2 \leftrightarrow x\ CO + x/2\ O_2$$

The total number of moles present at equilibrium is.

$$(1-x) + x + \frac{x}{2} = 1 + \frac{x}{2}$$

where $p_{CO_2} = p_{tot}\frac{(1-x)}{(1+x/2)}$

$$K_p = \frac{(p_{CO})(p_{O_2})^{1/2}}{(P_{CO_2})}$$

$p_{CO} = p_{tot}\frac{x}{(1+x/2)}$

$p_{O_2} = p_{tot}\frac{x/2}{(1+x/2)}$

(a) Substituting with p_{tot} = 1 atm and solving for x using trial-and-error or TK Solver.

x = 0.295 (0.295 kgmol CO, 0.147 kgmol O_2, 0.705 kgmol CO_2)

(b) Substituting with p_{tot} = 20 atm and solving for x using trial-and-error or TK Solver.

x = 0.1223 (0.1223 kgmol CO, 0.06115 kgmol O_2, 0.8777 kgmol CO_2)

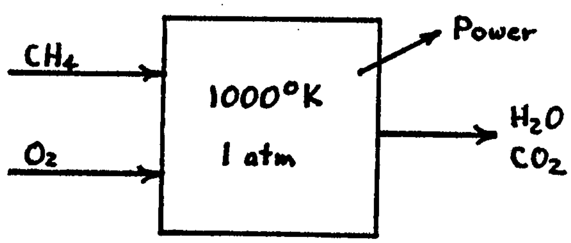
Problem 12.73

Determine the ideal-cell voltage and efficiency for a methane-oxygen fuel cell at 298°K and 1000°K and 1 atm.

Given: Fuel cell oxidizing methane and oxygen at 1000°K and 1 atm.

Find: Ideal-cell voltage and efficiency.

Sketch and Given Data:



Assumptions:

1) Combustion is complete.
2) The water leaves as a vapor.
3) The reactants and products behave like ideal gases.

Analysis: The balanced reaction equation is.

$$CH_4(g) + 2\,O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

Solving for the change in enthalpy and Gibbs function.

$$\Delta H = \sum_P n_j(\bar{h})_j - \sum_R n_i(\bar{h})_i$$

$$\Delta H = [(1)(-393\,757 + 33\,405) + (2)(-241\,971 + 25\,978)]$$

$$-\,[(1)(-74\,917 + (2.1347)(16.043)(1000 - 298) + (2)(22\,707)]$$

$$\Delta H = -786\,876 \text{ kJ/kgmol fuel}$$

$$\Delta G = \Delta H - T_o[\sum n_j\bar{s}_j^\circ - \sum n_i\bar{s}_i^\circ]$$

$$\Delta G = -786\,876 \text{ kg/kgmol} - (1000)[(269.325 + (2)(232.706))$$

$$- (186.27 + (2.1347)(16.043)\left(\ln\left(\frac{1000}{298}\right)\right) + (2)(243.585)]$$

$$\Delta G = -806\ 711 \text{ kJ/kgmol fuel}$$

The fuel cell efficiency is.

$$\eta_{fc} = \frac{\Delta G}{\Delta H} = \frac{-806\ 711 \text{ kJ/kgmol}}{-786\ 876 \text{ kJ/kgmol}} = 1.025(102.5\%)$$

The ideal-cell voltage is.

$$V = \frac{\Delta G}{nF} = \frac{(806\ 711 \text{ kJ/kgmol})}{(4)(96\ 500 \text{ kJ/V-kgmol})} = 2.09 \text{ volts}$$

Comment: Since the enthalpy and entropy for methane are not tabulated in the Appendix, the ideal gas relationships were used. The use of constant specific heat introduces some error.

Problem *12.1

Write the reaction equation for hydrogen with 120% theoretical air. Determine the mass of hydrogen required if 2000 lbm of air is available.

Given: H_2 reacting with 120% theoretical air.

Find: Reaction equation and mass of H_2 with 2000 lbm air.

Assumptions:

1) Combustion is complete.
2) The reactants and products behave like ideal gases.
3) The molal ratio of nitrogen to oxygen for air is 3.76.

Analysis: Writing the balanced reaction equation for 100% theoretical air.

$$H_2 + 0.5\ O_2 + (0.5)(3.76)\ N_2 \rightarrow H_2O + 1.88\ N_2$$

Writing the equation for 120% theoretical air.

$$H_2 + 0.6\ O_2 + 2.256\ N_2 \rightarrow H_2O + 0.1\ O_2 + 2.256\ N_2$$

Solving for the air/fuel ratio.

$$r_{a/f}=\frac{(0.6+2.256\ \text{mol air})(28.97\ \text{lbm/pmol})}{(1\ \text{mol}\ H_2)(2.016\ \text{lbm/pmol})}=41.04\ \text{lbm air/lbm}\ H_2$$

$$m_{H_2}=\frac{2000\ \text{lbm air}}{41.04\ \text{lbm air/lbm}\ H_2}=48.73\ \text{lbm}$$

Problem *12.5

The dry volumetric analysis of the products of the combustion of a hydrocarbon fuel is 13.6%CO_2, 0.8%CO, 0.4%CH_4, 0.4%O_2, and 84.8%N_2. Determine (a) the reaction equation and find the *x* and *n* of the fuel, C_nH_{xn}; (b) find the percentage of excess or deficient air.

Given: Dry volumetric analysis of products of combustion of C_nH_{xn}.

Find: Reaction equation, values of x and n, and percent excess or deficient air.

Assumptions:
1) The reactants and products behave like ideal gases.
2) The molal ratio of nitrogen to oxygen for air is 3.76.

Analysis: Writing the balanced reaction equation for 100 moles of dry product.

$$C_nH_{xn} + aO_2 + 3.76aN_2 \rightarrow 13.6\ CO_2 + 0.8CO + 0.4\ CH_4$$
$$+ 0.4O_2 + 84.8N_2 + b\ H_2O$$

N_2 balance: $3.76a = 84.8 \quad a = 22.55$

O_2 balance: $22.55 = 13.6 + \frac{0.8}{2} + 0.4 + \frac{b}{2}$

$b = 16.3$

C balance: $n = 13.6 + 0.8 + 0.4 \qquad n = 14.8$

H balance: $14.8x = (4)(0.4) + (2)(16.3) \qquad x = 2.31$

(a) $$C_{14.8}H_{34.2} + 22.55\ O_2 + 84.8N_2 \rightarrow 13.6\ CO_2 + 0.8CO$$
$$+ 0.4CH_4 + 0.4\ O_2 + 84.8\ N_2 + 16.3\ H_2O$$

Writing the balanced reaction equation for 100% theoretical air.

$$C_{14.8}H_{34.2} + aO_2 + 3.76aN_2 \rightarrow 14.8\ CO_2 + 17.1\ H_2O + 3.76aN_2$$

O_2 balance: $a = 14.8 + \frac{17.1}{2} \qquad a = 23.35$

Calculating the actual air/fuel ratio.

$$r_{a/f}=\frac{(22.55+84.8)\text{mol air}}{1\text{ mol fuel}}=107.35\text{ mol air/mol fuel}$$

Calculating the theoretical air/fuel ratio.

$$r_{a/f}=\frac{23.35+(3.76)(23.35)\text{mol air}}{1\text{ mol fuel}}=111.15\text{ mol air/mol fuel}$$

$$\%\text{ air}=\frac{107.35\text{ mol air/mol fuel}}{111.15\text{ mol air/mol fuel}}=0.966$$

(b) 3.4% deficient air

Problem *12.9

Garbage, or municipal waste, has an ultimate analysis of 80.5% C, 5.0% H_2, 1.6%S, 1.5% N_2, and 5.5% O_2, with the balance ash. Determine the balanced reaction equation and the mass air/fuel ratio.

Given: Garbage with known ultimate analysis being burned.

Find: Balanced reaction equation and mass air/fuel ratio.

Assumptions:
1) The combustion is complete with theoretical air.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.

Analysis: Determine the mole fractions of garbage's constituents on an ashless basis. See example 12.3

	x_i	M	x_i/M	y_i
C	0.8555	12	0.07129	0.7073
H_2	0.0531	12	0.02657	0.2636
S	0.0170	32	0.00053	0.0053
O_2	0.0584	32	0.00183	0.0181
N_2	0.0159	28	0.00057	0.0056
	1.0000		0.10078	1.0000

Writing the equation for 100% theoretical air.

$$0.7073C + 0.2636\,H_2 + 0.0053S + (0.0181 + a)O_2$$

$$+ (0.0056 + 3.76a)N_2 \rightarrow 0.7073\,CO_2 + 0.2636\,H_2O$$

$$+ 0.0053\,SO_2 + (0.0056 + 3.76a)N_2$$

$$O_2 \text{ balance: } 0.0181 + a = 0.7073 + \frac{0.2636}{2} + 0.0053$$

$$a = 0.8263$$

The balanced equation is thus.

$$0.7073C + 0.2636\ H_2 + 0.0053S + 0.8444\ O_2 + 3.1125\ N_2 \rightarrow$$

$$0.7073\ CO_2 + 0.2636\ H_2O + 0.0053\ SO_2 + 3.1125\ N_2$$

$$r_{a/f}=\frac{(0.8263\ \text{pmol})\left(32\ \frac{\text{lbm}}{\text{pmol}}\right)+(3.76)(0.8263\ \text{pmol})\left(28\ \frac{\text{lbm}}{\text{pmol}}\right)}{(0.7073)(12)+(0.2636)(2)+(0.0053)(32)+(0.0181)(32)+(0.0056)(28)}$$

$$r_{a/f}=11.43\frac{\text{lbm air}}{\text{lbm fuel}}\ \text{(without ash)}$$

$$r_{a/f}=(11.43)(0.941)=10.76\frac{\text{lbm air}}{\text{lbm fuel}}\ \text{(with ash)}$$

Problem *12.13

A residual fuel with a mass analysis of 90%C, 8%H_2, and 2%S is burned with air at 100°F and 50% relative humidity. In addition steam atomization is used, requiring 0.05 lbm steam/lbm fuel. Determine the dew point of the products.

Given: Residual fuel oil with known ultimate analysis is burned with air at 40°C and 50% RH. Atomizing steam at 0.05 lbm/lbm air is also supplied.

Find: Dew point.

Assumptions:

1) Combustion is complete with 100% theoretical air; no CO is formed.
2) The molal ratio of nitrogen to oxygen is 3.76.
3) The products behave like an ideal gas.
4) The pressure of the products is 14.696 psia.

Analysis: Writing the equation for 100% theoretical dry air based on 100 moles of fuel.

$$\frac{90}{12}C + \frac{8}{2}H_2 + \frac{2}{32}S + aO_2 + 3.76aN_2 \rightarrow 7.5\ CO_2 + 4H_2O + 0.0625SO_2 + 3.76aN_2$$

$$O_2 \text{ Balance: } a = 7.5 + \frac{4}{2} + 0.0625 = 9.5625$$

From Appendix B.4(b), at 100°F and 50% RH, the humidity ratio is 0.021 lbm water/lbm dry air. The moles of water in the products due to the air humidity is.

$$\frac{[(9.5625)(32)+(3.76)(9.5625)(28)\ \text{lbm/air}]\left(0.021\ \dfrac{\text{lbm water}}{\text{lbm air}}\right)}{(18\ \text{lbm/pmol})}=1.532\ \text{pmol}$$

Determining the moles of atomizing steam supplied.

$$\frac{(100\ \text{lbm fuel})\left(0.05\dfrac{\text{lbm water}}{\text{lbm fuel}}\right)}{(18\ \text{lbm/pmol})}=0.278\ \text{pmol}$$

$$\text{mol\% } H_2O = \frac{4+1.532+0.278}{7.5+4+0.0625+35.955+1.532+0.278}=0.118$$

$$(14.696 \text{ psia})(0.118) = 1.73 \text{ psia}.$$

From Table A.15, dew point = 121°F.

Problem *12.17

A fuel C_xH_y burns with air. The products have the following molal analysis on a dry basis: 11%CO_2, 0.5% CO, 2% CH_4, 1.5%H_2, 6% O_2, and 79% N_2. Determine (a) the percentage of excess air; (b) the fuel composition.

Given: A fuel of unknown carbon-hydrogen ration burns in air producing a given product molal analysis.

Find: Percentage of excess air and fuel composition.

Assumptions:

1) The molal ratio of nitrogen to oxygen for air is 3.76.
2) The products behave like an ideal gas.

Analysis: Writing the reaction equation for 100 moles of dry products.

$$C_xH_y + a\,O_2 + 3.76aN_2 \rightarrow 11\,CO_2 + 0.5\,CO + 2\,CH_4$$

$$+ 1.5\,H_2 + 6\,O_2 + 79\,N_2 + b\,H_2O$$

C balance: $x = 11 + 0.5 + 2 = 13.5$

N_2 balance: $3.76a = 79 \quad a = 21.0$

O_2 balance: $21 = 11 + \frac{0.5}{2} + 6 + \frac{b}{2} \quad b = 7.5$

H balance: $y = 8 + 3 + 15 = 26$

(b) The fuel is thus $C_{13.5}\,H_{26}$

Writing the reaction equation for 100% theoretical air.

$$C_{13.5}\,H_{26} + aO_2 + 3.76aN_2 \rightarrow 13.5\,CO_2 + 13\,H_2O + 3.76aN_2$$

O_2 balance: $a = 13.5 + \frac{13}{2} = 20$

$$\%\text{ theoretical air} = \frac{\text{actual moles } O_2}{\text{theoretical moles } O_2} = \frac{21}{20} = 1.05$$

105% theoretical air = 5% excess air.

Comment: 1. Despite the addition of 5% excess air, the combustion is incomplete as evidenced by the CO, CH_4 and H_2 in the products. This indicates inadequate mixing of the fuel and air.

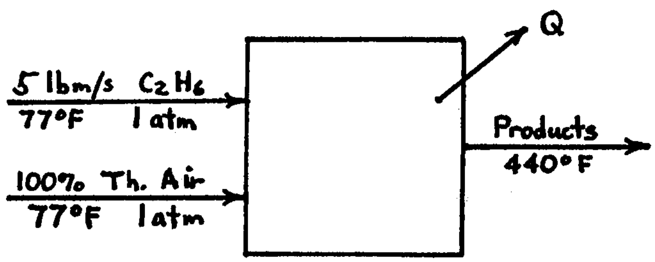
Problem *12.21

Five lbm/sec of ethane gas enters a furnace at 77°F and 1 atm pressure and burns with 100% theoretical air at the same temperature and pressure. The products leave at 440°F. Determine the rate of heat transfer to the surroundings.

Given: Ethane burns with 100% theoretical air, leaving at 440°F.

Find: Heat transferred.

Sketch and Given Data:



Assumptions:

1) The combustion is complete; no CO is formed.
2) The molal ratio of nitrogen to oxygen for air is 3.76.
3) The products behave like an ideal gas.
4) Work is zero and kinetic and potential energies can be neglected.

Analysis: Writing the balanced reaction equation for 1 mole of fuel.

$$C_2H_6 + aO_2 + 3.76aN_2 \rightarrow 2\ CO_2 + 3\ H_2O + 3.76\ aN_2$$

$$O_2 \text{ balance: } a = 2 + \frac{3}{2} = 3.5$$

Heat transfer per mole of fuel is, from First Law.

$$Q = H_p - H_R = \sum_P n_j \bar{h}_j - \sum_R n_j \bar{h}_i$$

$$H_p = (2)(-169{,}297 + 3577) + (3)(-104{,}036 + 2977) + (13.16)(2543)$$

$$H_p = -601{,}151 \text{ Btu/pmol fuel}$$

$H_R = (1)(-36{,}425) + 0 + 0 = -36{,}425$ Btu/pmol fuel

$Q = -601{,}151 - (-36{,}425) = -564{,}726$ Btu/pmol fuel

$$\dot{n}_f = \frac{5 \text{ lbm/s}}{30.07 \text{ lbm/pmol}} = 0.1663 \text{ pmol/s}$$

$\dot{Q} = (-564{,}726$ Btu/pmol fuel$)(0.1663$ kgmol fuel/s$)$

$\dot{Q} = -93{,}914$ Btu/s

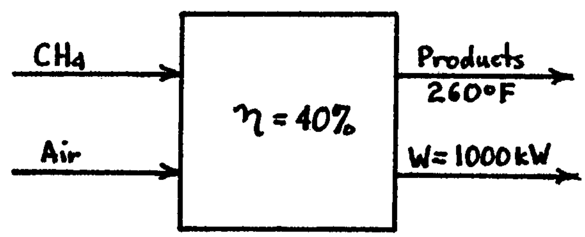
Problem *12.25

A power plant operates with an overall efficiency of 40%. The plant uses methane as the fuel and air, both at 77°F and 1 atm. The products of combustion of the steam generator leave at 260°F. Determine the mass flow rate of methane per 1000 kW of power produced.

Given: Power burning methane has 40% overall efficiency.

Find: Mass flow rate of methane per 1000kW of net power.

Sketch and Given Data:



Assumption: 1) Overall efficiency is based on higher heating value and includes loss due to products leaving at 400°K.

Analysis: From definition of thermal efficiency.

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_{net}}{\dot{m}_f\, h_{RP}}$$

With higher heating value from Appendix C.3.

$$\dot{m}_f = \frac{W_{net}}{\eta_{th} h_{RP}} = \frac{(1000\ \text{kW})\left(\frac{1\ \text{Btu/s}}{1.0551\ \text{kW}}\right)}{(0.40)(23{,}861\ \text{Btu/lbm})}$$

$$= 0.0993\ \text{lbm/s}$$

$$U_p = (2)[-169{,}297 + 5557 - (1.986)(1080)]$$

$$+ (2)[-104{,}036 + 4516 - (1.986)(1080)]$$

$$U_p = -535{,}100 \text{ Btu/pmol}$$

$$Q = -535{,}100 - 18{,}227 = -553{,}327 \text{ Btu/pmol fuel}$$

Problem *12.29

Determine the heating value at 77°F and 1 atm of the municipal waste described in Problem *12.9.

Given: Garbage of known ultimate analysis.

Find: Heating value at 77°F and 1 atm.

Assumptions:

1) The products and reactants behave as ideal gases.

2) The nitrogen can be neglected since it appears as a product and reactant and will cancel.

3) The enthalpy of the SO_2 will be neglected.

Analysis: From the definition of heating value.

$$\bar{h}_{RP} = (H_P - H_R)$$

Using balanced equation from problem *12.9 and the enthalpy data from Appendix C.1.

$$H_R = 0 \text{ (all are elements)}$$

For H_2O as a vapor.

$$H_P = (0.7073)(-169{,}297) + (0.2636)(-104{,}036)$$

$$= -147{,}168 \text{ Btu/pmol fuel}$$

$$\bar{h}_{RP} = \frac{(-147{,}168 - 0 \text{ Btu/pmol fuel})}{(9.92 \text{ lbm/pmol})}$$

$$= -14{,}835 \text{ Btu/lbm (ashless)}$$

$$= -13{,}960 \text{ Btu/lbm (with ash)}$$

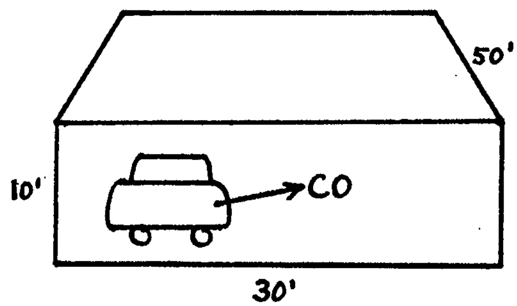
Problem *12.33

The exhaust from an automoblile engine is the same as in Problem *12.5. The engine consumes 15 lbm/hr of fuel and is located in a garage with dimensions 10 x 30 x 50 ft. If a concentration of 1 part carbon monoxide to 100,000 parts air is hazardous to human life and the surroundings remain at 77°F and 1 atm, what is the maximum time the engine can safely run?

Given: Engine exhausting into 10 x 30 x 50 ft. garage.

Find: Time engine runs for CO concentration of 1 part in 100,000.

Sketch and Given Data:



Assumptions:

1) All CO produced by engine is retained in the garage.
2) The garage remains at 1 atm and 77°F.
3) Total mass in the garage doesn't change.

Analysis: From Problem *12.5, $r_{a/f}$ = 107.35 mol air/mol fuel

$$r_{a/f} = \frac{(107.35)(28.97)}{(12)(14.8)+(1)(34.2)} = 14.68 \text{ lbm air/lbm fuel}$$

Using ideal gas law to find mass of air in garage.

$$m = \frac{pV}{RT} = \frac{(14.696 \text{ psia})(144 \text{ in}^2/\text{ft}^2)(10 \text{ ft})(30 \text{ ft})(50 \text{ ft})}{(53.34 \text{ ft-lbf/lbm-R})(537°\text{R})} = 1108 \text{ lbm}$$

From Problem *12.5, 0.8 mol CO is produced per mol fuel.

$$r_{CO/fuel} = \frac{(0.8 \text{ pmol})(28 \text{ lbm/pmol})}{(1 \text{ pmol})(211.8 \text{ lbm/pmol})} = 0.1058 \text{ lbm CO/lbm fuel}$$

Mass of CO required for hazardous concentration.

$$(1108 \text{ lbm air})\left(\frac{1}{100{,}000}\right) = 0.01108 \text{ lbm CO}$$

Time to produce mass of CO.

$$(15 \text{ lbm fuel/hr})(0.1058 \text{ lbm CO/lbm fuel})(t) = 0.01108 \text{ lbm CO}$$

$$t = 0.006982 \text{ hr} = 25.1 \text{ secs.}$$

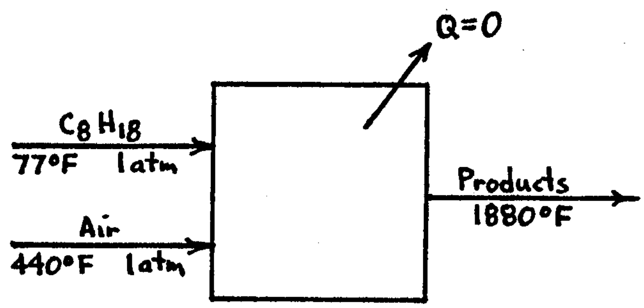
Problem *12.37

Liquid octane at 77°F and 1 atm steadily enters an adiabatic combustion chamber and burns with air at 440°F and 1 atm. The products leave at 1880°F. Determine the percentage of excess air supplied.

Given: Liquid octane burned adiabatically with 440°F air results in products at 1880°F.

Find: Percent excess air.

Sketch and Given Data:



Assumptions:

1) The products and reactants behave like ideal gases.

2) Combustion is complete; no CO is formed.

3) The molal ratio of nitrogen to oxygen for air is 3.76.

4) No work is done and the changes in kinetic and potential energies may be neglected.

5) No dissociation occurs.

Analysis: Writing the balanced reaction equation for 100% theoretical air.

$$C_8H_{18} + aO_2 + 3.76\ aN_2 \rightarrow 8\ CO_2 + 9\ H_2O + 3.76aN_2$$

$$O_2 \text{ balance: } a = 8 + \frac{9}{2} = 12.5$$

Using COMBUST.TK, cancelling the Rules for the equilibrium constants, and entering zero for x, y, z, the product and reactant temperatures, and the theoretical moles of CO_2, H_2O, and solving

$$\%ThO_2 = 307.307\% \text{ (207.3\% Excess Air)}$$

Comment: 1. A solution by hand will be trial-and-error, guessing the excess air until the enthalpy of the products equals the enthalpy of the reactants.

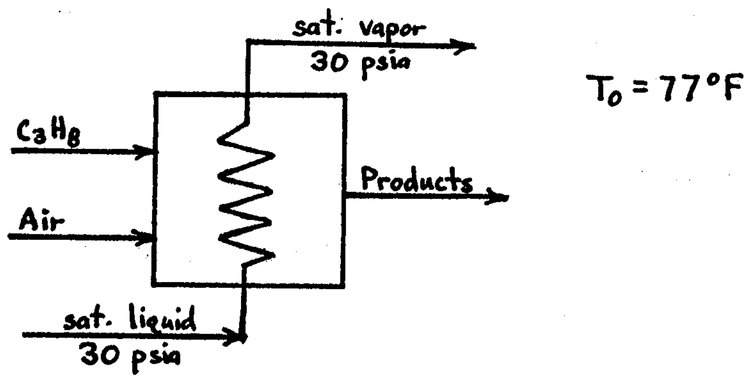
Problem *12.41

A mixture of gaseous propane and 150% theoretical air enters a furnace at 77°F and 1 atm. Complete combustion occurs, and the products exit at 1340°F and 1 atm. The furnace is water-cooled, with water entering as a saturated liquid at 30 psia and leaving as a saturated vapor at the same pressure. Determine (a) the mass flow rate of water per pmol of fuel; (b) the rate of entropy production per pmol of fuel; (c) the irreversiblity rate per pmol of fuel if T_o = 77°F.

Given: Propane burned with 150% theoretical air, boiling water at 30 psia. Combustion products leave at 1340°F and 1 atm.

Find: Mass flow of water, entropy production, and the irreversibility.

Sketch and Given Data:



Assumptions:

1) The molal ratio of nitrogen to oxygen for air is 3.76.

2) The reactants and products behave like ideal gases.

3) No work is done and the changes in potential and kinetic energies may be neglected.

4) All energy removed from the combustion products results in boiling water.

Analysis: The balanced reaction equation is.

$$C_3H_8 + (1.5)(5)\ O_2 + (1.5)(5)(3.76)N_2 \rightarrow 3\ CO_2$$

$$+\ 4\ H_2O + 2.5\ O_2 + 28.2\ N_2$$

The first law equation is.

$$H_P - H_R = \dot{m}_{H_2O} h_{fg}$$

With enthalpy data from Appendices C.1, C.2 and A.15.

$$H_p=\sum_P n_j(\bar{h})_j=(3)(-169{,}297+14{,}371)+(4)(-104{,}036+11{,}176)$$

$$+(2.5)(9769)+(28.2)(9232)$$

$$H_p=-551{,}453 \text{ Btu/pmol fuel}$$

$$H_R=\sum_R n_j(\bar{h})_j=(1)(-44{,}676)+0+0=-44{,}676 \text{ Btu/pmol}$$

$$h_{fg}=945.41 \text{ Btu/lbm}$$

Solving for $\dot{m}_{H_2O}$.

$$\dot{m}_{H_2O}=\frac{H_p-H_R}{h_{fg}}=\frac{(551{,}453-44{,}676 \text{ Btu/pmol fuel})}{(945.41 \text{ Btu/lbm})}$$

(a) $\dot{m}_{H_2O}=536$ lbm/pmol fuel

Solving for the entropy production.

$$\Delta S_{prod}=\sum_P n_j\bar{s}_j-\sum_R n_i\bar{s}_i+\dot{m}_{H_2O}s_{fg}$$

$$\Delta S_{prod}=[(3)(64.344)+(4)(55.592)+(2.5)(58.192)$$

$$+(28.2)(54.507)]-[(1)(64.51)+(7.5)(49.004)$$

$$+(28.2)(45.77)]+(536)(1.3317)$$

(b) $\Delta S_{prod}=1089$ Btu/pmol fuel-K

The irreversibility is calculated from.

$$I = T_o\,(\Delta S_{prod})$$

$$I = (537)(1089) = 584{,}793 \text{ Btu/pmol fuel}$$

Problem *12.45

Determine the higher and lower heating values of coal at 77°F and 1 atm, given the following mass analysis; 49.8%C, 19.4% ash, 14.1% H_2O, 6.8% O_2, 6.4%S, and 3.5% H_2.

Given: Coal with given mass analysis.

Find: Higher and lower heating values.

Assumptions:
1) The reactants and products behave like ideal gases.
2) The combustion is complete; no CO is formed.
3) The water in the coal is a liquid.
4) The sulphur reacts to form SO_2.
5) The enthalpy of formation for SO_2 is -127,725 Btu/pmol.
6) The ash is inert.

Analysis: Since the reactants and products are both at 537°R, the enthalpies of all elements are zero and the ash can be ignored. The only reactant that must be considered is thus the H_2O, and the only products are the CO_2, H_2O and SO_2.

Determining the enthalpy of the reactants per lbm of coal.

$$H_R = n_{H_2O}\bar{h}^\circ_{f_{H_2O(l)}} = \left(\frac{0.141\ \text{lbm/lbm}}{18\ \text{lbm/pmol}}\right)(-122{,}971\ \text{Btu/pmol})$$

$$= -970\ \text{Btu/lbm coal}$$

Determining the enthalpy of the products per lbm of coal with water as a liquid.

$$H_p = n_{CO_2}\bar{h}^\circ_{f_{CO_2}} + n_{H_2O}\bar{h}^\circ_{f_{H_2O(l)}} + n_{SO_2}\bar{h}^\circ_{f_{SO_2}}$$

$$H_p=\left(\frac{0.498\ \text{lbm}}{12\ \text{lbm/pmol}}\right)(-169{,}297\ \text{Btu/pmol})$$

$$+\left[\frac{0.141}{18\ \text{lbm/pmol}}+\frac{0.035\ \text{lbm}}{2\ \text{lbm/pmol}}\right](-122{,}971\ \text{Btu/pmol})$$

$$+\left(\frac{0.064\ \text{lbm}}{32\ \text{lbm/pmol}}\right)(-127{,}725\ \text{Btu/pmol})$$

$$H_p=-10{,}397\ \text{Btu/lbm coal}$$

The higher heating value is thus.

$$\bar{h}_{RP}=H_p-H_R=-10{,}397+970+2538=-9{,}427\text{Btu/lbm coal}$$

Recalculating H_p with the enthalpy of water as a vapor.

$$H_p = 9{,}917\ \text{Btu/lbm coal}$$

The lower heating value is thus.

$$\bar{h}_{RP}=H_p-H_R=-8{,}947\ \text{Btu/lbm coal}$$

Problem *12.49

In an internal-combustion engine the local flame temperature in the combustion process reaches 5040°R. Determine the composition of the dissociation reaction $0.5N_2 + 0.5\ O_2 \leftrightarrow NO$ at a pressure of 1 atm.

Given: Dissociation of N_2 and O_2 into NO at 5040°R and 1 atm.

Find: Mixture equilibrium composition.

Assumptions: 1) The reactants and products behave like ideal gases.

Analysis: From Appendix C.4, the $\ln(K_p)$ at 2800°K (5040°R) for the reaction $\frac{1}{2}N_2 + \frac{1}{2}O_2 \leftrightarrow NO$ is -2.372 ($K_p = 0.0933$). The dissociation reaction is.

$$\left(\frac{1}{2}-\frac{x}{2}\right)N_2+\left(\frac{1}{2}-\frac{x}{2}\right)O_2\rightarrow xNO$$

The total moles present at equilibrium are.

$$\left(\frac{1}{2}-\frac{x}{2}\right)+\left(\frac{1}{2}-\frac{x}{2}\right)+x=1$$

$$K_p=\frac{(p_{NO})}{(p_{O_2})^{1/2}(p_{N_2})^{1/2}} \quad \text{where} \quad p_{NO}=x$$

$$p_{O_2}=\left(\frac{1}{2}-\frac{x}{2}\right)$$

$$p_{N_2}=\left(\frac{1}{2}-\frac{x}{2}\right)$$

Substituting and solving for x using trial-and-error or TK Solver.

$x = 0.0446$ (0.0446 pmol NO, 0.4777 pmol N_2,
0.4777 pmol O_2)

Problem C12.1

Methane is being burned in air. The excess air is varied from 0 to 100% in steps. Use ORSAT.TK (or develop a spreadsheet template or computer program) to calculate the percentage of carbon dioxide and oxygen in the combustion products. Plot the results versus percentage of excess air.

Given: Methane burned in varying percentages of excess air.

Find: Percent CO_2 and O_2 in products.

Assumptions:
1) The products and reactants behave like ideal gases.
2) The combustion is complete; no CO is formed.
3) The molal ratio of nitrogen to oxygen for air is 3.76.

Analysis: Using ORSAT.TK, entering zero for CO%, and S, N, O and Ash. Since methane is CH_4.

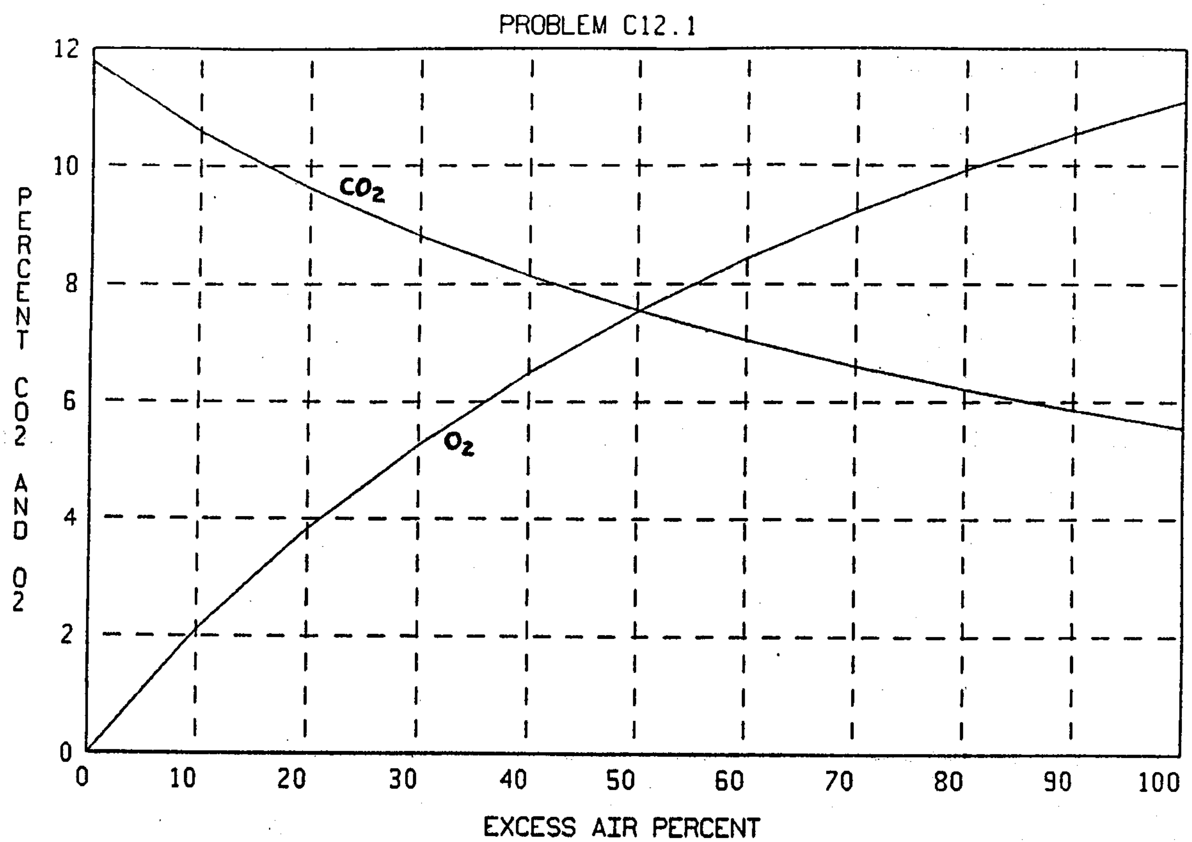
$$C=\frac{12\ kgC}{16\ kg\ CH_4}=0.75 \qquad H=\frac{4\ kg\ H}{16\ kg\ CH_4}=0.25$$

With ExAir% as an input list, and CO2% and O2% as output lists.

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					ENGINEERING THERMODYNAMICS 4/E
					M. David Burghardt & James A. Harbach
					ORSAT ANALYSIS
					Fuel Ultimate Analysis
	.75	C		kg/kg	Carbon
	.25	H		kg/kg	Hydrogen
	0	S		kg/kg	Sulfur
	0	N		kg/kg	Nitrogen
	0	O		kg/kg	Oxygen
	0	Ash		kg/kg	Ash
					Orsat Analysis - Dry Basis
L		CO2%	11.774	%	Carbon Dioxide
L		O2%	0	%	Oxygen
	0	CO%		%	Carbon Monoxide
					Air-Fuel Ratio
		ThRaf	17.092	kg/kg	Stoichiometric Air-Fuel Ratio
L	0	ExAir%		%	Excess Air
		Raf	17.092	kg/kg	Actual Air-Fuel Ratio
		ThmolO2	.12445		Theoretical Moles Oxygen
		molCO2	.062448		
		molH2	.12401		
		molSO2	0		
		molN2	.46794		
		molO2	0		
		molTot	.53039		

Graphing the results.



Problem C12.5

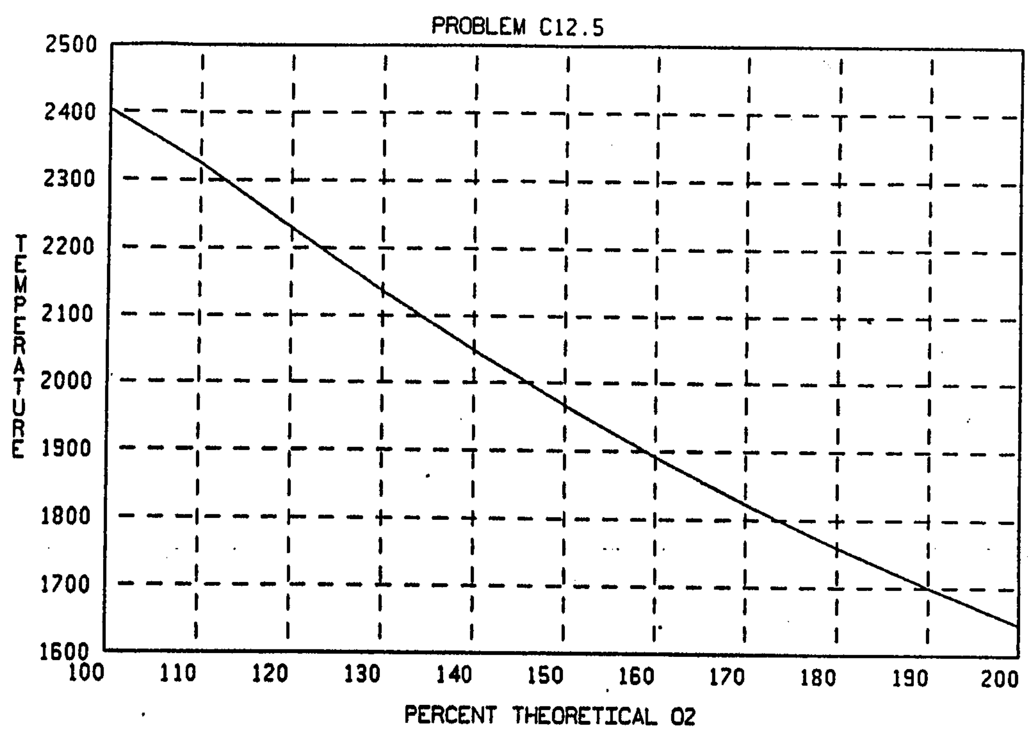
Use COMBUST.TK to calculate the adiabatic flame temperature of hydrogen being burned in air at 1 atm. Assume that the only products are water, oxygen, nitrogen, hydrogen, and hydroxyl. Vary the excess air from 0 to 100% in steps and plot the results. Compare your results with those from Problem C12.3.

Given: H_2 being burned in air at 1 atm with varying excess air.

Find: Adiabatic flame temperature.

Assumptions:
1) The combustion is complete.
2) The products and reactants behave like ideal gases.
3) The molal ratio of nitrogen to oxygen for air is 3.76.

Analysis: Using COMBUST.TK, entering required input data for the combustion of hydrogen, List Solving for %ThO2 between 100 and 200, and plotting.



Comment: Dissociation reduces the adiabatic flame temperature by over 100°K at 100% theoretical air. As excess air is increased, the lower temperature drastically reduces the dissociation and the adiabatic flame temperatures approach each other.

CHAPTER 13

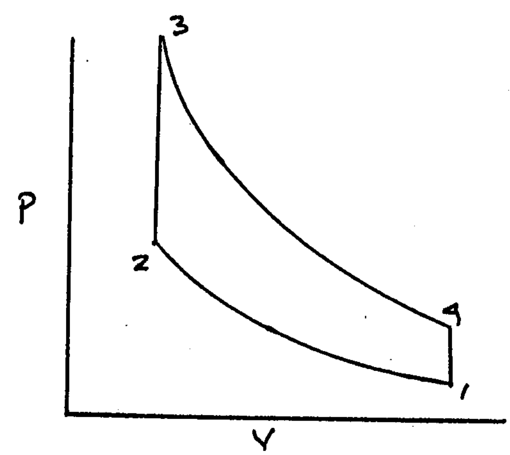
Problem 13.1

An air-standard Otto cycle has a compression ratio of 8.0 and has air conditions at the beginning of compression of 100 kPa and 25°C. The heat added is 1400 kJ/kg. Determine (a) the four cycle state points; (b) the thermal efficiency; (c) the mean effective pressure.

Given: The compression ratio, initial state and heat added in an air standard Otto cycle.

Find: The cycle state points, the efficiency and the mean effective pressure.

Sketch and Given Data:



$T_1 = 298$ K
$P_1 = 100$ kPa
$r = 8$
$q_{in} = 1400$ kJ/kg

Assumptions:
1. Air in the piston/cylinder is a closed system.
2. Air is an ideal gas.
3. Changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle state points by proceeding around the cycle using process information. The process 1-2 is isentropic,

$$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{k-1} = (8)^{0.4}$$

$$T_2 = (298\ \text{K})(8)^{0.4} = 684.6\ \text{K}$$

$$p_2 = p_1(V_1/V_2)^k - (100\ \text{kPa})(8)^{1.4} = 1837.9\ \text{kPa}$$

The process form 2-3 is constant volume, hence

$$q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$(1400\ \text{kJ/kg}) = (0.7176\ \text{kJ/kg-K})(T_3 - 684.6\ \text{K})$$

$$T_3 = 2635.5\ \text{K}$$

$$p_3 = p_2(T_3/T_2) = (1837.9\ \text{kPa})\left(\frac{2635.5}{684.6}\right) = 7075.5\text{kPa}$$

The process from 3-4 is isentropic, hence

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1} = \left(\frac{1}{r}\right)^{k-1}$$

$$T_4 = (2635.5\ \text{K})\left(\frac{1}{8}\right)^{0.4} = 1147.2\ \text{K}$$

$$p_4 = p_3\left(\frac{V_3}{V_4}\right)^{k} = (7075.5\text{kPa})\left(\frac{1}{8}\right)^{1.4} = 385\ \text{kPa}$$

The cycle thermal efficiency is

$$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}} = 1 = \frac{1}{(8)^{0.4}} = \underline{0.565\ \text{or}\ 56.5\%}$$

$$w_{net} = (0.565)(1400\ \text{kJ/kg}) = 791\ \text{kJ/kg}$$

The specific volumes at states 1 and 2 are

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287\ \text{kJ/kg-K})(298\ \text{K})}{(100\ \text{kN/m}^2)} = 0.855\ \text{m}^3/\text{kg}$$

$$v_2 = \frac{RT_2}{p_2} = \frac{(0.287)(684.6)}{(1837.9)} = 0.107\ \text{m}^3/\text{kg}$$

The mean effective pressure is

$$p_m = \frac{w_{net}}{v_1 - v_2} = \frac{(791\ \text{kJ/kg})}{(0.855 - 0.107\ \text{m}^3/\text{kg})} = \underline{1057.5\ \text{kPa}}$$

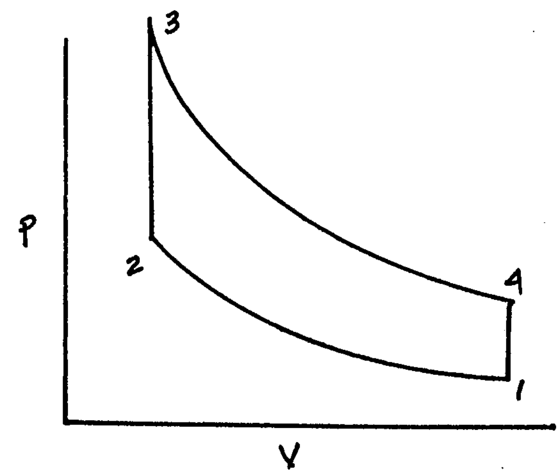
Problem 13.5

An air-standard Otto cycle has the following cycle states, where state 1 is at the beginning of the isentropic compression: p_1 = 101 kPa, T_1 = 333°K, V_1 = 0.28 m^3, T_3 = 2000°K, r = 5. Determine (a) the remaining cycle state points; (b) the thermal efficiency; (c) the heat added; (d) the heat rejected; (e) if $T_1 = T_0$, the available portions of the heat rejected.

Given: An air-standard Otto cycle, the initial state at the beginning of compression, the maximum temperature and the compression ratio.

Find: The cycle state points, the efficiency, the heats added and rejected and the available portion of the heat rejected.

Sketch and Given Data:



p_1 = 101 kPa
T_1 = 333 K
V_1 = 0.28 m^3
T_3 = 2000 K
r = 5

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the mass of air in the system

$$m = \frac{p_1 V_1}{R T_1} = \frac{(101\ \text{kN/m}^2)(0.28\ \text{m}^3)}{(0.287\ \text{kJ/kg-K})(333\ \text{K})} = 0.296\ \text{kg}$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (333\ \text{K})(5)^{0.4} = 633.9\ \text{K}$$

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^{k} = (101\ \text{kPa})(5)^{1.4} = 961.3\ \text{kPa}$$

$$V_2 = V_1/5 = \frac{0.28}{5} = 0.056\ \text{m}^3$$

$$V_3 = V_2 = 0.056\ m^3\ T_3 = 2000\ K$$

$$p_3 = \frac{mRT_3}{V_3} = \frac{(0.296)(0.287)(2000)}{(0.056)} = 3034\ kPa$$

$$V_4 = V_1$$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = (2000\ k)\left(\frac{1}{5}\right)^{0.4} = 1050.6\ K$$

$$p_4 = p_3\left(\frac{V_3}{V_4}\right)^{k} = (3034\ kPa)\left(\frac{1}{5}\right)^{1.4} = 318.8\ kPa$$

The thermal efficiency is

b) $$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}} = 1 - \frac{1}{(5)^{0.4}} = 0.475 \quad or \quad 47.5\%$$

The heat added is $Q_{2\text{-}3} = m(U_3 - u_2) = m\ c_v(T_3 - T_2)$

c) $Q_{2\text{-}3} = (0.296\ kg)(0.7176\ kJ/kg\text{-}K)(200 - 633.9\ K) = \underline{290.2\ kJ}$

The heat rejected is $Q_{4\text{-}1} = m(u_1 - u_4) = m\ c_v(T_1 - T_4)$

d) $Q_{4\text{-}1} = (0.296)(0.7176)(333 - 1050.6) = \underline{-152.4\ kJ}$

The available portion of $Q_{4\text{-}1}$ is

$$AE_{4\text{-}1} = Q_{4\text{-}1} - T_o(S_1 - S_4)$$

$$T_o(S_1 - S_4) = T_o\left[m\ c_v\ \ln\left(\frac{T_1}{T_4}\right) + m\ R\ \ln\left(\frac{V_1}{V_4}\right)\right]$$

$$T_o(S_1 - S_4) = (333\ K)(0.296\ kg)\left(0.7176\ \frac{kJ}{kg\text{-}K}\right)\ \ln\left(\frac{333}{1050.6}\right)$$

$$= -81.3\ kJ$$

e) $AE_{4\text{-}1} = -152.4 - (-81.3) = \underline{-71.1\ kJ}$

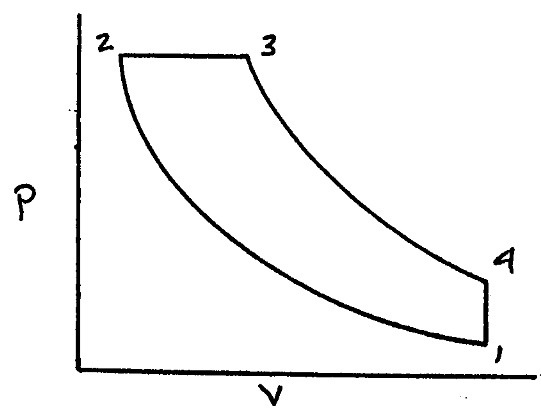
Problem 13.9

An air-standard Diesel cycle receives 28.5 kJ/cycle of heat while operating at 300 rpm. At the beginning of compression, p_1 = 100 kPa, T_1 = 305°K, and V_1 = 0.0425 m^3. At the beginning of heat addition, the pressure is 3450 kPa. Determine (a)p, V and T at each cycle state point; (b) the work; (c) the power; (d) the mean effective pressure.

Given: An air standard Diesel cycle engine has known heat input, rpm, initial state and maximum pressure.

Find: The cycle state points, the work, power and mean effective pressure.

Sketch and Given Data:



Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: The mass of air in the cycle is

$$m = \frac{p_1 V_1}{RT_1} = \frac{(100\ \text{kN/m}^2)(0.0425\ \text{m}^3)}{(0.287\ \text{kJ/kg-K})(305\ \text{K})} = 0.0486\ \text{kg}$$

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (305\ \text{K})\left(\frac{3450}{100}\right)^{\frac{0.4}{1.4}} = 838.8\ \text{K}$$

$$V_2 = \frac{mRT_2}{p_2} = \frac{(0.0486)(0.287)(838.8)}{(3450)} = 0.00339\ \text{m}^3$$

$$Q_{2\text{-}3} = H_3 - H_2 = m\,c_p\,(T_3 - T_2)$$

$$(25.8\ \text{kJ}) = (0.0486\ \text{kg})(1.0047\ \text{kJ/kg-K})(T_3 - 838.8\ \text{K})$$

$$T_3 = 1422.5\ \text{K} \qquad p_3 = p_2 = 3450\ \text{kPa}$$

$$V_3 = \frac{mRT_3}{p_3} = \frac{(0.0486)(0.287)(1422.5)}{(3450)} = 0.00575\ m^3$$

$$V_4 = V_1 = 0.0425\ m^3$$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = (1422.5K)\left(\frac{0.00575}{0.0425}\right)^{0.4} = 639.1\ K$$

$$p_4 = \frac{mRT_4}{V_4} = \frac{(0.0486)(0.287)(639.1)}{(0.0425)} = 209.7\ kPa$$

The heat out is

$$Q_{4\text{-}1} = U_1 - U_4 = m\, c_v(T_1 - T_4)$$

$$Q_{4\text{-}1} = (0.0486\ kg)(0.7176\ kJ/kg\text{-}K)(305 - 639.1\ K) = -11.65\ \frac{kJ}{cycle}$$

b) $W_{net} = \sum Q = 28.5 - 11.65 = \underline{16.85}$ kJ/cycle

$$\dot{W}_{net} = N\ W_{net} = \left(300\ \frac{cycles}{min}\right)\left(\frac{1}{60\ sec/min}\right)\left(16.85\ \frac{kJ}{cycle}\right)$$

c) $\dot{W}_{net} = \underline{84.25\ kW}$

The mean effective pressure is

d) $$p_m = \frac{W_{net}}{V_1 - V_2} = \frac{(16.85\ kJ)}{(0.0425 - 0.00339\ m^3)} = \underline{430.8\ kPa}$$

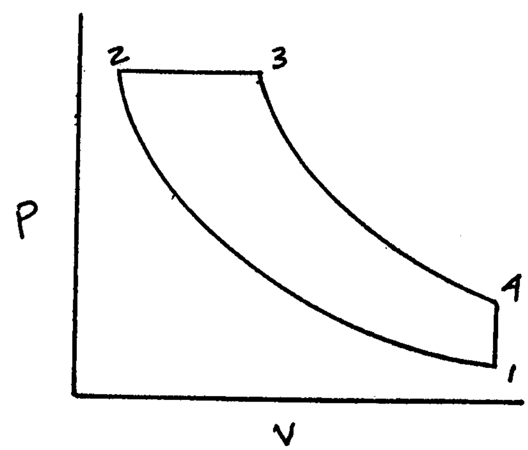
Problem 13.13

In an air-standard Diesel cycle, the compression ratio is 17. The cutoff ratio, the ratio of the volume after heat addition to that before heat addition (V_3/V_2), is 2.5:1. The air conditions at the beginning of compression are 101 kPa and 300°K. Determine (a) the thermal efficiency; (b) the heat added per kg of air, (c) the mean effective pressure.

Given: The air-standard Diesel's compression ratio, cutoff ratio, and the initial conditions.

Find: The cycle efficiency, heat added and mean effective pressure.

Sketch and Given Data:



$r = 17$

$r_c = 2.5$

$P_1 = 101$ kPa

$T_1 = 300$ K

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: The thermal efficiency may be found from Equation 13.15

$$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right] = 1 - \frac{1}{(17)^{0.4}}\left[\frac{2.5^{1.4} - 1}{(1.4)(2.5 - 1)}\right]$$

$$\eta_{Th} = 0.600 \text{ or } 60\%$$

The temperature at state 2 is

$$T_2 = T_1\left(\frac{v_1}{v_2}\right)^{k-1} = (300\text{ K})(17)^{0.4} = 931.8\text{ K}$$

For a constant pressure process, $T/v = c$

$$T_3 = T_2\left(\frac{v_3}{v_2}\right) = (931.8\ \text{K})(2.5) = 2329.5\ \text{K}$$

The heat added is

$$q_{2\text{-}3} = h_3 - h_2 = c_p(T_3 - T_2) = \left(1.0047\ \frac{\text{kJ}}{\text{kg-K}}\right)(2329.5 - 931.8\ \text{K})$$

b) $q_{2\text{-}3} = 1404.3$ kJ/kg

The net work is

$$w_{net} = (\eta_{Th})(q_{2\text{-}3}) = (0.60)(1404.3) = 842.6\ \text{kJ/kg}$$

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287\ \text{kJ/kg-K})(300\ \text{K})}{(101\ \text{kN/m}^2)} = 0.8525\ \frac{\text{m}^3}{\text{kg}}$$

$$v_2 = v_1/r = \frac{0.8525}{17} = 0.0501\ \text{m}^3/\text{kg}$$

The mean effective pressure is

c) $$p_m = \frac{w_{net}}{v_1 - v_2} = \frac{(842.6\ \text{kJ/kg})}{(0.8525 - 0.0501\ \text{m}^3/\text{kg})} = \underline{1050\ \text{kPa}}$$

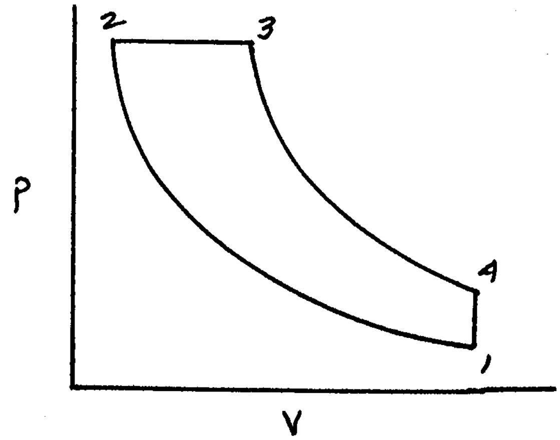
Problem 13.17

A four-cylinder engine with a 9.5-cm bore and a 8.75-cm stroke has a 7% clearance. The engine rotates at 2500 rpm. The conditions at the beginning of compression are 17°C and 98 kPa. The maximum cycle temperature is 2900°K. The engine may be assumed to operate on an air-standard Diesel cycle. Determine the cycle work and the power produced by the engine.

Given: An air-standard cycle engine has four cylinders of known bore and stroke and percent clearance. The rpm and initial temperature and pressure are specified as is the maximum temperature.

Find: The engine's power and net work per cycle.

Sketch and Given Data:



$D = 9.5\text{ cm}$ $L = 8.75\text{ cm}$

$c = 7\%$ 2500 rpm

$T_1 = 17°C = 290\text{ K}$

$P_1 = 98\text{ kPa}$

$T_3 = 2900\text{ K}$

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle state points, then the net work.

$$c = \frac{V_2}{V_1 - V_2} = 0.07 \qquad 1.07\,V_2 = 0.07\,V_1$$

$$r = \frac{V_1}{V_2} = \frac{1.07}{0.07} = 15.28$$

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (290\text{ K})(15.28)^{0.4} = 863\text{ K}$$

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^{k} = (98\text{ kPa})(15.28)^{1.4} = 4456.5\text{ kPa}$$

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287\ \text{kJ/kg-K})(290\ \text{K})}{(98\ \text{kN/m}^2)} = 0.8493\ \text{m}^3\text{/kg}$$

$$v_2 = \frac{RT_2}{p_2} = \frac{(0.287)(863)}{(4456.5)} = 0.0556\ \text{m}^3\text{/kg}$$

$$v_3 = v_2\left(\frac{T_3}{T_2}\right) = (0.0556\ \text{m}^3\text{/kg})\left(\frac{2900}{863}\right) = 0.1868\ \text{m}^3\text{/kg}$$

$$p_3 = p_2 = 4456.5 \qquad v_4 = v_1$$

$$T_4 = T_3\left(\frac{v_3}{v_4}\right)^{k-1} = (2900\ \text{K})\left(\frac{0.1868}{0.8493}\right)^{0.4} = 1582.4\ \text{K}$$

$$q_{in} = q_{2\text{-}3} = h_3 - h_2 = c_p\,(T_3 - T_2)$$

$$q_{2\text{-}3} = (1.0047\ \text{kJ/kg-K})(2900 - 863\ \text{K}) = 2046.6\ \text{kJ/kg}$$

$$q_{out} = q_{4\text{-}1} = u_1 - u_4 = c_v(T_1 - T_4)$$

$$q_{4\text{-}1} = (0.7176\ \text{kJ/kg-K})(290 - 1582.4\ \text{K}) = -927.4\ \text{kJ/kg}$$

$$w_{net} = \sum q = 2046.6 - 927.4 = 1119.2\ \text{kJ/kg}$$

Find the mass of air in the engine

$$V_{PD} = V_1 - V_2 = 4\,\frac{\pi}{4}\,D^2\,L = \pi(0.095)^2(0.0875) = 0.00248\ \text{m}^3$$

$$V_2 = \frac{V_1}{15.28} = 0.0654V_1$$

$$V_1 - 0.0654\ V_1 = 0.00248$$

$$V_1 = 0.002654\ \text{m}^3$$

$$m = \frac{p_1V_1}{RT_1} = \frac{(98\ \text{kN/m}^2)(0.002654\ \text{m}^3)}{(0.287\ \text{kJ/kg-k})(290\ \text{K})} = 0.003125\ \text{kg}$$

$$W_{net} = m\,w_{net} = (0.003125\ \text{kg})(1119.2\ \text{kJ/kg}) = \underline{3.4975}\ \text{kJ/cycle}$$

$$\dot{W}_{net} = N * w_{net} = \left(2500\ \frac{cyc}{min}\right)\left(\frac{1\ min}{60\ sec}\right)\left(3.4975\ \frac{kJ}{cyc}\right)$$

$$\dot{W}_{net} = \underline{145.7\ kW}$$

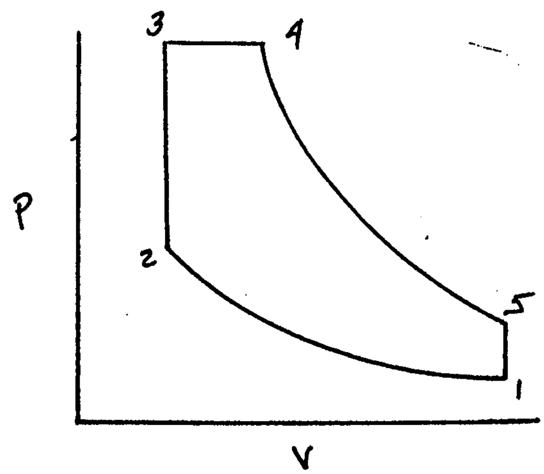
Problem 13.21

In an air-standard dual cycle, the isentropic compression starts at 100 kPa and 300°K. The compression ratio is 13, the maximum temperature is 2750°K, and the maximum pressure is 6894 kPa. Determine (a) the cycle work per kg; (b) the heat added per kg: (c) the mean effective pressure.

Given: An air-standard dual cycle, its compression ratio, initial state and maximum temperature and pressure.

Find: The cycle work, heat added and mean effective pressure.

Sketch and Given Data:



$P_1 = 100$ kPa

$T_1 = 300$ K

$r = 13$

$T_4 = 2750$ K

$P_3 = P_4 = 6894$ kPa

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle states.

$$T_2 = T_1 \left(\frac{v_1}{v_2}\right)^{k-1} = 300(13)^{0.4} = 836.9 \text{ K}$$

$$p_2 = p_1 \left(\frac{v_1}{v_2}\right)^{k} = (100)(13)^{1.4} = 3627 \text{ kPa}$$

$$v_1 = \frac{RT_1}{p_1} = \frac{(0.287 \text{ kJ/kg-K})(300 \text{ K})}{(100 \text{ kN/m}^2)} = 0.861 \text{ m}^3\text{/kg}$$

$$v_2 = \frac{v_1}{r} = \frac{0.861}{13} = 0.06621 \text{ m}^3\text{/kg}$$

The process 2-3 is V = c, T/p = C

$$T_3 = T_2\left(\frac{p_3}{p_2}\right) = (836.9\ \text{K})\left(\frac{6894}{3627}\right) = 1590.7\ \text{K}$$

$$v_3 = v_2 = 0.0662$$

$$T_4 = 2750\ \text{K} \quad p_4 = 6894\ \text{kPa}$$

$$v_4 = \frac{RT_4}{p_4} = \frac{(0.287)(2750)}{(6894)} = 0.1145\ \text{m}^3/\text{kg}$$

The process 4-5 is isentropic

$$T_5 = T_4\left(\frac{v_4}{v_5}\right)^{k-1} = (2750\ \text{K})\left(\frac{0.1145}{0.861}\right)^{0.4} = 1227\ \text{K}$$

The heat added is

$$q_{2\text{-}3} = u_3 - u_2 = c_v(T_3 - T_2)$$

$$q_{2\text{-}3} = (0.7176\ \text{kJ/kg-K})(1590.7 - 836.9\ \text{K}) = 540.9\ \text{kJ/kg}$$

$$q_{3\text{-}4} = h_4 - h_3 = c_p\,(T_4 - T_3)$$

$$q_{3\text{-}4} = (1.0047\ \text{kJ/kg-K})(2750 - 1590.7\ \text{K}) = 1164.7\ \text{kJ/kg}$$

b) $$q_{in} = 540.9 + 1164.7 = \underline{1705.6\ \text{kJ/kg}}$$

$$q_{out} = u_1 - u_5 = c_v\,(T_1 - T_5)$$

$$q_{out} = (0.7176)(300 - 1227) = -665.2\ \text{kJ/kg}$$

$$w_{net} = \sum q = 1705.6 - 665.2 = \underline{1040.4\ \text{kJ/kg}}$$

The mean effective pressure is

c) $$p_m = \frac{w_{net}}{v_1 - v_2} = \frac{(1040.4\ \text{kJ/kg})}{(0.861 - 0.0662\ \text{m}^3/\text{kg})} = \underline{1309\ \text{kPa}}$$

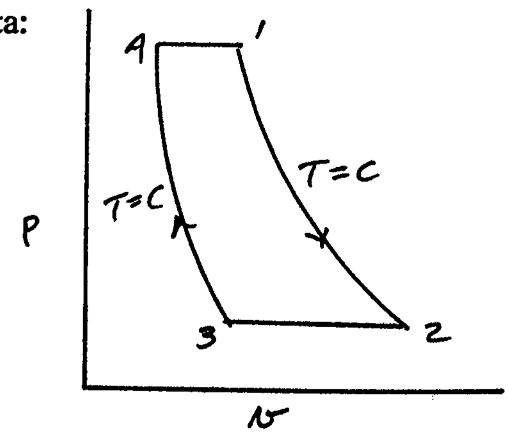
Problem 13.25

An Ericsson cycle uses helium as the working fluid. The isothermal compression process begins at 300°K and 120 kPa, and 175 kJ/kg of heat is rejected. Heat addition occurs at 1100°K. Determine (a) the cycle maximum pressure; (b) the net work produced per unit mass; (c) the thermal efficiency.

Given: An Ericsson cycle uses helium and has the state specified beginning isothermal compression and the heat rejected during the compression. The high temperature is known.

Find: The maximum cycle pressure, the net work and the efficiency.

Sketch and Given Data:



$p_3 = 120$ kPa

$T_3 = 300$ K

$q_{3-4} = -175$ kJ/kg

$T_1 = 1100$ K

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the specific volume at state 3 and knowing the work for process find p_4.

$$v_3 = \frac{RT_3}{p_3} = \frac{(2.077 \text{ kJ/kg-K})(300 \text{ K})}{(120 \text{ kN/m}^2)} = 5.1925 \text{ m}^3\text{/kg}$$

$$q_{2\text{-}3} = w_{3\text{-}4} = p_3\, v_3 \ln\left(\frac{v_4}{v_3}\right) = RT_3 \ln\left(\frac{p_3}{p_4}\right)$$

$$(-175 \text{ kJ/kg}) = (2.077 \text{ kJ/kg-K})(300 \text{ K}) \ln\left(\frac{120}{p_4}\right)$$

a) $p_4 = \underline{158.9 \text{ kPa}}$

$$q_{1\text{-}2} = q_{in} = w_{1\text{-}2} = p_1 \, v_1 \ln\left(\frac{v_2}{v_1}\right) = RT_1 \ln\left(\frac{p_1}{p_2}\right)$$

$$q_{1\text{-}2} = (2.077 \text{ kJ/kg-K})(1100 \text{ K}) \ln\left(\frac{158.9}{120}\right) = 641.5 \text{ kJ/kg}$$

b) $w_{net} = \sum q = 641.5 - 175 = \underline{466.5 \text{ kJ/kg}}$

c) $\eta_{Th} = \dfrac{w_{net}}{q_{in}} = \dfrac{466.5}{641.5} = 0.727$ or 72.7%

Check on the thermal efficiency

$$\eta_{Th} = 1 - \frac{T_L}{T_H} = 1 - \frac{300}{1100} = 0.727$$

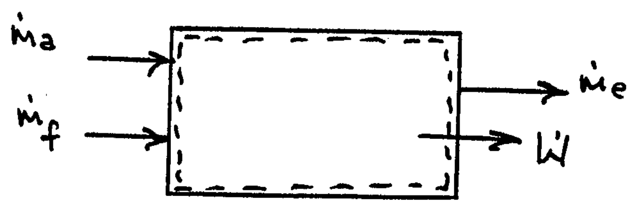
Problem 13.29

A six-cylinder spark-ignition engine has a bore and stroke of 10.9 x 10.5 cm. The engine requires 0.0035 kg/s of $C_8 H_{18}$ (1) when operating at half-load with a speed of 3000 rpm. The reduction of engine speed to axle speed is 3.78:1. The tires have an effective radius of 35.5 cm. (a) Determine the car speed in km/h and the fuel consumption in km/liter (the specific gravity may be assumed to be 0.85). (b) The air-fuel ratio on the mass basis is 15.3; the products of combustion leave the engine at 900°K, with air and fuel inlet temperature of 25°C. Determine the percentage of the heat release lost to the products of combustion.

Given: An actual engine's bore and stroke, fuel consumption, rpm, gear reduction and the car's tire size are known.

Find: The car's speed, fuel consumption, energy loss in exhaust.

Sketch and Given Data:



6 cyl
$D = 10,9$ cm
$L = 10,5$ cm
$N = 3000$ rpm
3,78 :1 reduction
$r = 0,355$ m

Assumptions:
1) Complete combustion.
2) Model exhaust with 200% Theoretical air tables.

Analysis: The rear axle speed is

$$\frac{3000 \text{ rpm}}{3.78} = 793.65 \text{ rpm}$$

For each revolution the car moves $2\pi r$.

$$v = \frac{x}{t} = \left(793.65 \ \frac{\text{rev}}{\text{min}}\right)\left(60 \ \frac{\text{min}}{\text{h}}\right)(2\pi)(0.355 \text{ m})\left(\frac{1}{1000 \text{ m/km}}\right)$$

a) $v =$ <u>106.2 km/h</u>

The fuel consumption per hour is

$$(\dot{m}_f) = (0.0035 \text{ kg/s})(3600 \text{ s/h}) = 12.6 \text{ kg/h}$$

$$\dot{V}_f = \frac{\dot{m}_f}{\rho_f} = \frac{12.6 \text{ kg/h}}{(0.85)(1000 \text{ kg/m}^3)}$$

$$\dot{V}_f = 0.01482 \frac{\text{m}^3}{\text{h}} = 14.82 \frac{\text{liter}}{\text{h}}$$

a) $$\text{km/liter} = \frac{(106.2 \text{ km/h})}{(14.82 \text{ liter/h})} = \underline{7.16 \text{ km/liter}}$$

The total heat release, assuming complete combustion, is

$$q_{in} = r_{f/a}\, h_{RP} = \left(\frac{1 \text{ kg fuel}}{15.3 \text{ kg air}}\right)(+47886) = 3129.8 \frac{\text{kJ}}{\text{kg}}$$

The exhaust may be modelled as an ideal gas with constant specific heats, assuming c_p from example problems, or use the 200% theoretical air tables. If the tables are used,

$$h_{900} = 966.2 \text{ kg/kg} \quad h_{298} = 303.0 \text{ kJ/kg}$$

To cool the exhaust to 298 K requires

$$q = (1 + r_{f/a})(h_{900} - h_{298}) = \left(1 + \frac{1}{15.3}\right)(966.2 - 303.0) = 706.5 \frac{\text{kJ}}{\text{kg}}$$

The percent heat release exiting with the exhaust is

b) $$\% = \frac{706.5}{3129.8} = 0.225 \text{ or } \underline{22.5\%}$$

Problem 13.33

An eight-cylinder diesel engine with a bore and stroke of 10 x 10 cm operates at 2000 rpm. Dodecane ($C_{12}H_{26}$[1]) fuel is used with 80% excess air. The air enters the engine at 100 kPa and 37°C and is compressed to 3.0 MPa. The heat loss from the engine is one-third of the work produced. Use the open-system diesel cycle to calculate state points. Determine (a) the compression ratio; (b) the fuel consumption; (c) the thermal efficiency; (d) the power produced; (e) the engine-cooling water required if the water enters at 21°C and leaves at 49°C.

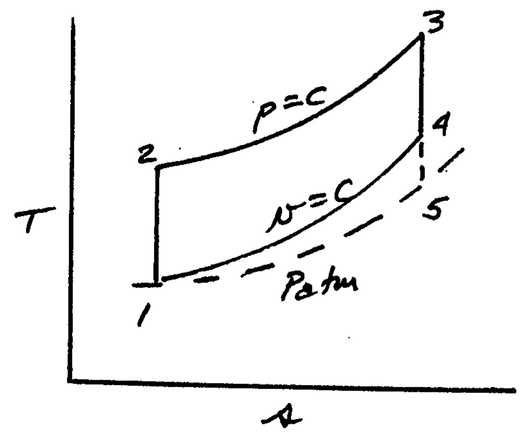
Given: A diesel engine operates on the open-system, the bore and stroke, rpm, excess air, initial air state and compression pressure are known. The heat loss as a percent of work is given.

Find: The compression ratio, fuel consumption, efficiency, power output, and cooling water required.

Sketch and Given Data:

$P_2 = 3000$ kPa

$Q_{loss} = 1/3\, W_{net}$



D = L = 10 cm

2000 rpm

$C_{12}H_{26}(l)$

80% excess air

T_1 = 37°C = 310 K

P_1 = 100 kPa

Assumptions:
1) The products gas properties are k = 1.383, c_{pp} = 1.048 kJ/kg-K, c_v = 0.7537 kJ/kg-K.
2) Gases are ideal gases.
3) Neglect changes in kinetic and potential energies.
4) Use properties per Example 13.6.

Analysis: The total displacement volume of the engine is

$$V_1 = V_2 = 8\,\frac{\pi}{4}\,(0.1)^2(0.1)^2 = 0.006283 \text{ m}^3$$

The compression ratio is

$$\text{a)} \quad r = \left(\frac{V_1}{V_2}\right) = \left(\frac{p_2}{p_1}\right)^{1/k} = \left(\frac{3000}{100}\right)^{1/1.398} = \underline{11.4}$$

Thus, V_1 = 11.4 V_2 and hence

$V_2 = 0.0006041\ m^3 \quad V_1 = 0.006887\ m^3$

The fraction empurged products, z, is

$$z = \frac{V_2}{V_1 - V_2} = \frac{(0.0006041)}{(0.006283)} = 0.096 \qquad 1 - z = 0.904$$

Assume the value of the exhaust is 767 K (1380 R). Determine the temperature at the start of compression.

$$u_{r_1} = (1 - z)u_{a_1} + u_{x_1}$$

$$c_{v_r} T_{r_1} = (0.904)c_v T_a + (0.096)c_v T_{x_1}$$

$$c_{v_r} = (0.904)(0.7176) + (0.096)(0.7537) = 0.7211 \text{ kJ/kg-K}$$

$$(0.7211)T_r = (0.904)(0.7176)(310) + (0.096)(0.7537)(767)$$

$$T_1 = T_r = 355.8 \text{ K}$$

$$T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{k-1} = (355.8 \text{ K})(11.4)^{0.398} = 937.2 \text{ K}$$

$$p_2 = 3000 \text{ kPa}$$

Balance the combustion equation for 180% theoretical air

$$C_{12}H_{26} + (1.8)(18.5)O_2 + 125.2\,N_2 \rightarrow 12CO_2 + 13\,H_2O + 14.8\,O_2 + 125.2\,N_2$$

$$r_{a/f} = \frac{(158.5 \text{ moles air})(28.97 \text{ kg/kgmol})}{(1 \text{ mole fuel})(170.3 \text{ kg/kgmol})} = 26.962 \frac{\text{kg air}}{\text{kg fuel}}$$

$$r_{f/a} = 1/r_{a/f} = 0.03709 \text{ kg fuel/kg air}$$

$$r_{f/r} = z\, r_{a/f} = (0.904)(0.03709) = 0.03353 \frac{\text{kg fuel}}{\text{kg reactant}}$$

For the combustion process

$$h_{r_2} + r_{f/r}\, h_{RP} = (1 + r_{f/r})h_{p_3}$$

$$c_{pr} = k\, c_{vr} = (1.398)(0.7211) = 1.0081 \text{ kJ/kg-K}$$

$$c_{pr}\,T_2 + r_{f/r}\,h_{RP} = (1 + r_{f/r})c_{pp}\,T_3$$

$$(1.0081)(937.2) + (0.03353)(44102) = (1.03353)(1.0428)\,T_3$$

$$T_3 = 2249\text{ K} \qquad p_3 = 3000\text{ kPa}$$

$$r_c = \frac{V_3}{V_2} = \frac{T_3}{T_2} = \frac{2249}{937.2} = 2.4$$

The expansion ratio, r_e, is

$$r_e = \frac{r}{r_c} = \frac{11.4}{2.4} = 4.75 = \frac{V_4}{V_3}$$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = (2249\text{ K})\left(\frac{1}{4.75}\right)^{0.383} = 1238.3$$

$$T_5 = T_3\left(\frac{p_5}{p_3}\right)^{\frac{k-1}{k}} = (2249\text{ K})\left(\frac{100}{3000}\right)^{\frac{0.383}{1.383}} = 876.8\text{ K}$$

The net adiabatic work is

$$w_{net} = r_{f/r}\,h_{RP} + u_{r_1} - (1 + r_{f/r})u_{p_4}$$

$$w_{net} = (0.03353)(44102) + (0.7211)(355.8) - (1.03353)(0.7537)(1238.3)$$

$$w_{net} = 770.7\text{ kJ/kg}$$

The heat loss is 1/3 the net work, hence for the non-adiabatic case

$$w_{net} + 1/3\,w_{net} = 770.7$$

$$w_{net} = 578\text{ kJ/kg}$$

The thermal efficiency is

c) $$\eta_{Th} = \frac{w_{net}}{r_{f/r}\,h_{RP}} = \frac{(578\text{ kJ/kg})}{(0.3353)(44102)} = 0.391\text{ or }39.1\%$$

The air flow at inlet is

$$\dot{V}_1 = \left(\frac{2000}{2}\ \frac{\text{cycle}}{\text{min}}\right)(0.006283\ \text{m}^3)\left(\frac{1}{60}\ \frac{\text{min}}{\text{sec}}\right) = 0.1047\ \text{m}^3/\text{s}$$

$$\dot{m}_a = \frac{p_1\dot{V}_1}{RT_1} = \frac{(100\ \text{kN/m}^2)(0.1047\ \text{m}^3/\text{s})}{(0.287\ \text{kJ/kg-K})(310\ \text{K})} = 0.1177\ \text{kg/s}$$

d) $\dot{W}_{net} = \dot{m}_a\, w_{net} = (0.1177\ \text{kg/s})(578\ \text{kJ/kg}) = \underline{68\ \text{kW}}$

The fuel flow-rate is $\dot{m}_f = \dot{m}_a\, r_{f/a} = (0.1177\ \text{kg/s})\left(0.03709\ \frac{\text{kg fuel}}{\text{kg air}}\right) = \underline{0.00436\ \text{kg/s}}$

$$q_{out} = 770.7 - 578 = 192.7\ \text{kJ/kg}$$

$$\dot{Q}_{out} = \dot{m}_a\, q_{out} = (0.1177)(192.7) = 22.68\ \text{kW}$$

The cooling water receives this at constant pressure

$$(22.68\ \text{kW}) = \dot{m}_{cw}(h_o - h_i) = (\dot{m}_{cw}\ \text{kg/s})(205.3 - 87.1\ \text{kJ/kg})$$

e) $\dot{m}_{cw} = \underline{0.192\ \text{kg/s}}$

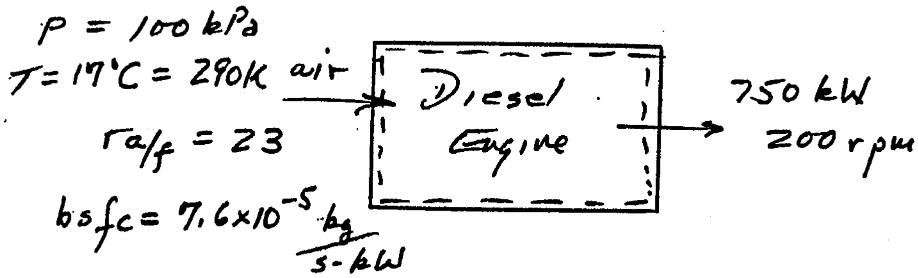
Problem 13.37

A Diesel engine develops 750 kW at 200 rpm when the ambient pressure is 100 kPa and the temperature is 17°C. The air/fuel ratio is 23 kg air/kg fuel, and 7.6 x 10^{-5} kg/s of fuel is consumed per brake kW developed. Determine for h_{RP} = 43 200 kJ/kg (a) the thermal efficiency; (b) the fuel consumption for 52 kW if the thermal efficiency is constant; (c) the second-law efficiency.

Given: A Diesel engine's output power, rpm and ambient conditions. The air-fuel ratio and bsfac is known.

Find: The efficiency, fuel consumption and second law efficiency.

Sketch and Given Data:



Assumptions:
1) Engine operates at steady-state.
2) Thermal efficiency is constant at different loads.
3) For part (c) assume a compression ratio of 15.

Analysis: The fuel flowrate is

$$\dot{m}_f = (\text{bsfc})(\dot{W}_b) = \left(7.6 \times 10^{-5} \frac{\text{kg}}{\text{s-kW}}\right)(750 \text{ kW}) = 0.057 \text{ kg/s}$$

a) $$\eta_{Th} = \frac{\dot{W}_b}{\dot{m}_f\, h_{RP}} = \frac{(750 \text{ kW})}{(0.057 \text{ kg/s})\left(43\ 200 \dfrac{\text{kJ}}{\text{kg}}\right)} = \underline{0.304}$$

For a load of 52 kW

b) $$\dot{m}_f = \left(7.6 \times 10^{-5} \frac{\text{kg}}{\text{s-kW}}\right)(52 \text{ kW}) = \underline{0.00395 \text{ kg/s}}$$

For a compression ratio of 15

$$T_2 = T_1 \left(\frac{V_1}{V_2}\right)^{k-1} = (290)(15)^{0.4} = 856.7 \text{ K}$$

The heat is added at constant pressure for an ideal Diesel cycle.

$$h_2 + r_{f/a}\, h_{RP} = (1 + r_{f/a})h_3$$

$$c_p T_2 + r_{f/a}\, h_{RP} = (1 + r_{f/a})c_p T_3$$

$$r_{f/a} = 1/23 = 0.0435 \text{ kg fuel/kg air}$$

$$(1.0047 \text{ kJ/kg-K})(856.7\text{K}) + \left(0.0435 \frac{\text{kg fuel}}{\text{kg air}}\right)(43\ 200 \text{ kJ/kg})$$

$$= \left(1.0435 \frac{\text{kg prod}}{\text{kg air}}\right)\left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right)(T_3 \text{ K})$$

$$T_3 = 2613 \text{ K}$$

$$\eta_{carnot} = 1 - \frac{T_L}{T_H} = 1 - \frac{290}{2613} = 0.889$$

c) $$\eta_2 = \frac{\eta_{engine}}{\eta_{carnot}} = \frac{0.304}{0.889} = \underline{0.342}$$

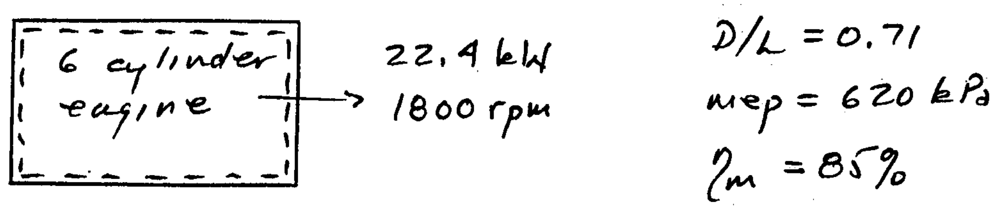
Problem 13.41

Calculate the bore and stroke of a six-cylinder engine that delivers 22.4 kW at 1800 rpm with a ratio of bore to stroke of 0.71. Assume the mean effective pressure in the cylinder is 620 kPa and the mechanical efficiency is 85%.

Given: An 6-cylinder engine, its power, rpm, ratio of D/L, mean effective pressure and mechanical efficiency.

Find: The bore and stroke.

Sketch and Given Data:



Assumptions:
1) Steady-state operation.
2) Four-stroke cycle.

Analysis: Find the indicated power, $\dot{W}_i$

$$\dot{W}_i = \frac{\dot{W}_b}{\eta_m} = \frac{(22.4\ \text{kW})}{(0.85)} = 26.35\ \text{kW}$$

$$\dot{W}_i = (\text{mep})(\dot{V}_{PD})$$

$$(26.35\ \text{kW}) = (620\ \text{kPa})(\dot{V}_{PD})$$

$$\dot{V}_{PD} = 0.0425\ \text{m}^3/\text{s} = 6\left(\frac{\pi}{4}\ D^2L\right)\left(\frac{1800\ \text{rev/min}}{2}\right)\left(\frac{1}{60\ \text{s/min}}\right)$$

$$0.0425\ \text{m}^3/\text{s} = 22.5\ \pi\ (0.71\ L)^2\ L$$

$$L = 0.106\ \text{m} = \underline{10.6\ \text{cm}}$$

$$D = (0.71)(10.6) = \underline{7.5\ \text{cm}}$$

Problem 13.45

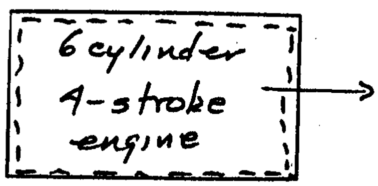
A six-cylinder four-stoke cycle spark-ignition engine with a compression ratio of 9.5 must be designed to produce 67.1 kW with a torque of 194 N-m. At these conditions the mechanical efficiency is 78%, and the brake mean effective pressure is 550 kPa. For the air-standard cycle, p_1 = 101 kPa, T_1 = 308°K, and k = 1.32. The fuel flow rate is 0.353 kg/h-kW, where the power is indicated power and the fuel has a lower heating value of 43 970 kJ/kg. The ratio of the piston bore to stroke is 1.1. Determine (a) the bore and stroke; (b) the indicated thermal efficiency; (c) the brake engine efficiency.

Given: A six-cylinder engine, its compression ratio, brake power and torque. The mechanical efficiency and bmep are specified and the initial conditions for the air standard cycle. The indicated specific fuel consumption is also given.

Find: The engine's bore and stroke, indicated thermal efficiency and brake engine efficiency.

Sketch and Given Data:

$p_1 = 101$ kPa
$T_1 = 308$ K
$k = 1.32$
$isfc = 0.353 \frac{kg}{h \cdot kW}$



$r = 9.5$ $D/L = 1.1$
$\dot{W}_b = 67.1$ kW
$\tau = 194$ N m
$\eta_m = 78\%$ bmep = 550 kPa

Assumptions:
1) Engine operates at steady-state.
2) Theoretical cycle is the air standard Otto cycle.

Analysis: The bore and stroke may be found from the engine's displacement volume.

$$\dot{W}_b = (\text{bmep})(\dot{V}_{PD})$$

$$(67.1\ \text{kW}) = (550\ \text{kN/m}^2)(\dot{V}_{PD}\ \text{m}^3/\text{s})$$

$$\dot{V}_{PD} = 0.122\ \text{m}^3/\text{s}$$

The engine's rpm is not given but

$$\dot{W}_b = 2\,\pi\,\tau\,N$$

$$(67.1\ \text{kW}) = \frac{(2\,\pi)(194\ \text{N m})(N\ \text{rev/sec})}{(1000\ \text{J/kJ})}$$

$$N = 55.05 \text{ rev/sec}$$

Find $\dot{V}_{PD}$ per cylinder as

$$\dot{V}_{PD} = \frac{0.122}{6} = 0.0203 \text{ m}^3/\text{s}$$

$$\dot{V}_{PD} = \frac{\pi}{4} D^2 L n \qquad \text{where } n = N/2 \text{ intakes per revolution}$$

$$(0.0203 \text{ m}^3/\text{s}) = \frac{\pi}{4}\frac{(D)^3}{1.1}\left(\frac{55.05}{2}\right)$$

a) $D = 0.101 \text{ m} = \underline{10.1 \text{ cm}}$

$L = D/1.1 = 0.092 \text{ m} = \underline{9.2 \text{ cm}}$

The indicated power is

$$\dot{W}_i = \frac{\dot{W}_b}{\eta_m} = \frac{67.1 \text{ kW}}{0.78} = 86 \text{ kW}$$

$$\dot{m}_f = (0.353 \text{ kg/h-kW})(86 \text{ kW})(1/3600 \text{ s/h}) = 0.008433 \text{ kg/s}$$

b) $$(\eta_{Th})_i = \frac{(86 \text{ kW})}{(0.008433 \text{ kg/s})(43\ 970 \text{ kJ/kg})} = \underline{0.232}$$

The theoretical power may be found using the air standard Otto cycle expression.

$$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}} = 1 - \frac{1}{(9.5)^{0.32}} = 0.513$$

$$\eta_{Th} = \frac{\dot{W}}{\dot{m}_f\, h_{RP}} \qquad \dot{W} = (0.513)(0.08433)(43970)$$

$$\dot{W} = 190.2 \text{ kW}$$

The brake engine efficiency, η_b, is

c) $$\eta_b = \frac{\dot{W}_b}{\dot{W}} = \frac{67.1}{190.2} = \underline{0.353}$$

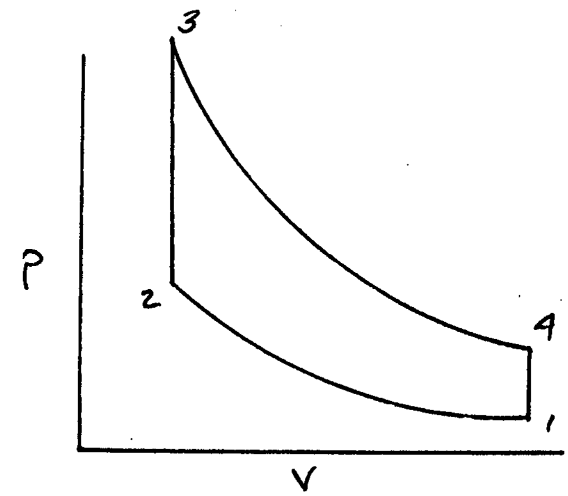
Problem *13.1

An air-standard Otto cycle has an initial temperature of 100°F, a pressure of 14.7 psia, and a compression pressure p_2 = 356 psia. the pressure at the end of heat addition is 1100 psia. Determine (a) the compression ratio; (b) the thermal efficiency; (c) the percentage of clearance; (d) the maximum temperature.

Given: An air standard Otto cycle, the initial air state, the pressure at states 2 and 3.

Find: The compression ratio, thermal efficiency, percent clearance and maximum temperature.

Sketch and Given Data:



$T_1 = 100 F = 560 R$
$P_1 = 14.7$ psia
$P_2 = 356$ psia
$P_3 = 1100$ psia

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: For isentropic compression

$$\frac{p_2}{p_1} = \left(\frac{v_1}{v_2}\right)^k ; \quad \frac{v_1}{v_2} = \left(\frac{p_2}{p_1}\right)^{1/k} = \left(\frac{356}{14.7}\right)^{1/1.4} = 9.74$$

a) $$r = \frac{v_1}{v_2} = \underline{9.74}$$

b) $$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}} = 1 - \frac{1}{(9.74)^{0.4}} = \underline{0.598}$$

$$v_1 = \frac{RT_1}{p_1} = \frac{\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(560\ \text{R})}{(14.7\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)} = 14.11\ \text{ft}^3/\text{lbm}$$

$$v_2 = \frac{v_1}{r} = \frac{14.11}{9.74} = 1.449 \text{ ft}^3/\text{lbm}$$

c) $$c = \frac{v_2}{v_1 - v_2} = \frac{1.449}{(14.111 - 1.449)} = 0.114 \text{ or } 11.4\%$$

$$T_2 = \frac{p_2 v_2}{R} = \frac{(356 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)(1.449 \text{ ft}^3/\text{lbm})}{(53.34 \text{ ft-lb}_f/\text{lbm-R})} = 1393 \text{ R}$$

For V = C,

d) $$T_3 = T_{max} = T_2 \left(\frac{p_3}{p_2}\right) = (1393 \text{ R})\left(\frac{1100}{356}\right) = \underline{4304\text{R}}$$

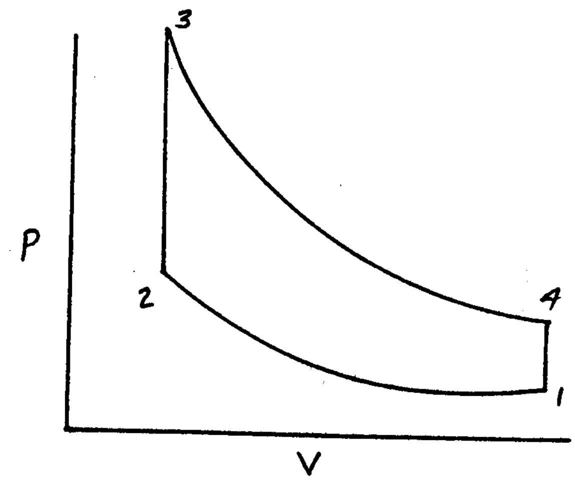
Problem *13.5

A four-cylinder engine with a 3.75-in. bore and a 3.4-in. stroke has a 10% clearance. The engine rotates at 2500 rpm. The conditions at the beginning of compression are 65°F and 14.5 psia. The maximum cycle temperature is 5220°R. The engine may be assumed to operate on an air-standard Otto cycle. Determine the cycle work and the power produced by the engine.

Given: An engine with known bore and stroke, percent clearance, rpm, maximum temperature and initial conditions operates on the air standard Otto cycle.

Find: The net work per cycle and power produced.

Sketch and Given Data:



$D = 3.75''$
$L = 3.4''$
$c = 10\%$
$N = 2500$ rpm
$T_1 = 65F = 525R$
$P_1 = 14.5$ psia
$T_3 = 5220$ R

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the piston displacement volume.

$$V_{PD} = \frac{\pi}{4} D^2 L = \frac{\pi}{4}\left(\frac{3.75}{12}\right)^2\left(\frac{3.4}{12}\right) = 0.02173 \text{ ft}^3$$

For the total engine $V_{PD} = (4)(0.02173) = 0.08692 \text{ ft}^3$

$$c = \frac{V_2}{V_1 - V_2} = 0.1; \quad V_{PD} = V_1 - V_2 = 0.08692$$

$$V_2 = 0.08692 \text{ ft}^3$$

$$V_1 = 0.09561 \text{ ft}^3$$

$$r = \frac{V_1}{V_2} = \frac{0.09561}{0.008692} = 11$$

The mass of air in the engine is

$$m = \frac{p_1 V_1}{R T_1} = \frac{(14.5\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(0.09561\ \text{ft}^3)}{(53.34\ \text{ft-lb}_f/\text{lbm-R})(525\ \text{R})} = 0.00713\ \text{lbm}$$

The temperature at state 2 is

$$T_2 = T_1 \left(\frac{V_1}{V_2} \right)^{k-1} = (525\ \text{R})(11)^{0.4} = 1370\ \text{R}$$

The heat added is

$$Q_{2\text{-}3} = U_3 - U_2 = m\, c_v (T_3 - T_2)$$

$$Q_{2\text{-}3} = (0.00713\ \text{lbm})(0.1714\ \text{Btu/lbm-R})(5220 - 1370\ \text{R})$$

$$= 4.705\ \frac{\text{Btu}}{\text{cycle}}$$

$$\eta_{Th} = 1 - \frac{1}{(r)^{k-1}} = 1 - \frac{1}{(11)^{0.4}} = 0.617$$

$$W_{net} = \eta_{Th}\, Q_{2\text{-}3} = (0.617)(4.705) = \underline{2.902}\ \frac{\text{Btu}}{\text{cycle}}$$

The power is

$$\dot{W}_{net} = N\, W_{net} = \left(2500\ \frac{\text{cycle}}{\text{min}}\right)\left(2.902\ \frac{\text{Btu}}{\text{cycle}}\right)$$

$$\dot{W}_{net} = 7255\ \frac{\text{Btu}}{\text{min}} = \underline{171.1}\ \text{hp}$$

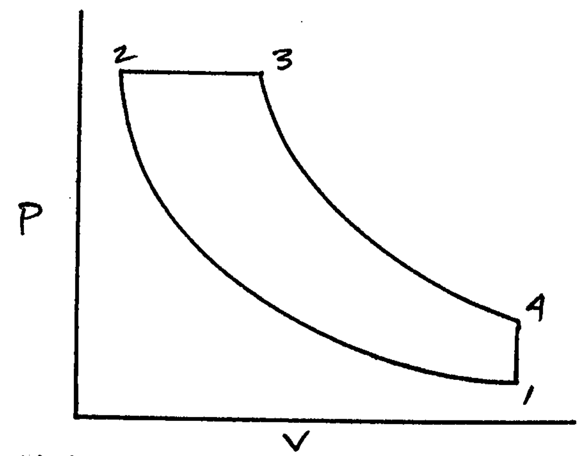
Problem *13.9

A one-cylinder Diesel engine operates on the air-standard cycle and receives 27 Btu/rev. The inlet pressure is 14.7 psia, the inlet temperature is 90°F, and the volume at bottom dead center is 1.5 ft³. At the end of compression, p_2 = 500 psia. Determine (a) the cycle state points; (b) the power if the engine runs at 300 rpm; (c) the mean effective pressure.

Given: An air-standard Diesel cycle, the heat added, the initial temperature and pressure and volume. The pressure at the end of compression.

Find: The cycle state points, the power at 300 rpm and the mean effective pressure.

Sketch and Given Data:



Q_{in} = 27 Btu/cycle
P_1 = 14.7 psia
T_1 = 90 F = 550 R
V_1 = 1.5 ft³
P_2 = 500 psia

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the mass of air in the cycle.

$$m = \frac{p_1V_1}{RT_1} = \frac{(14.7\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(1.5\ \text{ft}^3)}{(53.34\ \text{ft-lb}_f/\text{lbm-R})(550\ \text{R})} = 0.1082\ \text{lbm}$$

$$T_2 = T_2\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (500\ \text{R})\left(\frac{500}{14.7}\right)^{\frac{0.4}{1.4}} = \underline{1506.5\ \text{R}}$$

$$V_2 = V_1\left(\frac{p_1}{p_2}\right)^{1/12} = (1.5\ \text{ft}^3)\left(\frac{14.7}{500}\right)^{1/1.4} = \underline{0.1208\ \text{ft}^3}$$

The process from 2-3 is constant pressure, heat addition

$$Q_{2\text{-}3} = H_3 - H_2 = m\,c_p(T_3 - T_2)$$

$$(27\ \text{Btu}) = (0.1082\ \text{lbm})(0.24\ \text{Btu/lbm-R})(T_3 - 1506.5\ \text{R})$$

$$T_3 = \underline{2546.2\ \text{R}} \qquad p_3 = 500\ \text{psia}$$

$$V_3 = \frac{mRT_3}{p_3} = \frac{(0.1082)(53.34)(2546.2)}{(500)(144)} = \underline{0.2041\ \text{ft}^3}$$

$$T_4 = T_3\left(\frac{V_3}{V_4}\right)^{k-1} = (2546.2\ \text{R})\left(\frac{0.2041}{1.5}\right)^{0.4} = \underline{1146.5\ \text{R}}$$

$$p_4 = p_3\left(\frac{V_3}{V_4}\right)^{k} = (500\ \text{psia})\left(\frac{0.2041}{1.5}\right)^{1.4} = \underline{30.6\ \text{psia}}$$

The process 4-1 is constant volume heat rejection.

$$Q_{4\text{-}1} = Q_{out} = U_1 - U_4 = m\,c_v(T_1 - T_4)$$

$$Q_{4\text{-}1} = (0.1082)(0.1714)(550 - 1146.5) = -11.1\ \text{Btu/cycle}$$

$$W_{net} = \sum Q = 27 - 11.1 = 15.9\ \text{Btu/cycle}$$

The mean effective pressure is

c) $$p_m = \frac{W_{net}}{V_1 - V_2} = \frac{(15.9\ \text{Btu})(778.16\ \text{ft-lb}_f/\text{Btu})}{(1.5 - 0.1208\ \text{ft}^3)(144\ \text{in}^2/\text{ft}^2)} = \underline{62.3\ \text{psi}}$$

$$\dot{W}_{net} = (W_{net})(N) = (15.9\ \text{Btu/cycle})(300\ \text{cycle/min})$$

b) $$\dot{W}_{net} = 4770\,\frac{\text{Btu}}{\text{min}} = \underline{112.5\ \text{hp}}$$

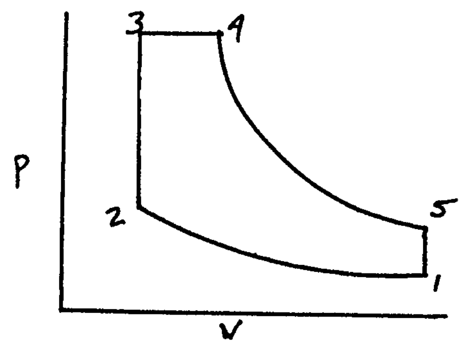
Problem •13.13

The compression ratio of an air-standard dual cycle is 12, and the pressure at the beginning of compression is 14.7 psia, the volume is 75 in.^{3}, and the temperature is 100°F. During the heat-addition processes, 0.4 btu is transferred at constant volume and 1.0 Btu at constant pressure. Determine (a) the cycle thermal efficiency; (b) the pressure at the beginning of heat rejection.

Given: An air standard dual cycle, its compression ratio, the state at the beginning of compression, the heats added.

Find: The cycle efficiency and the pressure at the beginning of heat rejection.

Sketch and Given Data:



$r = 12$

$P_1 = 14.7$ psia

$V_1 = 75\ in^3 = 0.0434\ ft^3$

$T_1 = 100\ F = 560\ R$

$Q_{2-3} = 0.4$ Btu

$Q_{3-4} = 1.0$ Btu

Assumptions:
1) Air in the piston/cylinder is a closed system.
2) Air is an ideal gas.
3) Changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle state points

$$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{k-1} = (560\ R)(12)^{0.4} = 1513\ R$$

$$p_2 = p_1\left(\frac{V_1}{V_2}\right)^{k} = (14.7\ psia)(12)^{1.4} = 476.6\ psia$$

$$V_2 = \frac{V_1}{r} = \frac{75}{12} = 6.25\ in^3$$

The process 2-3 is constant volume

$$Q_{2\text{-}3} = U_3 - U_2 + \cancelto{0}{W_{2\text{-}3}} = U_3 - U_2 = m\,c_v(T_3 - T_2)$$

$$m = \frac{p_1V_1}{RT_1} = \frac{(14.7\ lb_f/in^2)(144\ in^2/ft^2)(0.0454\ ft^3)}{(53.34\ ft\text{-}lb_f/lbm\text{-}R)(560\ R)} = 0.00308\ lbm$$

$$(0.4 \text{ Btu}) = (0.00308 \text{ lbm})(0.1714 \text{ Btu/lbm-R})(T_3 - 1513 \text{ R})$$

$$T_3 = 2271 \text{ R}$$

$$p_3 = p_2\left(\frac{T_3}{T_2}\right) = (476.6 \text{ psia})\left(\frac{2271}{1513}\right) = 715.3 \text{ psia}$$

$$V_3 = V_2 = 6.25 \text{ in}^3$$

The process 3-4 is constant pressure

$$Q_{3\text{-}4} = H_4 - H_3 = m\,c_p(T_4 - T_3)$$

$$Q_{3\text{-}4} = (0.00308 \text{ lbm})(0.24 \text{ Btu/lbm-R})(T_4 - 2271 \text{ R}) = (1.0 \text{ Btu})$$

$$T_4 = 3624 \text{ R} \qquad p_4 = p_3 = 715.3 \text{ psia}$$

$$V_4 = V_3\left(\frac{T_4}{T_3}\right) = (6.25 \text{ in}^3)\left(\frac{3624}{2271}\right) = 9.97 \text{ in}^3$$

$$V_5 = V_1 = 75 \text{ in}^3$$

$$T_5 = T_4\left(\frac{V_4}{V_5}\right)^{k-1} = (3624 \text{ R})\left(\frac{9.97}{75}\right)^{0.4} = 1617 \text{ R}$$

b) $$p_5 = p_4\left(\frac{V_4}{V_5}\right)^{k} = (715.3 \text{ psia})\left(\frac{9.97}{75}\right)^{1.4} = \underline{42.4 \text{ psia}}$$

$$Q_{out} = U_1 - U_5 = m\,c_v(T_1 - T_5)$$

$$Q_{out} = (0.00308 \text{ lbm})(0.1714 \text{ Btu/lbm-R})(560 - 1617 \text{ R})$$

$$Q_{out} = -0.56 \text{ Btu}$$

$$W_{net} = \sum Q = 0.4 + 1.0 - 0.56 = 0.84 \text{ Btu}$$

a) $$\eta_{Th} = \frac{W_{net}}{Q_{in}} = \frac{0.84}{1.4} = \underline{0.60 \text{ or } 60\%}$$

Problem *13.17

An adiabatic four-stroke cycle, six-cylinder Diesel engine has a bore of 12-in. and a stroke of 15 in. and operates at 500 rpm, receiving air at 90°F and 14.5 psia. The compression ratio is 18, and the dodecane fuel is injected at 100°F with a ratio of 0.0444 lbm fuel/lbm air. Assume the products of combustion have properties as in Example 13.6, but let k = 1.3 for products and reactants. Determine (a) the percentage of unpurged products; (b) the thermal efficiency; (c) the power produced.

Given: A Diesel engine operates on the open Diesel cycle, bore and stroke, rpm intake air state, compression ratio, fuel and air/fuel ratio are specified.

Find: The percent of unperged products, efficiency and power output.

Sketch and Given Data:

6 cylinder

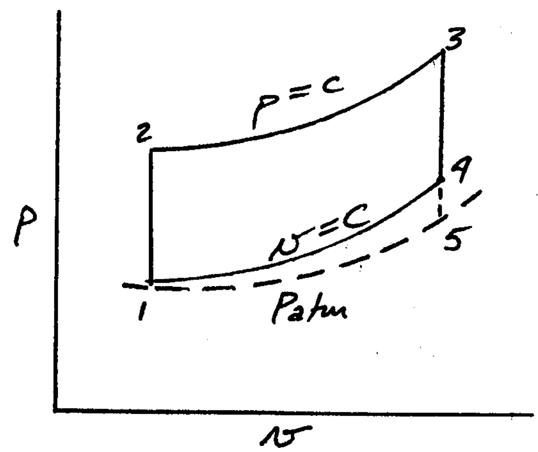
$D = 12''$ $L = 15''$

$T_1 = 90\ F = 550\ R$

$P_1 = 14.5\ psia$

$r = 18$ $k = 1.3$

$r_{f/a} = 0.0444$



Assumptions:
1) Reactants and products are ideal gases, k = 1.3
2) Air is an ideal gas.
3) Properties per Example 13.6

Analysis: Determine the percent unpurged products.

$$V_1 - V_2 = V_{PD} = \frac{\pi}{4} D^2 L = \frac{\pi}{4}(1)^2\left(\frac{15}{12}\right) = 0.9817 \text{ ft}^3$$

$$r = \frac{V_1}{V_2} = 18 \quad 18\,V_2 = V_1$$

$$V_2 = 0.0577 \text{ ft}^3 \qquad V_1 = 1.0394 \text{ ft}^3$$

a) $$z = \frac{V_2}{V_1 - V_2} = \frac{0.0577}{0.9817} = \underline{0.059 \text{ or } 5.9\%}$$

$$u_{r_2} = (1 - z)u_{az} + z\, u_{x_2}$$

$$c_{v_s} T_2 = (1 - z)c_{va} T_a + z\, c_{vp} T_p$$

Assume $T_p = 1380$ R, $c_{vr} = 0.1723 \dfrac{\text{Btu}}{\text{lbm-R}}$ $c_{vp} = 0.180 \dfrac{\text{Btu}}{\text{lbm-R}}$

$$\left(0.1723 \frac{\text{Btu}}{\text{lbm-R}}\right)(T_r) = (0.941)\left(0.1714 \frac{\text{Btu}}{\text{lbm-R}}\right)(550 \text{ R})$$

$$+ (0.059)\left(0.18 \frac{\text{Btu}}{\text{lbm-R}}\right)(1380 \text{ R})$$

$$T_r = 600 \text{ R} = T_1$$

$$T_2 = T_1 (r)^{k-1} = (600 \text{ R})(18)^{0.3} = 1428 \text{ R}$$

$$p_2 = p_1 (r)^k = (14.5 \text{ psia})(18)^{1.3} = 621.2 \text{ psia}$$

$$r_{f/r} = (r_{f/a})(0.941) = (0.0444)(0.941) = 0.0418 \frac{\text{lbm fuel}}{\text{lbm reactant}}$$

$$h_{r_2} + r_{f/r}\, h_{f_2} + r_{f/r}\, h_{RP} = (1 + r_{f/r})\, h_{p_3}$$

Assume h_{f_2} is negligible as the temperature is near 77°F.

$$c_{pr} T_2 + r_{f/r} h_{RP} = (1 + r_{f/r})\, c_{pp} T_3$$

$$\left(0.241 \frac{\text{Btu}}{\text{lbm-R}}\right)(1428 \text{ R}) + \left(0.0418 \frac{\text{lbm fuel}}{\text{lbm react.}}\right)\left(18{,}964 \frac{\text{Btu}}{\text{lbm}}\right)$$

$$= \left(1.0418 \frac{\text{lbm prod}}{\text{lbm react}}\right)\left(0.249 \frac{\text{Btu}}{\text{lbm-R}}\right)(T_3 \text{ R})$$

$T_3 = 4382$ R $\qquad p_3 = p_2 = 621.2$ psia

$$V_3 = V_2 \left(\frac{T_3}{T_2}\right) = (0.0577 \text{ ft}^3)\left(\frac{4382}{1428}\right) = 0.177$$

$$T_4 = T_3 \left(\frac{V_3}{V_4}\right)^{k-1} = (4382 \text{ R})\left(\frac{0.177}{1.0394}\right)^{0.3} = 2576.5 \text{ R}$$

The net adiabatic work is

$$w_{net} = r_{f/r} h_{RP} + u_{r_1} - (1 + r_{f/r})u_{p_4}$$

$$w_{net} = r_{f/r}\, h_{RP} + c_{vr}\, T_{r_1} - (1 + r_{f/r})\, c_{vp} T_4$$

$$w_{net} = \left(0.0418\ \frac{\text{lbm fuel}}{\text{lbm react}}\right)\left(18{,}964\ \frac{\text{Btu}}{\text{lbm fuel}}\right)$$

$$+ \left(0.1723\ \frac{\text{Btu}}{\text{lbm-R}}\right)(600\ \text{R})$$

$$- \left(1.0418\ \frac{\text{lbm prod}}{\text{lbm react}}\right)\left(0.18\ \frac{\text{Btu}}{\text{lbm-R}}\right)(2576.5\ \text{R})$$

$$w_{net} = 412.9\ \text{Btu/lbm reactant}$$

The thermal efficiency is

b) $$\eta_{Th} = \frac{w_{net}}{r_{f/r}\, h_{RP}} = \frac{(412.9\ \text{Btu/lbm})}{\left(0.0418\ \frac{\text{lbm fuel}}{\text{lbm react}}\right)\left(18{,}964\ \frac{\text{Btu}}{\text{lbm}}\right)} = \underline{0.521}$$

Determine the mass flowrate through the engine

$$\dot{V}_{PD} = (6\ \text{cyl})(0.9817\ \text{ft}^3/\text{cyl})\left(\frac{500}{2}\ \frac{\text{intakes}}{\text{min}}\right) = 1472.5\ \text{ft}^3/\text{min}$$

$$\dot{m} = \frac{p_1 \dot{V}_1}{RT_1} = \frac{(14.5\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(1472.5\ \text{ft}^3/\text{min})}{(53.34\ \text{ft-lb}_f/\text{lbm-R})(600)} = 96.1\ \frac{\text{lbm}}{\text{min}}$$

c) $$\dot{W}_{net} = \left(412.9\ \frac{\text{Btu}}{\text{lbm}}\right)\left(96.1\ \frac{\text{lbm}}{\text{min}}\right) = 39679.7\ \frac{\text{Btu}}{\text{min}} = \underline{935.8\ \text{hp}}$$

Comments: 1) The gas constant in part c was assumed to be air rather than that of reactants.

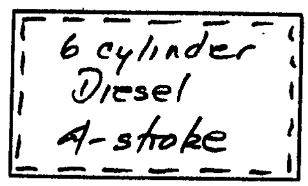
Problem *13.21

A six-cylinder Diesel engine with a bore and stroke of 17.5 x 25 in. operates at 225 rpm and produces 750 bhp. The fuel consumptions is 300 lbm/hr. The engine's mechanical efficiency is 85%, and the ideal cycle efficiency is 52.2%. Determine (a) the indicated power; (b) the indicated mean effective pressure; (c) the brake engine efficiency; (d) the brake mean effective pressure.

Given: A Diesel engine, its bore and stroke, power, rpm and fuel consumption. The mechanical and Theoretical cycle efficiencies are known.

Find: The indicated power and mean effective pressure, the brake engine efficiency and the brake mean effective pressure.

Sketch and Given Data:



$D = 17.5''$ $\quad L = 25''$

$\dot{W}_b = 750$ bhp

225 rpm

$\dot{m}_f = 300$ lbm/hr

$\eta_m = 85\%$ $\quad \eta_{Th} = 52.2\%$

Assumptions:
1) Engine operates at steady-state.
2) It operates on four-stroke cycle.
3) The fuel is dodecane.

Analysis: The indicated power may be determined from the expression for mechanical efficiency.

$$\eta_m = \frac{\dot{W}_b}{\dot{W}_i} \qquad 0.85 = \frac{(750\text{ hp})}{\dot{W}_i}$$

a) $\dot{W}_i = \underline{882.3\text{ hp}}$

The engine's total piston displacement is

$$\dot{V}_{PD} = \left(\frac{\pi}{4} D^2 L\, N\right)(6\text{ cyl})$$

$$\dot{V}_{PD} = \frac{6\,\pi}{4}\left(\frac{17.5}{12}\right)^2\left(\frac{25}{12}\right)\frac{(225\text{ rev/min})}{2\text{ rev/intake)}}$$

$$\dot{V}_{PD} = 2349\text{ ft}^3\text{/min}$$

b) $$\text{imep} = \frac{\dot{W}_i}{V_{PD}} = \frac{(882.3\text{ hp})\left(33\ 000\ \frac{\text{ft-lb}_f}{\text{hp-min}}\right)}{(144\text{ in}^2\text{/ft}^2)(2349\text{ ft}^3\text{/min})} = 86.1\text{ psia}$$

d) $$\text{bmep} = \frac{\dot{W}_b}{V_{PD}} = \frac{(750)(33\ 000)}{(144)(2349)} = \underline{73.2\text{ psi}}$$

The brake engine efficiency is

$$\eta_b = \frac{\dot{W}_b}{\dot{W}_{theoretical}}$$

$$\dot{W}_{theoretical} = (\eta_{Th})_{Theo}\ \dot{m}_f\ h_{RP}$$

$$\dot{m}_f\ h_{RP} = (300\text{ lbm/hr})\left(20{,}410\ \frac{\text{Btu}}{\text{lbm}}\right) = 6.123 \times 10^6\ \frac{\text{Btu}}{\text{hr}}$$

$$\dot{W}_{theo} = (0.522)(6.123 \times 10^6) = 3.196 \times 10^6\ \frac{\text{Btu}}{\text{hr}} = 1256\text{ hp}$$

c) $$\eta_b = \frac{(750\text{ hp})}{(1256\text{ hp})} = \underline{0.597}$$

Problem C13.1

Develop a computer program, spreadsheet template, or TK Solver model to compute the thermal efficiency of an air-standard Otto cycle. Compute the thermal efficiency of the cycle for compression ratios between 6 and 11 for specific heat ratios of 1.3, 1.35 and 1.4 and plot the results.

Given: Air-standard Otto cycle with compression ratios between 6 and 11 and k of 1.3, 1.35 and 1.4.

Find: Plot thermal efficiency.

Assumptions:

1) The engine is a closed system.

2) The air is an ideal gas.

3) The changes in kinetic and potential energies may be neglected.

Analysis: Use equation 13.9 to compute the thermal efficiency.

$$\eta_{th}=1-\frac{1}{(r)^{k-1}}$$

Developing a spreadsheet to determine efficiency with different values of r and k.

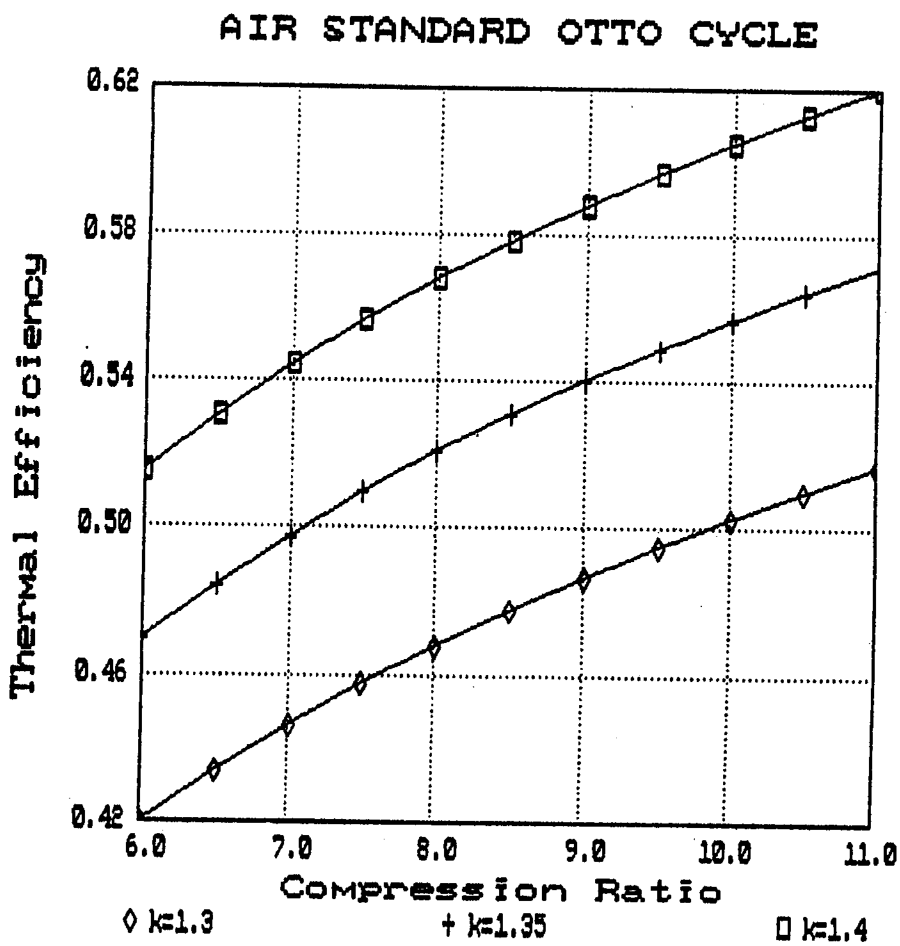
	A	B	C	D
1	Problem C13.1			
2	Otto Cycle			
3				
4	k=	1.3	1.35	1.4
5				
6	r	Eff	Eff	Eff
7				
8	6	1-1/(A8^($B$4-1))	1-1/(A8^($C$4-1))	1-1/(A8^($D$4-1))
9	6.5	1-1/(A9^($B$4-1))	1-1/(A9^($C$4-1))	1-1/(A9^($D$4-1))
10	7	1-1/(A10^($B$4-1))	1-1/(A10^($C$4-1))	1-1/(A10^($D$4-1))
11	7.5	1-1/(A11^($B$4-1))	1-1/(A11^($C$4-1))	1-1/(A11^($D$4-1))
12	8	1-1/(A12^($B$4-1))	1-1/(A12^($C$4-1))	1-1/(A12^($D$4-1))
13	8.5	1-1/(A13^($B$4-1))	1-1/(A13^($C$4-1))	1-1/(A13^($D$4-1))
14	9	1-1/(A14^($B$4-1))	1-1/(A14^($C$4-1))	1-1/(A14^($D$4-1))
15	9.5	1-1/(A15^($B$4-1))	1-1/(A15^($C$4-1))	1-1/(A15^($D$4-1))
16	10	1-1/(A16^($B$4-1))	1-1/(A16^($C$4-1))	1-1/(A16^($D$4-1))
17	10.5	1-1/(A17^($B$4-1))	1-1/(A17^($C$4-1))	1-1/(A17^($D$4-1))
18	11	1-1/(A18^($B$4-1))	1-1/(A18^($C$4-1))	1-1/(A18^($D$4-1))

This produces the following results.

```
Problem C13.1
Otto Cycle
```

k=	1.3	1.35	1.4
r	Eff	Eff	Eff
6	0.415809	0.465869	0.511640
6.5	0.429670	0.480625	0.527028
7	0.442210	0.493924	0.540843
7.5	0.453636	0.505998	0.553341
8	0.464113	0.517031	0.564724
8.5	0.473771	0.527171	0.575153
9	0.482718	0.536536	0.584756
9.5	0.491040	0.545224	0.593640
10	0.498812	0.553316	0.601892
10.5	0.506095	0.560879	0.609586
11	0.512940	0.567971	0.616784

Graphing.



Problem C13.5

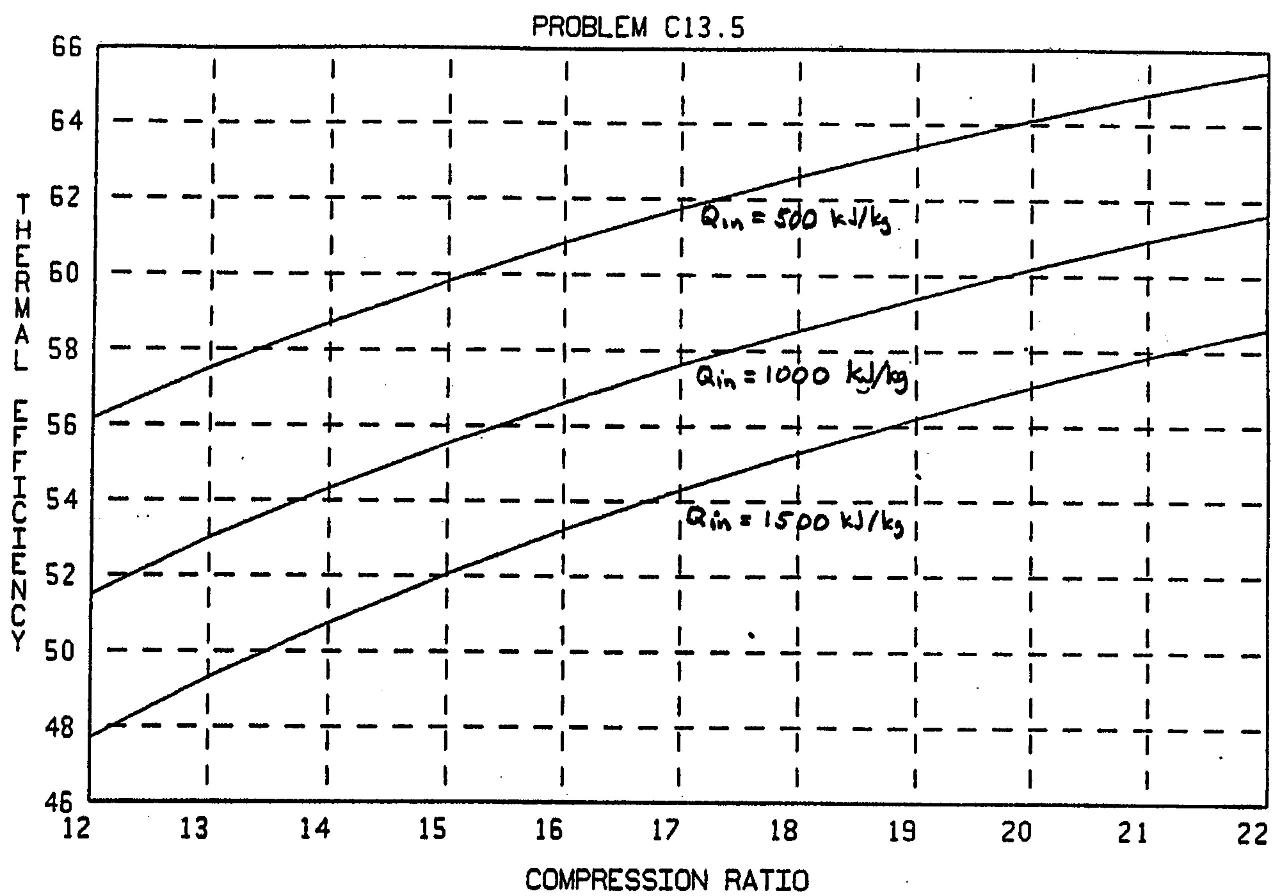
Using the TK Solver model DIESEL.TK, compute the thermal efficiency of an ideal Diesel cycle with compression ratios between 12 and 22, and for heat inputs 500 kJ/kg, 1000 kJ/kg and 1500 kJ/kg. Plot the results and compare them to those for the air-standard Diesel cycle from problem C13.2.

Given: Diesel cycle analyzed using DIESEL.TK.

Find: Thermal efficiency for range of compression ratios and heat inputs.

Assumptions:
1) The changes in kinetic and potential energies may be neglected.
2) Air at beginning of compression is 100 kPa and 300K.

Analysis: Entering data in the Rule Sheet, List Solving for a range of compression ratios from 12 to 22 and three heat inputs, and plotting.



Comments:

1. Maximum air temperature should not exceed 2000K for results to be accurate.

2. Cutoff ratios for given heat inputs are low and thus compare closest to data for air-standard cycle with $r_c = 2$.

CHAPTER 14

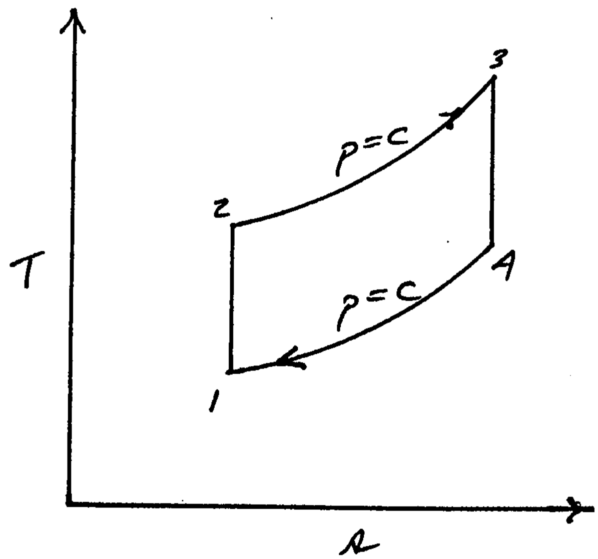
Problem 14.1

An air-standard Brayton cycle has a pressure ratio of 8. The air properties at the start of compression are 100 kPa and 25°C. The maximum allowable temperature is 1100°C. Determine (a) the thermal efficiency; (b) the net work; (c) the heat added.

Given: The initial temperature pressure and temperature, maximum temperature and pressure ratio of an air standard Brayton cycle.

Find: The thermal efficiency, net work and heat added.

Sketch and Given Data:



$T_1 = 298$ K

$P_1 = 100$ kPa

$T_3 = 1100°C = 1373$ K

$r_p = 8$

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The processes are for the air-standard Brayton cycle.
3) Air behaves as an ideal gas.
4) The changes in kinetic and potential energies may be neglected.

Analysis: The heat is added in process 2-3 at p = C.

$$q_{2\text{-}3} = h_3 - h_2 = c_p(T_3 - T_2)$$

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (298\text{ K})(8)^{0.4/1.4} = 539.8\text{ K}$$

c) $$q_{2\text{-}3} = (1.0047\text{ kJ/kg-K})(1373 - 539.8\text{ K}) = \underline{837.1}\ \frac{\text{kJ}}{\text{kg}}$$

$$T_4 = T_3\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} = (1373\ \text{K})\left(\frac{1}{8}\right)^{\frac{0.4}{1.4}} = 757.9\ \text{K}$$

$$q_{out} = h_1 - h_4 = c_p(T_1 - T_4) = (1.0047)(298 - 757.9) = -462.1\ \frac{\text{kJ}}{\text{kg}}$$

$$w_{net} = \sum q = 837.1 - 462.1 = 375\ \frac{\text{kJ}}{\text{kg}}$$

$$\eta_{Th} = \frac{w_{net}}{q_{in}} = \frac{375}{837.1} = 0.448$$

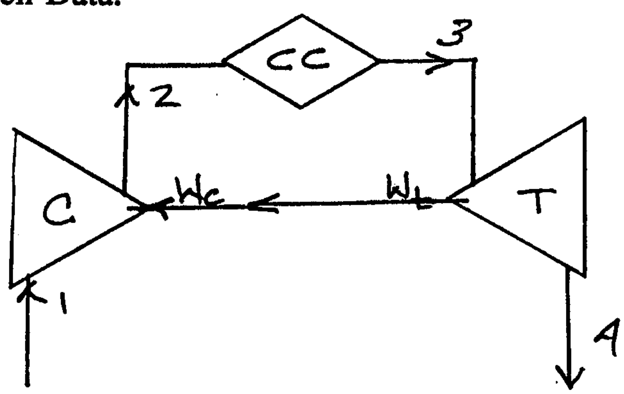
Problem 14.5

A furnace needs hot pressurized gas at 200 kPa. This gas is to be provided by the exhaust from a gas turbine operating on the Brayton cycle. The turbine will produce no power beyond that required by the compressor. The compressor inlet conditions are 100 kPa and 290°K. The turbine inlet temperature is 815°C. Determine the compressor pressure ratio.

Given: A gas turbine unit produces power to drive a compressor. The turbine discharge pressure is known as is inlet temperature and the compressor inlet state.

Find: The compressor pressure ratio.

Sketch and Given Data:



$P_4 = 200$ kPa
$P_1 = 100$ kPa
$T_1 = 290$ K
$T_3 = 815°C = 1088$ K

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) Air behaves as an ideal gas.
3) The changes in kinetic and potential energies may be neglected.
4) The system is open.

Analysis: Determine the temperatures T_2 and T_4 in terms of pressure ratios.

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (290\ \text{K})\left(\frac{p_2}{100}\right)^{0.286}$$

$$T_4 = T_3\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} = (1088\ \text{K})\left(\frac{200}{p_2}\right)^{0.286}$$

From a first law analysis

$$w_t = w_c$$

$$h_3 - h_4 = h_2 - h_1$$

$$c_p(T_3 - T_4) = c_p(T_2 - T_1)$$

$$(1088)\left(1 - \left(\frac{200}{p_2}\right)^{0.286}\right) = (290)\left(\left(\frac{p_2}{100}\right)^{0.286} - 1\right)$$

Solve by trial and error for p_2.

$p_2 \approx 279$ kPa $\quad \therefore \quad r_p = \underline{2.79}$

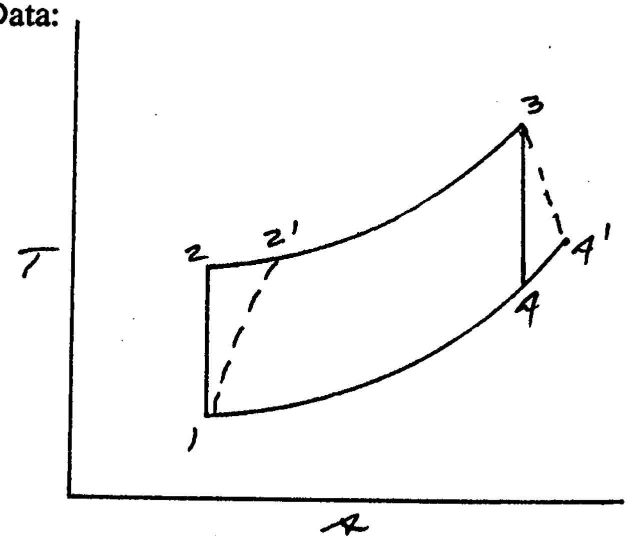
Problem 14.9

A Brayton cycle uses argon as the working substance. At the beginning of compression, the temperature is 335°K and the pressure is 480 kPa. The compression process is adiabatic with discharge conditions of 645°K and 1930 kPa. The argon is heated and enters the turbine at 1390°K and 1930 kPa and expands adiabatically to 890°K and 480 kPa. Determine (a) the compressor efficiency; (b) the turbine efficiency; (c) the thermal efficiency.

Given: An argon standard Brayton cycle, the states at the compressor inlet, compressor discharge, the turbine inlet and discharge.

Find: The compressor, turbine and cycle efficiencies.

Sketch and Given Data:



$T_1 = 335 K$
$P_1 = 480 kPa$
$T_2' = 645 K$
$P_2 = 1930 kPa$
$T_3 = 1390 K$
$P_3 = P_2$
$T_4' = 890 K$
$P_4 = P_1$

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The processes follow a Brayton cycle modified by turbine and compressor efficiencies.
3) Argon is an ideal gas.
4) The changes in kinetic and potential energies may be neglected.

Analysis: Find the isentropic states 2 and 4. the pressures actual and isentropic are the same.

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (335\ K)\left(\frac{1930}{480}\right)^{\frac{0.666}{1.666}} = 584.3\ K$$

$$T_4 = T_3\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}} = (1390\ K)\left(\frac{480}{1930}\right)^{\frac{0.666}{1.666}} = 797.0\ K$$

a) $$\eta_c = \frac{h_2 - h_1}{h_2' - h_1} = \frac{\not{c}_p(T_2 - T_1)}{\not{c}_p(T_2' - T_1)} = \frac{584.3 - 335}{645 - 335} = \underline{0.804}$$

b) $$\eta_t = \frac{h_3 - h_4'}{h_3 - h_4} = \frac{\not{c}_p(T_3 - T_4')}{\not{c}_p(T_3 - T_4)} = \frac{1390 - 890}{1390 - 797} = \underline{0.843}$$

$$w_c = h_1 - h_2' = c_p(T_1 - T_2') = \left(0.5208 \frac{kJ}{kg\text{-}K}\right)(335 - 645\ K)$$

$$w_c = -161.4\ kJ/kg$$

$$w_t = h_3 - h_4' = c_p(T_3 - T_4') = \left(0.5208 \frac{kJ}{kg\text{-}K}\right)(1390 - 890\ K)$$

$$w_t = 260.4\ kJ/kg$$

$$w_{net} = w_t + w_c = 260.4 - 161.4 = 99\ kJ/kg$$

$$q_{in} = h_3 - h_2' = c_p(T_3 - T_2') = (0.5208)(1390 - 645) = 388\ \frac{kJ}{kg}$$

c) $$\eta_{Th} = \frac{w_{net}}{q_{in}} = \frac{99}{388} = \underline{0.255}$$

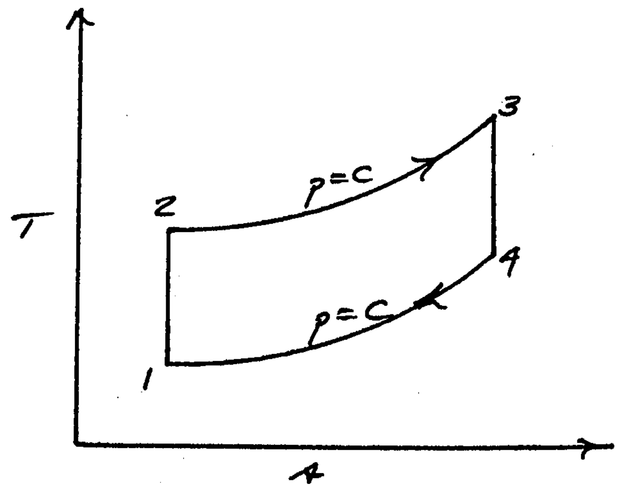
Problem 14.13

An air-standard Brayton cycle has compressor inlet conditions of 310°K and 98 kPa and turbine inlet conditions of 882 kPa and 1200°K. The heat transferred to the air in the high-temperature heat exchanger is 25 MW. Determine the net power produced, assuming (a) constant specific heats; (b) variable specific heats.

Given: An air standard Brayton cycle, the compressor and turbine inlet states and the heat supplied.

Find: The net power using constant specific heats and variable specific heats (tables).

Sketch and Given Data:



$T_1 = 310\ K$

$P_1 = 98\ kPa$

$P_3 = 882\ kPa$

$T_3 = 1200\ K$

$\dot{Q}_{in} = 25\ MW$

Assumptions:

1) Each component is analyzed as a steady-state open system.
2) The processes are for the air-standard Brayton cycle.
3) Air behaves as an ideal gas.
4) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the pressure ratio, knowing $p_2 = p_3$.

$$r_p = \frac{p_2}{p_1} = \frac{882}{98} = 9.0$$

For constant specific heat

$$\eta_{Th} = 1 - \frac{1}{(r_p)^{\frac{k-1}{k}}} = 1 - \frac{1}{(9)^{\frac{0.4}{1.4}}} = \underline{0.4662}$$

a) $\dot{W}_{net} = \eta_{Th}\,\dot{Q}_{in} = (0.4662)(25\ MW) = \underline{11.65\ MW}$

The expression for η_{Th} cannot be used in part *b*.

Determine the cycle state points using the air tables.

$$h_1 = 310.24 \text{ kJ/kg} \qquad p_{r_1} = 1.5546$$

$$p_{r_2} = p_{r_1}\left(\frac{p_2}{p_1}\right) = (1.5546)(9) = 13.991$$

$$h_2 = 581.4 \text{ kJ/kg}$$

$$h_3 = 1277.79 \qquad p_{r_3} = 238.0$$

$$p_{r_4} = p_{r_3}\left(\frac{p_4}{p_3}\right) = (238.0)\left(\frac{1}{9}\right) = 26.44$$

$$h_4 = 696.2 \text{ kJ/kg}$$

$$q_{in} = h_3 - h_2 = 1277.79 - 581.4 = 696.39 \text{ kJ/kg}$$

$$q_{out} = h_1 - h_4 = 310.24 - 696.2 = -385.96 \text{ kJ/kg}$$

$$w_{net} = \sum q = 696.39 - 385.96 = 310.43 \text{ kJ/kg}$$

$$\dot{m}_a\, q_{in} = \dot{Q}_{in}$$

$$\dot{m}_a = \frac{(25\,000 \text{ kW})}{(696.39 \text{ kJ/kg})} = 35.9 \text{ kg/s}$$

b) $$\dot{W}_{net} = \dot{m}_a\, w_{net} = (35.9 \text{ kg/s})\left(310.43\ \frac{\text{kJ}}{\text{kg}}\right) = \underline{11.14 \text{ MW}}$$

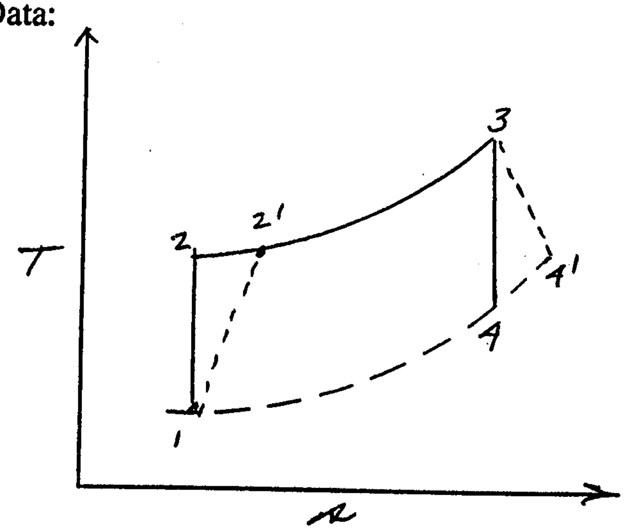
Problem 14.17

A gas turbine unit has compressor inlet conditions of 100 kPa and 310°K. The compressor discharge pressure is 700 kPa, and the temperature is 565°K. Fuel enters the combustion chamber and raises the air temperature to 1200°K. The turbine discharge temperature is 770°K, and the pressure is 100 kPa. Determine (a) the compressor and turbine adiabatic efficiencies; (b) the cycle thermal efficiency.

Given: A gas turbine unit, the compressor inlet and discharge states and the turbine inlet and discharge states.

Find: Compressor and turbine efficiencies and the cycle efficiency.

Sketch and Given Data:



$P_1 = 100\ kPa$

$T_1 = 310\ K$

$P_2 = 700\ kPa$

$T_{2'} = 565\ K$

$T_3 = 1200\ K$

$T_{4'} = 770\ K$

$P_4 = 100\ kPa$

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) Gases are ideal gases.
4) Neglect mass of fuel; use air tables.

Analysis: Determine the actual and isentropic enthalpy values around the cycle.

$h_1 = 310.24$ kJ/kg $\qquad p_{r1} = 1.5546$

$$p_{r2} = p_{r1}\left(\frac{p_2}{p_1}\right) = (1.5546)\left(\frac{700}{100}\right) = 10.882$$

$h_2 = 541.3$ kJ/kg $\qquad h_{2'} = 570.37$ kJ/kg

$h_3 = 1277.79$ kJ/kg $\qquad p_{r3} = 238.0$

$$p_{r4} = p_{r3}\left(\frac{p_4}{p_3}\right) = (238.0)\left(\frac{100}{700}\right) = 34.0$$

$$h_4 = 747.3 \text{ kJ/kg} \qquad h_4' = 789.10$$

a)

$$\eta_c = \frac{h_2 - h_1}{h_2' - h_1} = \frac{541.3 - 310.24}{570.37 - 310.24} = \underline{0.888}$$

$$\eta_t = \frac{h_3 - h_4'}{h_3 - h_4} = \frac{1277.79 - 789.10}{1277.79 - 747.3} = \underline{0.921}$$

$$w_c = h_1 - h_2' = 310.24 - 570.37 = -260.13 \text{ kJ/kg}$$

$$w_t = h_3 - h_4' = 1277.79 - 789.10 = 488.69 \text{ kJ/kg}$$

$$w_{net} = 488.69 - 260.13 = 228.56 \text{ kJ/kg}$$

The heat added is

$$q = h_3 - h_2' = 1277.79 - 570.37 = 707.42 \text{ kJ/kg}$$

b) $$\eta_{Th} = \frac{w_{net}}{q} = \frac{228.56}{707.42} = \underline{0.323}$$

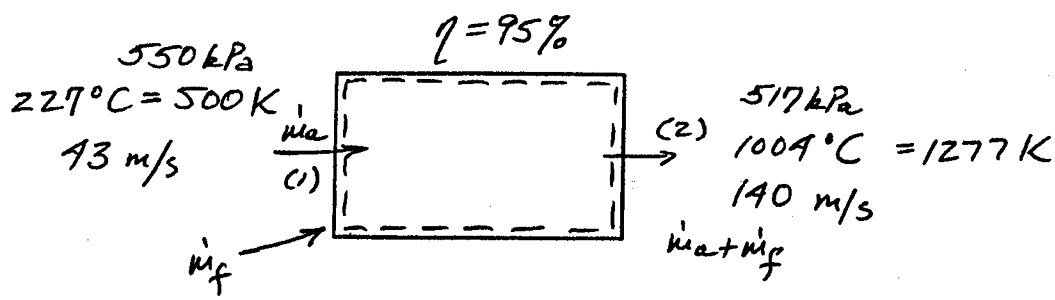
Problem 14.21

Air enters the combustion chamber of a gas turbine unit at 550 kPa, 227°C, and 43 m/s. The products of combustion leave the combustor at 517 kPa, 1004°C, and 140 m/s. Liquid fuel enters with a heating value of 43 000 kJ/kg. The combustor efficiency is 95%. Determine the fuel/air ratio.

Given: A combustion chamber, the air state entering, the combustion gas state leaving and the unit's efficiency.

Find: The fuel/air ratio.

Sketch and Given Data:



Assumptions:

1) Combustion chamber is a steady, open system.
2) The gases are ideal gases.
3) Neglect changes in potential energy.
4) The unit is adiabatic and the work is zero.

Analysis: Determine the enthalpies of air and the products.

$$h_1 = 503.02 \text{ kJ/kg} \qquad h_2 = 1398.3 \text{ kJ/kg}$$

Perform a first law analysis.

$$\dot{Q} + \dot{m}_a(h + ke + pe)_1 + \dot{m}_f\, h_{RP}\, \eta_{cc} = \dot{W} + \dot{m}_g(h + ke + pe)$$

Apply assumptions 3 and 4 and divide by $\dot{m}_a$.

$$h_1 + ke_1 + \eta_{cc}\, r_{f/a}\, h_{RP} = (1 + r_{f/a})(h_2 + ke_2)$$

$$\left(503.02\ \frac{kJ}{kg}\right) + \frac{(43\ m/s)^2}{(2)(1000\ J/kJ)}$$

$$+ (0.95)\left(r_{f/a}\ \frac{kg\ fuel}{kg\ air}\right)\left(43\ 000\ \frac{kJ}{kg\ fuel}\right)$$

$$= \left(1 + r_{f/a}\ \frac{kg\ prod}{kg\ air}\right)\left(1398.3 + \frac{140^2}{(2)(1000)}\ \frac{kJ}{kg\ prod}\right)$$

$$r_{f/a} = \underline{0.0229}\ \frac{kg\ fuel}{kg\ air}$$

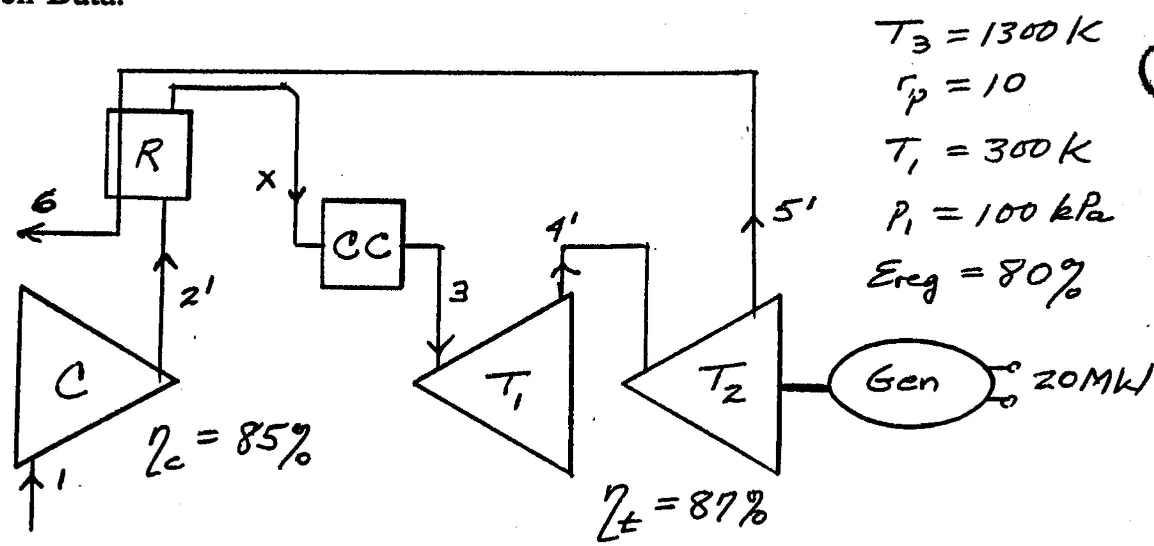
Problem 14.25

A regenerative gas turbine unit has two turbines; the first, located immediately following the combustion chamber, drives the compressor, and its discharge enters a second turbine that drives a generator. In addition, a regenerator receives the exhaust from the second turbine and the discharge from the compressor. Each turbine has an isentropic efficiency of 87%, and the compressor has an isentropic efficiency of 85%. The effectiveness of the regenerator is 80%. The turbine inlet temperature is 1300°K, and the fuel burned is dodecane. The electric power generated is 20 MW. The compressor inlet conditions are 300°K and 100 kPa, and the compressor pressure ratio is 10. Determine (a) the volume flow rate of air at compressor inlet conditions; (b) the fuel flow rate in kg/min; (c) the thermal efficiency; (d) the temperature of the products leaving the regenerator.

Given: A two-turbine, one-compressor, regenerative gas turbine unit with turbine and compressor efficiencies noted. The inlet conditions to the compressor and turbine are specified as is the net power output and pressure ratio.

Find: The air volume flow rate, the fuel flow rate, the unit's efficiency and the temperature of the products exiting the regenerator.

Sketch and Given Data:



Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The gases behave as ideal gases with constant specific heats.
3) The changes in kinetic and potential energies may be neglected.
4) Assume for the products c_p = 1.044 kJ/kg-K

Analysis: Determine the air and products temperatures around the cycle.

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (300\ K)(10)^{\frac{0.4}{1.4}} = 579.2\ K$$

$$\eta_c = \frac{h_2 - h_1}{h_2' - h_1} = \frac{T_2 - T_1}{T_2' - T_1}$$

$$0.85 = \frac{579.2 - 300}{T_2' - 300} \qquad T_2' = 628.5\ K$$

$$w_c = h_1 - h_2' = c_p(T_1 - T_2') = (1.0047)(300 - 628.5) = -330.0\ \frac{kJ}{kg}$$

$$w_{t_1} = (1 + r_{f/a})(h_3 - h_4') = 330\ kJ/kg$$

$$w_{t_1} = (1 + r_{f/a})c_p(T_3 - T_4')$$

Equation (a) $w_{t_1} = (1 + r_{f/a})(1.0047)(1300 - T_4') = 330$

Equation (b) $= (1 + r_{f/a})(h_4' - h_5') = (1 + r_{f/a})\, c_p\, (T_4' - T_5') = \omega_{t2}$

Equation (c) $\dot{m}_a\, w_{t_2} = 20\ 000\ kW$

Equation (d) $T_4 = T_3\left(\frac{p_4}{p_3}\right)^{\frac{k-1}{k}}$ (f) $T_4' = T_3 - (T_3 - T_4)\eta_t$

Equation (e) $T_5 = T_{4'}\left(\frac{p_5}{p_4}\right)^{\frac{k-1}{k}}$ (g) $T_5' = T_{4'} - (T_{4'} - T_5)\eta_t$

$$\varepsilon_{reg} = 0.8 = \frac{h_x - h_2'}{(1 + r_{f/a})(h_5' - h_c)} = \frac{c_{pa}(T_x - T_2')}{(1 + r_{f/a})c_{pg}(T_5' - T_2')}$$

Equation (h) $(0.8)(1.044)(1 + r_{f/a})(T_5' - T_2') = (1.0047)(T_x - T_2')$

$$h_x + r_{f/a}\, h_{RP} = (1 + r_{f/a})h_3$$

$$c_{p_a}\, T_x + r_{f/a}\, h_{RP} = (1 + r_{f/a})\, c_{pp}T_3$$

Equation (i) $(1.0047)(T_x) + (r_{f/a})(44102) = (1 + r_{f/a})(1.044)(1300)$

$p_5 = 100$ kPa

$p_3 = 1000$ kPa

Solve equations (a) through (i) simultaneously, iterating $r_{f/a}$, yielding

$r_{f/a} = 0.0147$ kg fuel/kg air

$T_5' = 743.3$ K

$w_{t_2} = 246.9$ kJ/kg

$p_4 = 307.2$ kPa

$T_4' = 976.3$ K

$T_x = 725.3$

$\dot{m}_a = 81.0$ kg/s

a) $$\dot{V} = \frac{\dot{m}\,RT_1}{p_1} = \frac{(81.0)(0.287)(300)}{(100)} = \underline{69.74}\ \text{m}^3/\text{s}$$

b) $$\dot{m}_f = \dot{m}_a\, r_{f/a} = (81.0)(0.0147)(60) = \underline{71.44}\ \text{kg/min}$$

c) $$\eta_{Th} = \frac{w_{t_2}}{r_{f/a}\, h_{RP}} = \frac{(246.9)}{(0.0147)(44\ 102)} = \underline{0.381}$$

From a first law analysis on the regenerator.

$$(h_x - h_2') = (1 + r_{f/a})(h_5' - h_6)$$

$$c_{pa}(T_x - T_2') = (1 + r_{f/a})c_p(T_5' - T_6)$$

$$(1.0047)(725.3 - 628.5) = (1.0147)(1.044)(743.3 - T_6)$$

d) $$T_6 = \underline{651.5\ \text{K}}$$

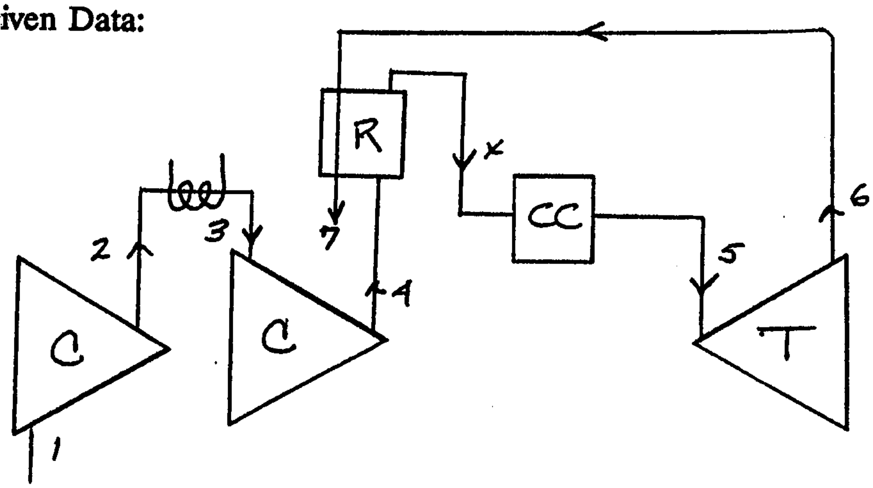
Problem 14.29

In designing a gas turbine for maximum efficiency, a decision is made to use intercooling of the compressor. The air is delivered form 100 kPa and 290°K to a final discharge pressure of 950 kPa. There are two stages of compression, with intercooling at the optimum interstage pressure. The intercooling cools the air temperature to 25°C of the inlet temperature. The regenerator has an effectiveness of 65%, and the maximum allowable turbine inlet temperature is 1350°K. All expansion and compression processes are isentropic. Determine, for h_{RP} = 43 000 kJ/kg, (a) the thermal efficiency; (b) the fuel/air ratio; (c) the turbine work per kg; (d) the compressor work per kg; (e) the heat removed in the intercooler; (f) the available energy of the products of combustion leaving the regenerator; (g) the thermal efficiency with no intercooling.

Given: A regenerative gas turbine unit has intercooling of the compressor. The compressor states are given as well as the temperature to the turbine.

Find: The unit's thermal efficiency, fuel/air ratio, turbine and compressor work, heat removed in intercooler, available energy of products leaving regenerator and the efficiency with no intercooling.

Sketch and Given Data:



$P_1 = 100$ kPa
$T_1 = 290$ K
$P_4 = 950$ kPa
$T_3 = 315$ K
$\varepsilon_{reg} = 65\%$
$T_5 = 1350$ K

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle state point enthalpies.

$$h_1 = 290.17 \text{ kJ/kg} \qquad p_{r_1} = 1.2311$$

$$p_2 = \sqrt{p_1\, p_4} = \sqrt{(100)(950)} = 308 \text{ kPa}$$

$$p_{r2} = p_{r1}\left(\frac{p_2}{p_1}\right) = (1.2311)\left(\frac{308}{100}\right) = 3.792$$

$h_2 = 400.5$ kJ/kg $\qquad h_3 = 315.26$ kJ/kg $\qquad p_{r3} = 1.6461$

$$p_{r4} = p_{r_3}\left(\frac{p_4}{p_3}\right) = (1.6461)\left(\frac{950}{308}\right) = 5.077$$

$h_4 = 445.6$ kJ/kg $\qquad T_4 = 433.9$ K

$h_5 = 1487.8$ kJ/kg $\qquad p_{r5} = 438.0$

$$p_{r6} = p_{r5}\left(\frac{p_6}{p_5}\right) = (438.0)\left(\frac{100}{950}\right) = 46.10$$

$h_6 = 813.3\ \dfrac{kJ}{kg}$ $\qquad h_c = h$ @ 433.9 K = 440.2 kJ/kg

$$\varepsilon_{reg} = 0.65 = \frac{h_x - h_4}{(1 + r_{f/a})(h_6 - h_c)} = \frac{h_x - 445.6}{(1 + r_{f/a})(813.3 - 440.2)}$$

$$h_x = 445.6 + (1 + r_{f/a})(242.5) = 242.5\ r_{f/a} + 688.1$$

From the first law analysis of the combustion chamber.

$$h_x + r_{f/a}\,h_{RP} = (1 + r_{f/a})h_5$$

$$688.1 + 242.5\ r_{f/a} + 43\,000\ r_{f/a} = (1 + r_{f/a})(1487.8)$$

b) $\qquad r_{f/a} = \underline{0.01915}\ \dfrac{\text{kg fuel}}{\text{kg air}}$

c) $\qquad w_t = (1 + r_{f/a})(h_5 - h_6) = (1.01915)(1487.8 - 813.3) = \underline{687.4\ \text{kJ/kg}}$

$$w_{c_1} = (h_1 - h_2) = (290.17 - 400.5) = -110.33$$

$$w_{c_2} = (h_3 - h_4) = (315.26 - 445.6) = -130.34$$

$$w_{net} = w_t + w_{c_1} + w_{c_2} = 687.4 - 110.33 - 130.34 = 446.7\ \text{kJ/kg}$$

a) $\eta_{Th} = \dfrac{w_{net}}{r_{f/a}\, h_{RP}} = \dfrac{(446.7)}{(0.01915)(43\ 000)} = \underline{0.542}$

d) $w_c = -110.33 - 130.34 = -241.7$ kJ/kg

From the first law on the intercooler

e) $q = h_3 - h_2 = (315.26 - 400.5) = \underline{-85.2}$ kJ/kg

Find the entropy and enthalpy at state 7

$$h_x - h_4 = (1 + r_{f/a})(h_6 - h_7)$$

$$h_x = (242.5)(0.01915) + 688.1 = 692.7\ \frac{kJ}{kg}$$

$$(692.7 - 445.6) = (0.01915)(813.3 - h_7)$$

$$h_7 = 570.8\ \frac{kJ}{kg} \qquad \Phi_7 = 7.3468\ \text{kJ/kg-K}$$

The change of available energy relative to the ambient air temperature of 290 K is

$$ae_{7\text{-}0} = (h_7 - h_0) - T_0(s_7 - s_0)$$

$$h_7 - h_0 = (570.8 - 292.4) = 278.4\ \text{kJ/kg}$$

$$s_7 - s_0 = (\Phi_7 - \Phi_0) - R \cancelto{0}{\ln\left(\frac{P_7}{P_0}\right)} = \Phi_7 - \Phi_0$$

f) $ae_{7\text{-}0} = (2778.4) - (290)(0.6786) = \underline{81.6}$ kJ/kg

With no intercooling the compressor work changes, as does h_x entering the combustion chamber. State 2 enters the regenerator.

$$P_{r2} = P_{r1}\left(\frac{P_2}{P_1}\right) = (1.2311)\left(\frac{950}{100}\right) = 11.695$$

$$h_2 = 552.5\ \text{kJ/kg} \qquad T_2 = 548\ \text{K}$$

$$w_c = h_1 - h_2 = (290.17 - 552.5) = -262.3\ \text{kJ/kg}$$

$$\varepsilon_{reg} = \frac{(h_x - h_2)}{(1 + r_{f/a})(h_6 - h_c)}$$

$$h_c = h_{prod} \text{ @ } 548 \text{ K} = 560.0 \text{ kJ//kg}$$

$$0.65 = \frac{(h_x - 552.5)}{(1 + r_{f/a})(813.3 - 560.0)}$$

From first law analysis of the combustion chamber.

$$h_x + r_{f/a}\, h_{RP} = (1 + r_{f/a})h_5$$

$$164.6\, r_{f/a} + 717.1 - r_{f/a}(43\,000) = (1 + r_{f/a})(1487.8)$$

$$r_{f/a} = 0.01849 \frac{\text{kg fuel}}{\text{kg air}}$$

$$w_t = (1 + r_{f/a})(h_5 - h_6) = (1.01849)(1487.8 - 813.3) = 687.0 \text{ kJ/kg}$$

$$w_{net} = w_t + w_c = 687.0 - 262.3 = 424.7 \text{ kJ/kg}$$

g) $$\eta_{Th} = \frac{w_{net}}{r_{f/a}\, h_{RP}} = \frac{(424.7)}{(0.1849)(43\,000)} = \underline{0.534}$$

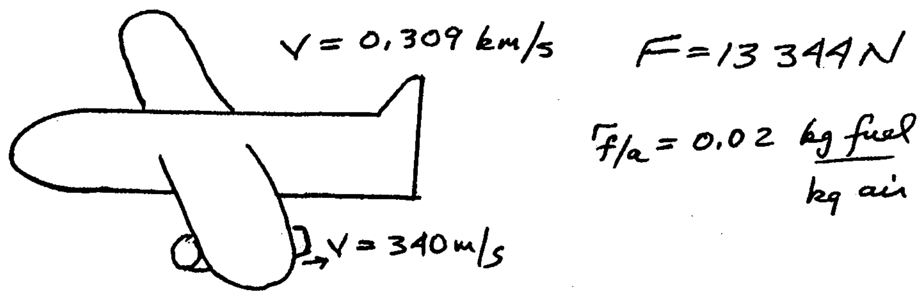
Problem 14.33

A jet plane is traveling at 0.309 km/s and has an engine that develops a thrust of 13 344 N. The gas exiting the engine has a relative velocity of 340 m/s, and the fuel/air ratio is 0.02 kg fuel/kg air. Determine (a) the air flow rate; (b) the propulsive efficiency; (c) the fuel flow rate.

Given: An airplane, its velocity and thrust and the relative velocity of the exit gas as well as the fuel/air ratio.

Find: The air and fuel flow rate and the propulsive efficiency.

Sketch and Given Data:



Assumptions:
1) The engine is a steady, open system.
2) Gases behave as ideal gases.

Analysis: The expression for thrust is found from Equation 14.18.

$$F = \dot{m}_a v_e \left[1 + r_{f/a} - \frac{v_p}{v_e}\right]$$

$$v_p = 309 \text{ m/s} \qquad v_e = 340 \text{ m/s} \quad r_{f/a} = 0.02 \ \frac{\text{kg fuel}}{\text{kg air}}$$

$$13\,444 = (\dot{m}_a)(340)\left[1.02 - \frac{309}{340}\right]$$

a) $\dot{m}_a = \underline{355.7}$ kg/s

c) $\dot{m}_f = \dot{m}_a \, r_{f/a} = (355.7)(0.02) = 7.11 \ \frac{\text{kg fuel}}{\text{s}}$

The propulsive efficiency is found from Equation 14.22.

b) $$\eta_p = \frac{2}{1 + (v_e/v_p)} = \frac{2}{1 + \left(\frac{340}{309}\right)} = \underline{0.952}$$

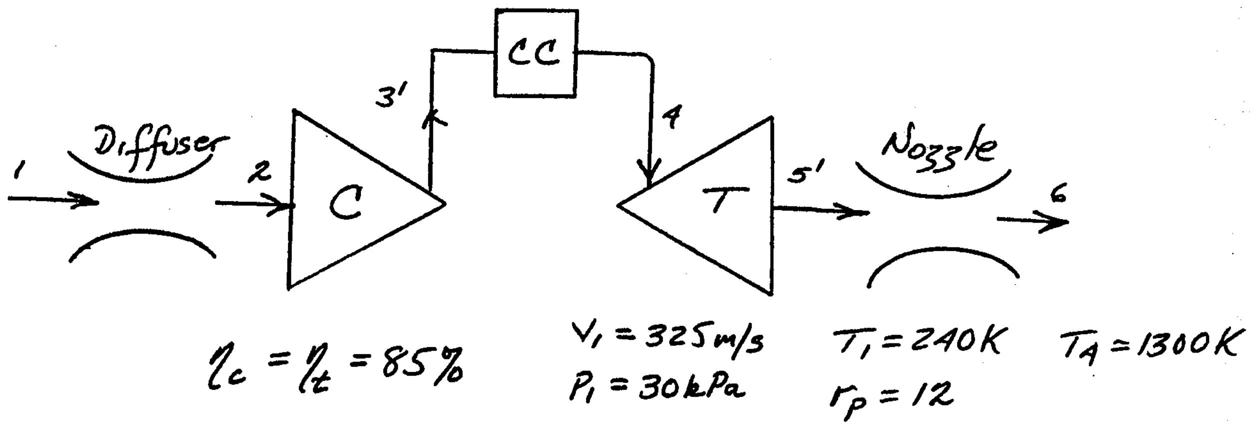
Problem 14.37

Calculate Problem 14.36 using variable specific heats for the gases and with turbine and compressor isentropic efficiencies of 85%.

Given: The airplane in Problem 14.36 is now considered using tables for the gases and with turbine and compressor efficiencies.

Find: The exhaust velocity, propulsive power and fuel consumption.

Sketch and Given Data:



Assumptions:
1) Each component is analyzed as a steady-state open system.
2) Gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the enthalpies around the cycle.

$$h_1 = 240.03 \text{ kJ/kg} \qquad p_{r1} = 0.6355$$

$$h_2 = h_1 + \frac{(v_1)^2}{2} = 240.03 + \frac{(325)^2}{(2)(1000)} = 292.8 \text{ kJ/kg}$$

$$p_{r2} = 1.2717$$

$$p_2 = p_1 \left(\frac{p_{r2}}{p_{r1}}\right) = (30 \text{ kPa})\left(\frac{1.2717}{0.6355}\right) = 60 \text{ kPa}$$

$$p_{r_3} = p_{r_2}\left(\frac{p_3}{p_2}\right) = (1.2717)(12) = 15.26$$

$$h_3 = 596.0 \text{ kJ/kg}$$

$$\eta_c = \frac{h_3 - h_2}{h_3' - h_2} = 0.85 = \frac{596.0 - 292.8}{h_3' - 292.8}$$

$$h_3' = 649.5 \text{ kJ/kg}$$

$$h_4 = 1426.4 \qquad p_{r4} = 372.6$$

The first law analysis of the combustion chamber yields

$$h_3' + r_{f/a}\, h_{RP} = (1 + r_{f/a})\, h_4$$

$$649.5 + (r_{f/a})(43\,000) = (1 + r_{f/a})(1426.4)$$

$$r_{f/a} = 0.01869 \ \frac{\text{kg fuel}}{\text{kg air}}$$

The turbine work only drives the compressor.

$$w_t = -w_c$$

$$(1 + r_{f/a})(h_4 - h_4') = -(h_2 - h_3') = -(292.8 - 649.5) = +356.7$$

$$\eta_t(1.01869)(1426.4 - h_5) = 356.7$$

$$h_4' = 1076.3 \text{ kJ/kg} \qquad p_{r5'} = 129.2$$

$$h_5 = 1014.4 \text{ kJ/kg} \qquad p_{r5} = 103.6$$

Use the isentropic value of pressure ratios to determine the pressure at state 5. The actual and ideal expand to the same pressure; the effect of the inefficiencies occur at this pressure.

$$p_5 = p_4\left(\frac{p_{r5}}{p_{r4}}\right) = (60)(12)\left(\frac{103.6}{372.6}\right) = 200.2 \text{ kPa}$$

$$p_{r6} = p_{r5'}\left(\frac{p_6}{p_5'}\right) = (129.2)\left(\frac{30}{200}\right) = 19.38$$

$$h_6 = 639.4 \text{ kJ/kg}$$

The first law analysis of the nozzle, assuming negligible velocity entering, yields.

$$h_5' = h_6 + \frac{(v_6)^2}{2}$$

$$1076.2 = 639.4 + \frac{(v_6)^2}{(2)(1000)} \qquad \text{a)} \qquad v_6 = \underline{934.7} \text{ m/s}$$

$$\dot{m}_f = \dot{m}_a\, r_{f/a} = (40 \text{ kg/s})\left(0.01869\ \frac{\text{kg fuel}}{\text{kg air}}\right) = 0.7476\ \frac{\text{kg fuel}}{\text{sec}}$$

The power is found from Equation 14.19

$$\dot{W} = \dot{m}_a\, v_e\, v_p\left[1 + r_{f/a} - \frac{v_p}{v_e}\right]$$

$$\dot{W} = \frac{(40 \text{ kg/s})(934.7 \text{ m/s})(325 \text{ m/s})}{(1000 \text{ J/kJ})}\left[1.01869 - \frac{325}{934.7}\right]$$

b) $\dot{W} = -\underline{8153 \text{ kW}}$

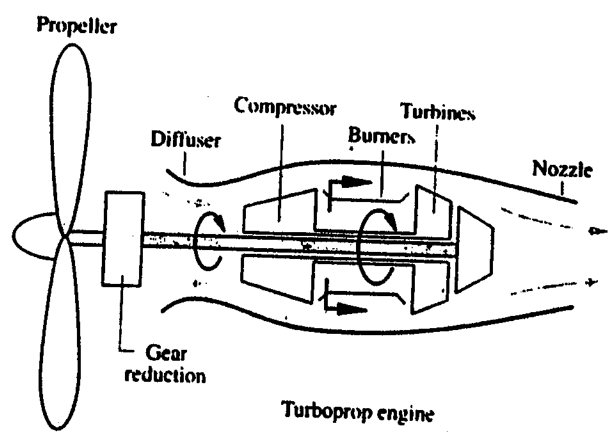
Problem 14.41

In the turboprop engine shown, the turbine's rotor is connected to the compressor and to the propeller. The engine is ideally designed such that turbine work is divided equally between the compressor and the propeller. The gas from the turbine discharges to a nozzle for additional thrust. Consider such an engine where the air enters the diffuser at 200 m/s, 40 kPa, 240°K, and a flow rate of 40 kg/s. The compressor pressure ratio is 11, and the turbine inlet temperature is 1200°K. The fuel used has a heating value of 43 000 kJ/kg. All processes are ideal. Determine (a) the fuel consumption; (b) the power delivered to the compressor; (c) the velocity from the nozzle.

Given: A turboprop engine, the air state entering the diffuser and the air flow. The pressure ratio and turbine inlet temperature are given.

Find: The fuel consumption, the power to the compressor and propeller and the gas velocity from the engine.

Sketch and Given Data:



$V_p = 200$ m/s

$P_1 = 40$ kPa

$T_1 = 240$ K

$\dot{m}_a = 40$ kg/s

$r_p = 11$

$T_4 = 1200$ K

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the enthalpies around the cycle.

$h_1 = 240.03$ kJ/kg $\qquad p_{r1} = 0.6355$

$$h_2 = h_1 + \frac{(v_1)^2}{2} = 240.03 + \frac{(200)^2}{(2)(1000)} = 260.03$$

$p_{r2} = 0.8398$

$$p_2 = p_1 \left(\frac{p_{r2}}{p_{r1}}\right) = (40 \text{ kPa})\left(\frac{0.8398}{0.6355}\right) = 52.9 \text{ kPa}$$

$$p_{r3} = p_{r2} \left(\frac{p_3}{p_2}\right) = (0.8398)(11) = 9.238$$

$h_3 = 516.6$ kJ/kg

$h_4 = 1304.5$ kJ/kg $\qquad p_{r4} = 265.4$

$$h_3 + r_{f/a}\, h_{RP} = (1 + r_{f/a})\, h_4$$

$$516.6 + (r_{fa})(43\,000) = (1 + r_{f/a})(1304.5)$$

$$r_{f/a} = 0.01890 \; \frac{\text{kg fuel}}{\text{kg air}}$$

Find the work of the high pressure turbine driving the compressor.

$$w_{t_1} = -w_c = (h_3 - h_2) = (516.6 - 260.02) = 256.6 \text{ kJ/kg}$$

$$(1 + r_{f/a})(h_4 - h_5) = 256.6$$

$$(1.0189)(1304.5 - h_5) = 256.6$$

$h_5 = 1052.6$ kJ/kg $\qquad p_{r5} = 118.8$

$$p_5 = p_4 \left(\frac{p_{r5}}{p_{r4}}\right) = (52.9)(11)\left(\frac{118.8}{265.4}\right) = 260.5 \text{ kPa}$$

$$w_{t2} = w_{t1} = (1 + r_{f/a})(h_5 - h_6) = 256.6$$

$$(1.0189)(1052.6 - h_6) = 256.6$$

$$h_6 = 800.7 \text{ kJ/kg} \qquad p_{r6} = 43.6$$

$$p_6 = p_5 \left(\frac{p_{r6}}{p_{r5}}\right) = (260.5)\left(\frac{43.6}{118.8}\right) = 95.6 \text{ kPa}$$

Assume the velocity entering the nozzle is negligible.

$$p_{r7} = p_{r6} \left(\frac{p_7}{p_6}\right) = (43.6)\left(\frac{40}{95.6}\right) = 18.24$$

$$h_7 = 628.5 \text{ kJ/kg}$$

$$h_6 = h_7 + \frac{(v_7)^2}{2}$$

$$800.7 = 628.5 + \frac{(v_7)^2}{(2)(1000)}$$

c) $v_7 = \underline{586.8 \text{ m/s}}$

a) $\dot{m}_f = \dot{m}_a \, r_{f/a} = (40 \text{ kg/s})\left(0.0189 \dfrac{\text{kg fuel}}{\text{kg air}}\right) = \underline{0.756} \text{ kg/s}$

The propeller and compressor works are assumed equal, but opposite in sign.

$$\dot{W}_c = \dot{m}_a (h_2 - h_3) = (40 \text{ kg/s})(260.03 - 516.6)$$

$$\dot{W}_c = \underline{-10\ 263 \text{ kW}}$$

b) $\dot{W}_p = \underline{10\ 263 \text{ kW}}$

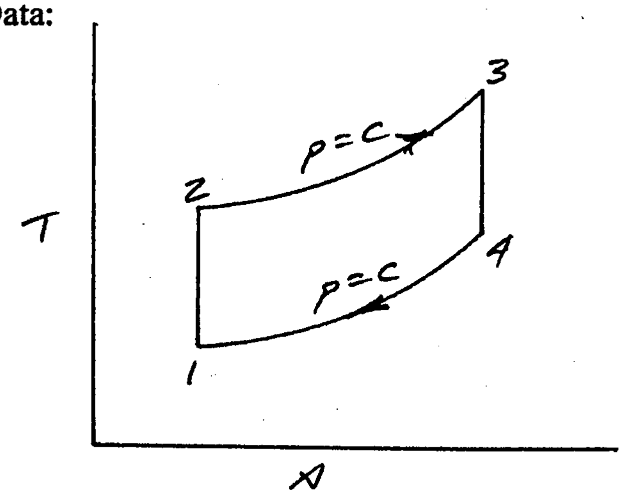
Problem *14.1

An air-standard Brayton cycle has temperature limits of 100°F and 1200°F and p_1 = 15 psia. Determine (a) the pressure ratio for maximum work; (b) the thermal efficiency.

Given: An air standard Brayton cycle, the temperature limits and the compressor inlet pressure.

Find: The pressure ratio for maximum work and the efficiency.

Sketch and Given Data:



Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The processes are for the air-standard Brayton cycle.
3) Air behaves as an ideal gas.
4) The changes in kinetic and potential energies may be neglected.

Analysis: For maximum work between fixed temperature limits the optimum presure ratio if found from Equation 14.6.

a) $$r_p = \left(\frac{T_3}{T_1}\right)^{\frac{k}{2(k-1)}} = \left(\frac{1660}{560}\right)^{\frac{1.4}{0.4}} = \underline{6.7}$$

b) $$\eta_{Th} = 1 - \frac{1}{(r_p)^{\frac{k-1}{k}}} = 1 - \frac{1}{(6.7)^{\frac{0.4}{1.4}}} = \underline{0.42}$$

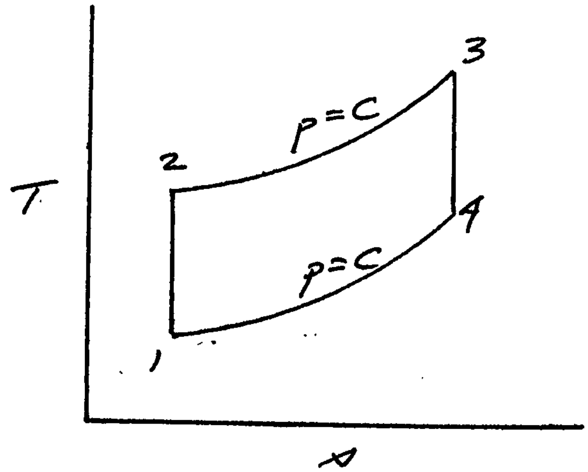
Problem *14.5

An air-standard Brayton cycle has compressor inlet conditions of 100°F and 14.5 psia and turbine inlet conditions of 130 psia and 2160°R. The heat transferred to the air in the high-temperature heat exchanger is 24 000 Btu/sec. Determine the net power produced, assuming (a) constant specific heats; (b) variable specific heats.

Given: An air standard Brayton cycle, the compressor and turbine inlet states and the heat supplied.

Find: The net power using constant specific heats and variable specific heats (tables).

Sketch and Given Data:



$T_1 = 100\ F$

$P_1 = 14.5\ psia$

$P_3 = 130\ psia$

$T_3 = 2160\ °R$

$\dot{Q}_{in} = 24000\ \frac{Btu}{sec}$

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The processes are for the air-standard Brayton cycle.
3) Air behaves as an ideal gas.
4) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the pressure ratio, knowing $p_2 = p_3$.

$$r_p = \frac{p_2}{p_1} = \frac{130}{14.5} = 9.0$$

For constant specific heat

a) $$\eta_{Th} = 1 \frac{1}{(r_p)^{\frac{k-1}{k}}} = 1 - \frac{1}{(9)^{\frac{0.4}{1.4}}} = \underline{0.4662}$$

Determine the cycle state points using the air tables.

$h_1 = 133.86$ Btu/lbm $\qquad p_{r1} = 1.5742$

$$p_{r2} = p_{r1}\left(\frac{p_2}{p_1}\right) = (1.5742)(9) = 14.168$$

$h_2 = 250.95$ Btu/lbm

$$h_3 = 549.35\ \frac{\text{Btu}}{\text{lbm}} \qquad p_{r3} = 238.0$$

$$p_{r4} = p_{r3}\left(\frac{p_4}{p_3}\right) = (238.0)\left(\frac{1}{9}\right) = 26.44$$

$h_4 = 299.2$ Btu/lbm

$q_{in} = h_3 - h_2 = 549.4 - 250.95 = 298.5$ Btu/lbm

$q_{out} = h_1 - h_4 = 133.9 - 299.2 = -165.3$ Btu/lbm

$w_{net} = \sum q = 298.5 - 165.3 = 133.2$ Btu/lbm

$\dot{m}_a\, q_{in} = \dot{Q}_{in}$

$$\dot{m}_a = \frac{(24\ 000)\ \text{Btu/sec})}{(298.5\ \text{Btu/lbm})} = 80.4\ \text{lbm/sec}$$

b) $$\dot{W}_{net} = \dot{m}_a\, w_{net} = \left(80.4\ \frac{\text{lbm}}{\text{sec}}\right)\left(133.2\ \frac{\text{Btu}}{\text{lbm}}\right) = \underline{10{,}709}\ \frac{\text{Btu}}{\text{sec}}$$

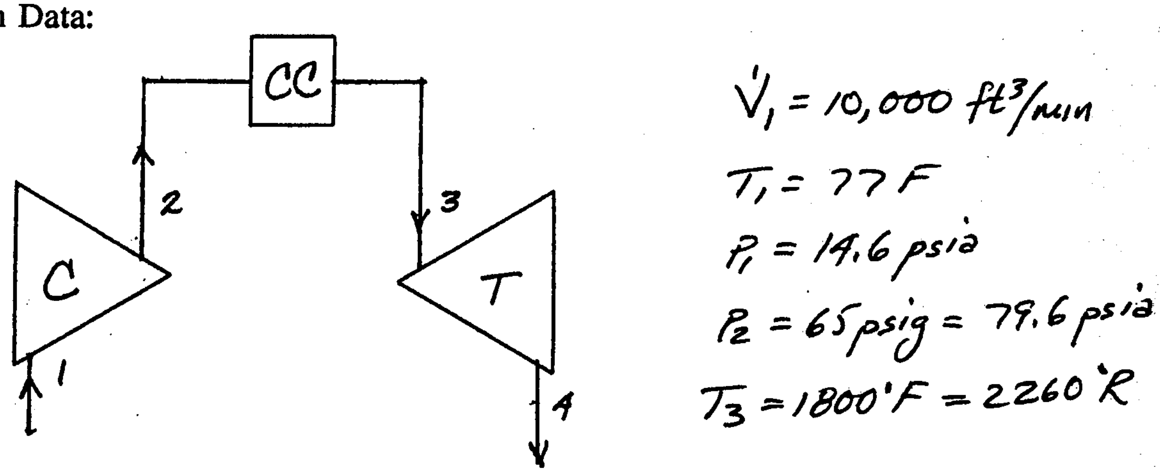
Problem *14.9

A gas turbine unit receives 10,000 ft³/min of air at 77°F and 14.6 psia and compresses it isentropically to 65 psig. In the combustion chamber, fuel with a heating value of 18,600 Btu/lbm is added so the maximum temperature is 1800°F. The turbine exhausts to atmospheric pressure. Determine (a) the fuel flow rate; (b) the unit thermal efficiency; (c) the turbine exit temperature; (d) the availability of the products of combustion leaving the turbine, if T_0 = 77°F.

Given: The volume flow rate of air entering a gas turbine unit, its state, the compressor discharge pressure and maximum temperature.

Find: The fuel flow rate, efficiency, turbine exit temeprture and the products' availability leaving the turbine.

Sketch and Given Data:



Assumptions:
1) Each component is analyzed as a steady-state open system.
2) Air behaves as an ideal gas.
3) The changes in kinetic and potential energies may be neglected.
4) Products have properties of air.

Analysis: Determine the enthalpies around the cycle.

h_1 = 128.34 Btu/lbm $\qquad p_{r1}$ = 1.3593

$$p_{r2} = p_{r1}\left(\frac{p_2}{p_1}\right) = (1.3593)\left(\frac{789.6}{14.6}\right) = 7.4110$$

h_2 = 208.6 Btu/lbm

$$h_3 = 577.5 \ \frac{\text{Btu}}{\text{lbm}} \qquad p_{r3} = 286.6$$

$$p_{r4} = p_{r3}\left(\frac{p_4}{p_3}\right) = (286.6)\left(\frac{14.6}{79.6}\right) = 52.57$$

$h_4 = 362.9$ Btu/lbm c) $T_4 = \underline{1476\ R}$

$$h_2 + r_{f/a}\, h_{RP} = (1 + r_{f/a})h_3$$

$$(208.6) + (r_{f/a})(18{,}600) = (1 + r_{f/a})(577.5)$$

$$r_{f/a} = 0.0205 \ \frac{\text{lbm fuel}}{\text{lbm air}}$$

$$\dot{m}_a = \frac{p_1\dot{V}_1}{RT_1} = \frac{(14.6\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)(10{,}000\ \text{ft}^3/\text{min})}{\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(536\ \text{R})} = 734\ \frac{\text{lbm}}{\text{min}}$$

a) $$\dot{m}_f = \dot{m}_a\, r_{f/a} = (734)(0.0205) = \underline{15.05}\ \frac{\text{lbm fuel}}{\text{min}}$$

$$w_c = (h_1 - h_2) = (128.34 - 208.6) = -80.26\ \text{Btu/lbm}$$

$$w_t = (1 + r_{f/a})(h_3 - h_4) = (1.0205)(577.5 - 362.9) = 219.0\ \text{Btu/lbm}$$

$$w_{net} = w_t + w_c = 219.0 - 80.26 = 138.7\ \frac{\text{Btu}}{\text{lbm}}$$

b) $$\eta_{Th} = \frac{w_{net}}{r_{f/a}\, h_{RP}} = \frac{(138.7)}{(0.0205)(18{,}600)} = \underline{0.364}$$

$$\Psi_4 - \Psi_0 = (h_4 - h_0) - T_0(s_4 - s_0)$$

$$h_0 = h_1$$

$$s_4 - s_0 = \Phi_4 - \Phi_0 - R\ln\left(\frac{p_4}{p_0}\right) = (0.8499 - 0.59945) = 0.25045\ \frac{\text{Btu}}{\text{lbm}}$$

$$\Psi_4 - \Psi_0 = \left(362.9 - 128.34\ \frac{\text{Btu}}{\text{lbm}}\right) - (537\ \text{R})\left(0.25045\ \frac{\text{Btu}}{\text{lbm-R}}\right)$$

$$\Psi_4 - \Psi_0 = 100\ \frac{\text{Btu}}{\text{lbm}}$$

$$\dot{m}\left(\Psi_4 - \Psi_0\right) = \left(734\ \frac{\text{lbm}}{\text{min}}\right)\left(100\ \frac{\text{Btu}}{\text{lbm}}\right) = 73{,}400\ \frac{\text{Btu}}{\text{min}}$$

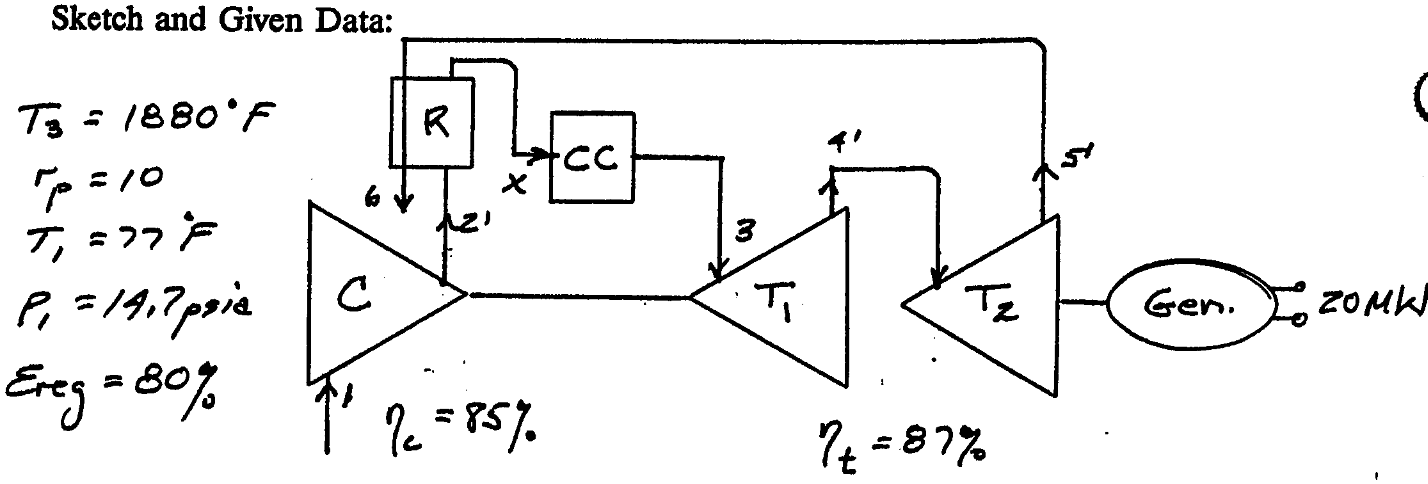
Problem *14.13

A regenerative gas turbine unit has two turbines; the first, located immediately following the combustion chamber, drives the compressor, and its discharge enters a second turbine that drives a generator. In addition, a regenerator receives the exhaust from the second turbine and the discharge form the compressor. Each turbine has an isentropic efficiency of 87%, and the compressor has an isentropic efficiency of 85%. The effectiveness of the regenerator is 80%. The turbine inlet temperature is 1880°F, and the fuel burned is dodecane. The electric power generated is 20 MW. The compressor inlet conditions are 77°F and 1 atm, and the compressor pressure ratio is 10. Determine (a) the volume flow rate of air at compressor inlet conditions; (b) the fuel flow rate in lbm/min; (c) the thermal efficiency; (d) the temperature of the products leaving the regenerator.

Given: A two-turbine, one-compressor, regenerative gas turbine unit with turbine and compressor efficiencies. The inlet conditions to the compressor and turbine are specified as is the net power output and pressure ratio.

Find: The air volume flow rate, the fuel flow rate, the unit's efficiency and the temperature of the products exiting the regenerator.

Sketch and Given Data:



Assumptions:
1) Each component is analyzed as a steady-state open system.
2) The gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.
4) Assume products have properties of air. Neglect mass of fuel.

Analysis: Determine the air and products enthalpies around the cycle.

$$h_1 = 128.34 \ \frac{\text{Btu}}{\text{lbm}} \qquad\qquad p_{r1} = 1.3593$$

$$p_{r2} = p_{r1}\left(\frac{p_2}{p_1}\right) = (1.3593)(10) = 13.593 \qquad h_2 = 247.95\ \frac{\text{Btu}}{\text{lbm}}$$

$$\eta_c = 0.85 = \frac{h_2 - h_1}{h_2' - h_1} = \frac{(247.95 - 128.34)}{(h_2' - 128.34)}$$

$$h_2' = 269.06\ \frac{\text{Btu}}{\text{lbm}} \qquad T_2' = 1112\ \text{R}$$

$$h_3 = 600.16\ \text{Btu/lbm} \qquad p_{r3} = 330.9$$

$$w_c = -(h_2' - h_1) = -(269.06 - 128.34) = -140.72\ \text{Btu/lbm}$$

$$w_{t1} = 140.72 = (h_3 - h_4)\eta_t = (600.16 - h_4)(0.87)$$

$$h_4 = 438.41 \qquad p_{r4} = 103.93$$

$$p_4 = p_3\left(\frac{p_{r4}}{p_{r3}}\right) = (147\ \text{lb}_f/\text{in}^2)\left(\frac{103.93}{330.9}\right) = 46.17\ \text{psia}$$

$$\eta_t = 0.87 = \frac{h_3 - h_4'}{h_3 - h_4} = \frac{(600.16 - h_4')}{(600.16 - 438.41)} = 46.17\ \text{psia}$$

$$h_4' = 459.44\ \text{Btu/lbm} \qquad p_{r4'} = 123.25$$

$$p_{r5} = p_{r4'}\left(\frac{p_5}{p_4}\right) = (123.25)\left(\frac{14.7}{46.17}\right) = 39.24$$

$$h_5 = 334.5\ \text{Btu/lbm}$$

$$\eta_t = 0.87 = \frac{h_4' - h_5'}{h_4' - h_5} = \frac{459.44 - h_5'}{459.44 - 334.5}$$

$$h_5' = 350.7\ \frac{\text{Btu}}{\text{lbm}}$$

$$\varepsilon_{reg} = 0.80 = \frac{h_x - h_2'}{(h_5' - h_2')} = \frac{h_x - 269.06}{(350.7 - 269.06)}$$

$$h_x = 334.4 \text{ Btu/lbm}$$

$$h_x + r_{f/a}\, h_{RP} = (1 + r_{f/a})h_3$$

$$(334.4) + (r_{f/a})(18{,}964) = (1 + r_{f/a})(600.16)$$

$$r_{f/a} = 0.01447 \ \frac{\text{lbm fuel}}{\text{lbm air}}$$

$$w_{t2} = (h_4' - h_5') = (459.44 - 350.7) = 108.74 \text{ Btu/lbm}$$

$$\dot{W}_{net} = \dot{m}_a\, w_{t_2}$$

$$(20\ 000 \text{ kW})\left(0.94777\ \frac{\text{Btu/sec}}{\text{kW}}\right) = \left(\dot{m}_a\ \frac{\text{lbm}}{\text{sec}}\right)\left(108.74\ \frac{\text{Btu}}{\text{lbm}}\right)$$

$$\dot{m}_a = 174.3 \text{ lbm/sec}$$

$$\dot{m}_f = \dot{m}_a\, r_{f/a} = \left(174.3\ \frac{\text{lbm}}{\text{sec}}\right)\left(0.01447\ \frac{\text{lbm fuel}}{\text{lbm air}}\right)\left(60\ \frac{\text{sec}}{\text{min}}\right)$$

b) $\dot{m}_f = \underline{151.3}\ \dfrac{\text{lbm fuel}}{\text{min}}$

$$\dot{V} = \frac{\dot{m}\, RT_1}{p_1} = \frac{(174.3 \text{ lbm/sec})\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(537 \text{ R})}{(14.7 \text{ lb}_f/\text{in}^2)(144 \text{ in}^2/\text{ft}^2)}$$

a) $\dot{V} = \underline{2358}\ \text{ft}^3/\text{sec}$

c) $\eta_{Th} = \dfrac{w_{t2}}{r_{f/a}\, h_{RP}} = \dfrac{(108.74)}{(0.01447)(18{,}964)} = \underline{0.396}$

From the first law on the regenerator.

$$(h_x - h_2') = (h_5' - h_6)$$

$(334.4 - 269.06) = (350.7 - h_6)$

$h_6 = 285.36$

d) $T_6 = \underline{1176\ R}$

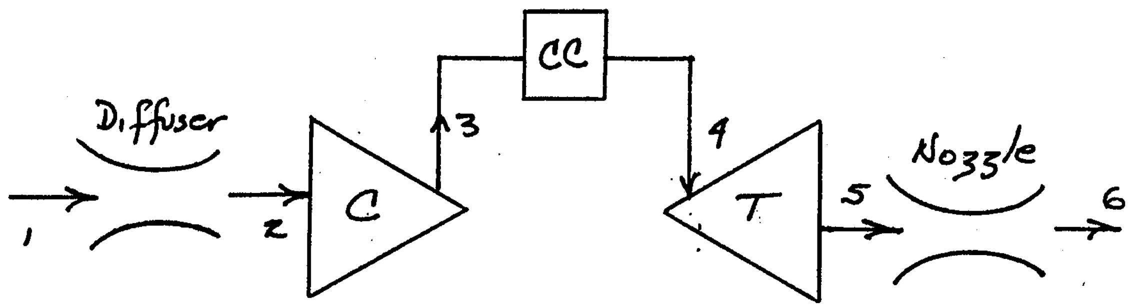
Problem *14.17

A turbojet aircraft has a velocity of 920 ft/sec and flies at an altitude of 20,000 ft. The air conditions at 20,000 ft are 7 psia and 5°F. The compressor's pressure ratio is 14, and the turbine inlet temperature is 2340°R. Determine for the ideal cycle (a) the pressure at the turbine exit; (b) the exhaust gas velocity; (c) the propulsive efficiency.

Given: An airplane, its velocity and the ambient air state. The gas turbine unit pressure ratio and turbine inlet temperature are specified.

Find: The turbine exit pressure, exhaust gas velocity from nozzle and propulsive efficiency.

Sketch and Given Data:



$V_1 = 920$ ft/sec $\quad T_1 = 5°F = 465°R \quad T_4 = 2340°R$

$P_1 = 7$ psia $\quad r_p = 14$

Assumptions:
1) Each component is analyzed as a steady-state open system.
2) Gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.
4) Assume fuel is dodecane.

Analysis: Determine the enthalpies around the cycle.

$h_1 = 111.1$ Btu/lbm $\qquad p_{r1} = 0.8218$

$$h_2 = h_1 + \frac{v_1^2}{2} = 111.1 + \frac{(920)^2}{(2)(32.174)(778.16)} = 128.0 \text{ Btu/lbm}$$

$p_{r2} = 1.3470$

$$p_2 = p_1 \left(\frac{p_{r2}}{p_{r1}}\right) = (7)\left(\frac{1.3470}{0.8218}\right) = 11.47 \text{ psia}$$

$$p_{r3} = p_{r2}\left(\frac{p_3}{p_2}\right) = (1.347)(14) = 18.86$$

$$h_3 = 271.0 \text{ Btu/lbm}$$

From the first law analysis of the combustion chamber.

$$h_3 + r_{f/a}\, h_{RP} = (1 + r_{f/a})\, h_4$$

$$h_4 = 600.16 \qquad p_{r4} = 330.9$$

$$271.0 + (r_{f/a})(18{,}964) = (1 + r_{f/a})(600.16)$$

$$r_{f/a} = 0.01792 \ \frac{\text{lbm fuel}}{\text{lbm air}}$$

Since $w_t = -w_c$ and

$$w_c = h_2 - h_3 = (128.0 - 271.0) = -143 \text{ Btu/lbm}$$

$$w_t = (1 + r_{f/a})(h_4 - h_5) = (1.01792)(600.16 - h_5) = 143.0$$

$$h_5 = 459.68 \text{ Btu/lbm} \qquad p_{r5} = 123.5$$

a) $$p_5 = p_4\left(\frac{p_{r5}}{p_{r4}}\right) = (14)(11.47 \text{ psia})\left(\frac{123.5}{330.9}\right) = \underline{59.9 \text{ psia}}$$

$$p_{r6} = p_{r5}\left(\frac{p_6}{p_5}\right) = (123.5)\left(\frac{7}{59.9}\right) = 14.43 \quad h_6 = 252.2 \text{ Btu/lbm}$$

From the first law analysis of the nozzle and assuming the velocity entering is negligible.

$$h_5 = h_6 + \frac{(v_6)^2}{2}$$

$$459.68 = 252.2 + \frac{(v_6)^2}{(2)(32.174)(778.16)}$$ b) $$v_6 = \underline{3223 \text{ ft/sec}}$$

c) $$\eta_p = \frac{2}{1 + \left(\frac{v_e}{v_p}\right)} = \frac{2}{1 + \left(\frac{3223}{920}\right)} = \underline{0.444}$$

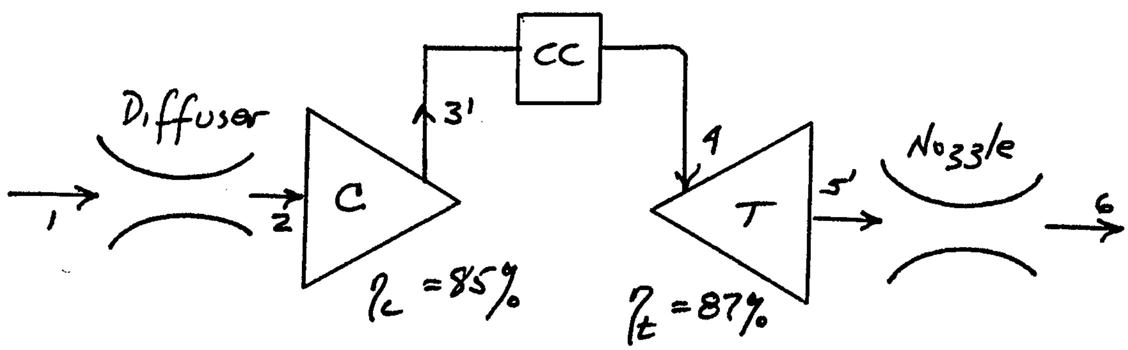
Problem *14.21

An aircraft driven by a turbojet engine is flying at an altitude of 33,000 ft where the air temperature is -46°F and the pressure is 3.4 kPa. The compressor pressure ratio is 12, and the turbine inlet temperature is 2250°R. The turbine and compressor isentropic efficiencies are 87% and 85% respectively. Determine (a) the velocity at the nozzle exit; (b) the pressure entering the nozzle.

Given: An airplane is flying through air at a known state. The pressure ratio, turbine inlet temperature and compressor and turbine efficiencies are known.

Find: The gas exit velocity from the engine and the pressure entering the nozzle.

Sketch and Given Data:



$T_1 = -46\ F$

$P_1 = 3.4\ psia$

$r_p = 12$

$T_4 = 2250\ °R$

Assumptions:

1) Each component is analyzed as a steady-state open system.
2) The gases behave as ideal gases.
3) The changes in kinetic and potential energies may be neglected.
4) The initial velocity is 300 ft/sec.
5) The fuel is dodecane.

Analysis: Determine the enthalpies around the cycle.

$$h_1 = 98.89 \text{ Btu/lbm} \qquad p_{r1} = 0.5477$$

$$h_2 = h_1 + \frac{(v_1)^2}{2} = (98.89) + \frac{(300)^2}{(2)(32.174)(778.16)} = 100.69 \text{ Btu/lbm}$$

$$p_{r_2} = 0.5830 \qquad p_2 = p_1\left(\frac{p_{r_2}}{p_{r_1}}\right) = (3.4)\left(\frac{0.5830}{0.5477}\right) = 3.62 \text{ psia}$$

$$p_{r3} = p_{r3}\left(\frac{p_3}{p_2}\right) = (0.5830)(12) = 6.996$$

$$h_3 = 205.2 \text{ Btu/lbm}$$

$$\eta_c = 0.85 = \frac{h_3 - h_2}{h_3' - h_2} = \frac{205.2 - 100.69}{h_3' - 100.69}$$

$$h_3' = 223.6 \text{ Btu/lbm}$$

$$h_4 = 574.69 \qquad p_{r4} = 281.4$$

$$h_3' + r_{f/a}\, h_{RP} = (1 + r_{f/a})\, h_4$$

$$223.6 + (r_{f/a})(18.964) = (1 + r_{f/a})(574.69)$$

$$r_{f/a} = 0.01909 \frac{\text{lbm fuel}}{\text{lbm air}}$$

The pressure entering the nozzle is the isentropic pressure. The irreversibilities are assumed added at constant pressure, p_5.

$$w_t = (1 + r_{f/a})(h_4 - h_5)(\eta_t) = -w_c(h_3' - h_2)$$

$$(1.01909)(574.69 - h_5)(0.87) = (223.6 - 100.69)$$

$$h_5 = 436.06 \text{ Btu/lbm} \qquad p_{r5} = 101.97$$

b) $$p_5 = p_4 \left(\frac{p_{r5}}{p_{r4}}\right) = (3.62)(12)\left(\frac{101.97}{281.4}\right) = \underline{15.74} \text{ psia}$$

$$\eta_t = 0.87 = \frac{h_4 - h_5'}{h_4 - h_5} = \frac{574.69 - h_5'}{574.69 - 436.06}$$

$$h_5' = 454.08 \text{ Btu/lbm} \qquad p_{r5'} = 118.12$$

Assume $v_5' \approx 0$

$$p_{r6} = p_{r5'} \left(\frac{p_6}{p_5}\right) = (118.12)\left(\frac{3.4}{15.74}\right) = 25.52$$

$$h_6 = 296.4 \text{ Btu/lbm}$$

$$h_5' = h_6 + \frac{(v_6)^2}{2}$$

$$454.08 = 296.4 + \frac{(v_6)^2}{(2)(32.174)(778.16)}$$

a) $v_6 = \underline{2810.0}$ ft/sec

Problem C14.1

Develop a computer program, spreadsheet template or TK Solver model to calculate the thermal efficiency of an air-standard Brayton cycle using equation (14.4). Calculate the cycle thermal efficiency for pressure ratios between 3 and 15 and for specific heat ratios of 1.3, 1.4, 1.5, 1.6 and 1.7. Plot the results.

Given: Air-standard Brayton cycle with pressure ratios between 3 and 15 and k of 1.3 to 1.7.

Find: Plot thermal efficiency.

Assumptions:

1) Each component is analyzed as a steady-state open system.

2) Air behaves like an ideal gas.

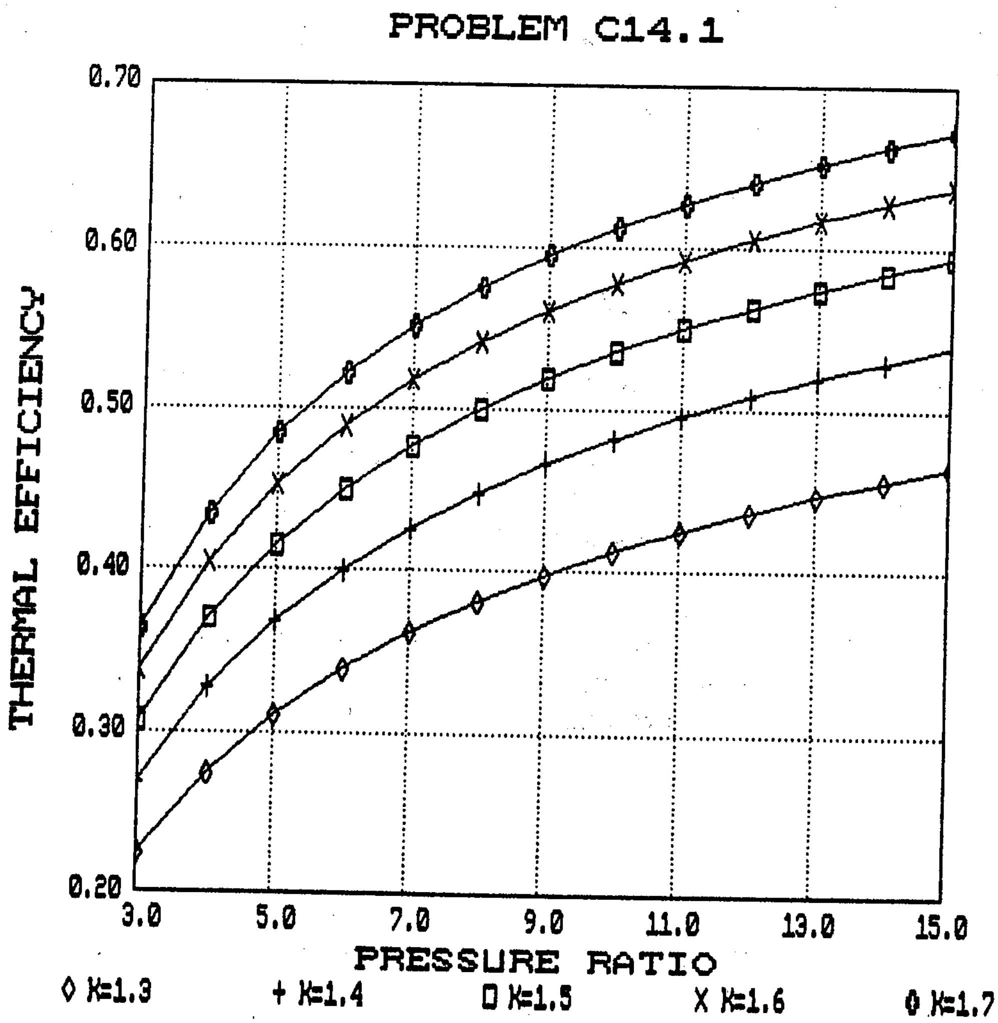
3) The changes in kinetic and potential energies may be neglected.

Analysis: Using a spreadsheet program, enter equation 14.4 and copy to a range of cells to permit calculating the thermal efficiency for different values of pressure ratio and specific heat ratio. The results calculated are.

AIR STANDARD BRAYTON CYCLE

k=	1.3	1.4	1.5	1.6	1.7
Rp	Eth	Eth	Eth	Eth	Eth
3	0.223940	0.269400	0.306638	0.337662	0.363881
4	0.273788	0.327049	0.370039	0.405396	0.434942
5	0.310238	0.368614	0.415196	0.453127	0.484547
6	0.338657	0.400663	0.449678	0.489267	0.521827
7	0.361769	0.426486	0.477242	0.517954	0.551235
8	0.381136	0.447955	0.5	0.541497	0.575244
9	0.397731	0.466223	0.519250	0.561308	0.595352
10	0.412198	0.482052	0.535841	0.578303	0.612532
11	0.424985	0.495966	0.550355	0.593109	0.627444
12	0.436416	0.508342	0.563209	0.606171	0.640555
13	0.446731	0.519458	0.574709	0.617817	0.652209
14	0.456112	0.529526	0.585086	0.628291	0.662662
15	0.464703	0.538710	0.594519	0.637785	0.672110

Graphing the results.



Comment: Thermal efficiency increases with higher values of pressure ratio and specific heat ratio.

Problem C14.5

Use the model developed for problem C14.4 to determine the effect of varying the maximum cycle temperature (T3). Calculate the thermal efficiency of a simple Brayton cycle with a pressure ratio of 10, compressor and turbine efficiencies of 100 percent and maximum cycle temperatures between 1000K and 1400K. Repeat for component efficiencies of 85 percent.

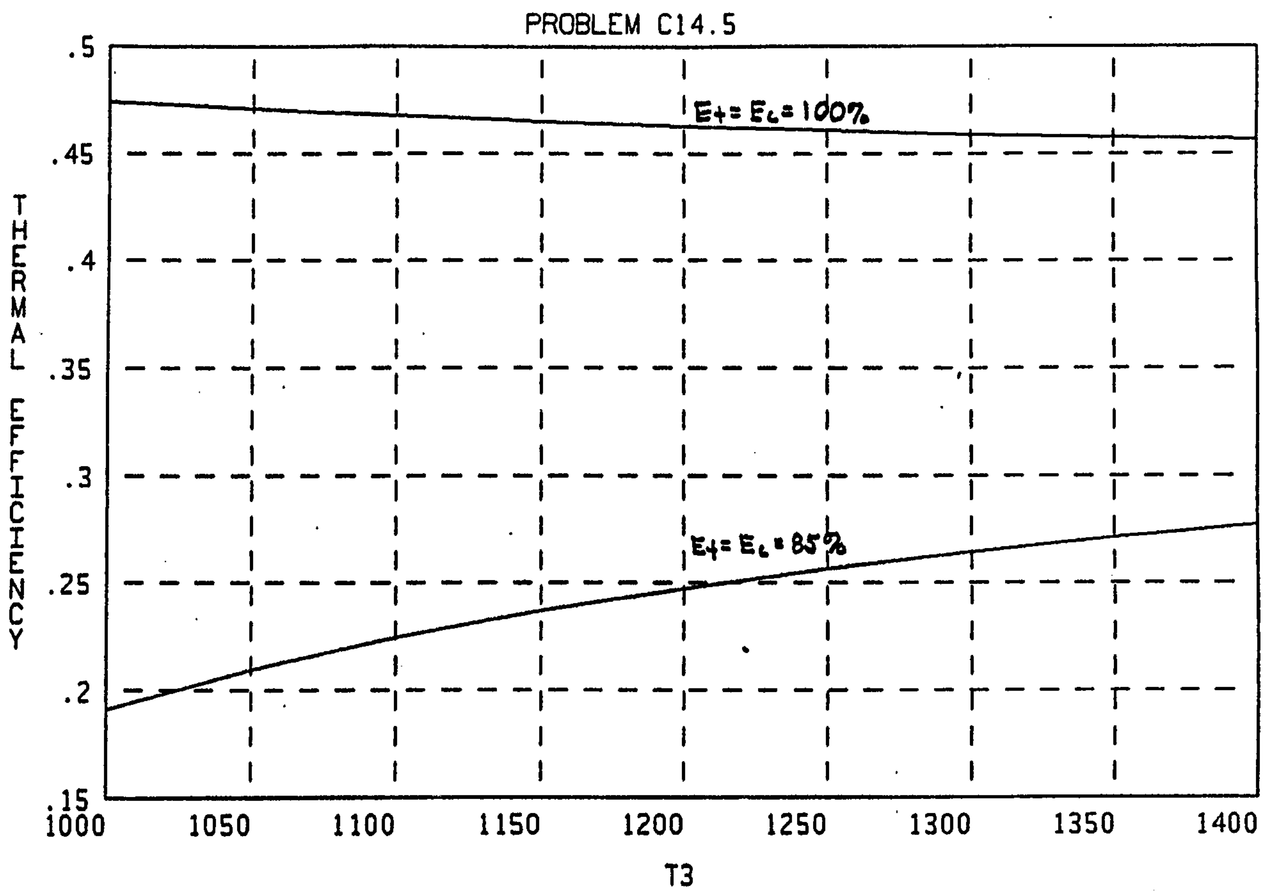
Given: Simple Brayton cycle with pressure ratio of 10, compressor and turbine efficiencies of 100 and 85 percent and maximum cycle temperatures between 1000K and 1400K.

Find: Cycle thermal efficiencies.

Assumptions:

1) Each component is analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Using the model from Problem C14.4, List Solving for a T3 between 1000K and 1400K, and plotting the results.



Comment: For component efficiencies below 100%, higher values of T3 result in higher thermal efficiencies.

CHAPTER FIFTEEN

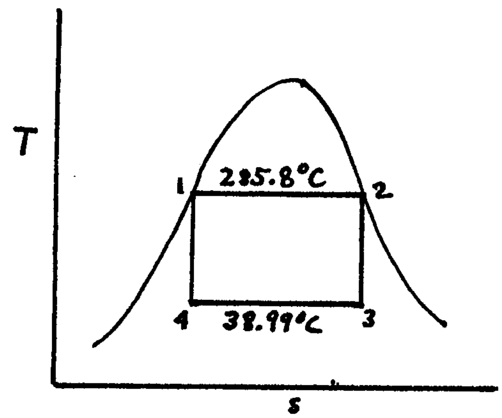
Problem 15.1

A Carnot cycle uses steam, as the working substance and operates between pressures of 7.0 MPa and 7 kPa. Determine (a) the thermal efficiency; (b) the turbine work per kg; (c) the compressor work per kg.

Given: Carnot cycle using steam operating between 7.0 MPa and 7 kPa.

Find: Thermal efficiency, turbine work, and compressor work.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Using Appendix A.6 or SATSTM.TK.

$h_1 = 1267.1$ kJ/kg $\qquad h_2 = 2772.5$ kJ/kg

$s_1 = 3.1203$ kJ/kg-K $\qquad s_2 = 5.8135$ kJ/kg-K

$s_4 = s_1 = 3.1203$ kJ/kg-K $\qquad s_3 = s_2 = 5.8135$ kJ/kg-K

$h_4 = 963.44$ kJ/kg $\qquad h_3 = 1804.1$ kJ/kg

$x = 0.33216$ $\qquad x = 0.68102$

The turbine work is.

(b) $w_t = h_2 - h_3 = 2772.5 - 1804.1 = 968.4$ kJ/kg

The compressor work is

(c) $w_c = h_4 - h_1 = 963.44 - 1267.1 = -303.66$ kJ/kg

The thermal efficiency is.

(a) $$\eta_{Th} = \frac{W_{net}}{Q_{in}} = \frac{w_t + w_c}{h_2 - h_1} = \frac{968.4 - 303.66 \text{ kJ/kg}}{2772.5 - 1267.1 \text{ kJ/kg}} = 0.442$$

or $$\eta_{Th} = \frac{559°K - 312°K}{559°K} = 0.442$$

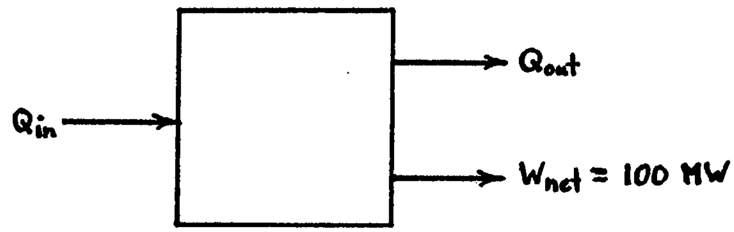
Problem 15.5

A Rankine cycle produces 100 MW of power with a condenser pressure of 7.5 kPa and an inlet turbine temperature of 500°C. Determine the cycle thermal efficiency and the steam flow rate required for an inlet turbine pressure of (a) 17.5 MPa; (b) 1750 kPa.

Given: 100 MW Rankine cycle with condenser pressure of 7.5 kPa and turbine inlet at 500°C and 17.5 MPa, and 1750 kPa.

Find: Thermal efficiency and steam flow rate.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.

Analysis: Determine the ideal cycle enthalpies for p_2 = 17.5 MPa following the procedure in Example 15.1 or using STMCYCLE.TK.

$$h_1 = 186.13 \text{ kJ/kg} \qquad h_3 = 1946.3 \text{ kJ/kg}$$

$$h_2 = 3281.1 \text{ kJ/kg} \qquad h_4 = 168.5 \text{ kJ/kg}$$

$$q_{in} = h_2 - h_1 = 3281.1 - 186.13 = 3095 \text{ kJ/kg}$$

$$w_{net} = (h_2 - h_3) - (h_1 - h_4) = (3281.1 - 1946.3) - (186.13 - 168.5)$$

$$w_{net} = 1317.1 \text{ kJ/kg}$$

(a) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1317.1 \text{ kJ/kg}}{3095 \text{ kJ/kg}} = 0.426$$

Solving for the steam flow.

$$\dot{W}_{net} = \dot{m}_s\, w_{net}$$

(a) $$\dot{m}_s = \frac{\dot{W}_{net}}{w_{net}} = \frac{100\ 000\ \text{kW}}{1317.1\ \text{kJ/kg}} = 75.9\ \text{kg/s}$$

For the ideal Rankine cycle with p_2 = 1750 kPa.

h_1 = 170.26 kJ/kg $\qquad$ h_3 = 2337.2 kJ/kg

h_2 = 3469.9 kJ/kg $\qquad$ h_4 = 168.5 kJ/kg

$$q_{in} = h_2 - h_1 = 3469.9 - 170.26 = 3299.6\ \text{kJ/kg}$$

$$w_{net} = (h_2 - h_3) - (h_1 - h_4) = (3469.9 - 2337.2) - (170.26 - 168.5)$$

$$w_{net} = 1130.9\ \text{kJ/kg}$$

(b) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1130.9\ \text{kJ/kg}}{3299.6\ \text{kJ/kg}} = 0.343$$

Solving for the steam flow.

(b) $$\dot{m}_s = \frac{\dot{W}_{net}}{w_{net}} = \frac{100\ 000\ \text{kW}}{1130.9\ \text{kJ/kg}} = 88.4\ \text{kg/s}$$

Problem 15.9

Concentrating solar collectors are used to provide the heat source for a Rankine cycle using water as the working substance. The design specification require a power output of 10 MW. Commercially available collectors allow steam to be generated at 2500 kPa and 300°C. The cycle low pressure is assumed to be 7.5 kPa. Determine (a) the cycle thermal efficiency; (b) the steam flow rate.

Given: 10 MW Rankine cycle operating at 2500 kPa and 300°C exhausting to 7.5 kPa.

Find: Cycle thermal efficiency and steam flow rate.

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.

Analysis: Determine the ideal cycle enthalpies following the procedure in Example 15.1 or using STMCYCLE.TK.

$$h_1 = 171.01 \text{ kJ/kg} \quad h_3 = 2071.4 \text{ kJ/kg}$$

$$h_2 = 3009.8 \text{ kJ/kg} \quad h_4 = 168.5 \text{ kJ/kg}$$

$$q_{in} = h_2 - h_1 = 3009.8 - 171.01 = 2838.8 \text{ kJ/kg}$$

$$w_{net} = (h_2 - h_3) - (h_1 - h_4) = (3009.8 - 2071.4) - (171.01 - 168.5)$$

$$w_{net} = 935.9 \text{ kJ/kg}$$

(a) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{935.9 \text{ kJ/kg}}{2838.8 \text{ kJ/kg}} = 0.330$$

$$\dot{W}_{net} = \dot{m}_s \, w_{net}$$

$$\dot{m}_s = \frac{\dot{W}_{net}}{w_{net}} = \frac{10\ 000 \text{ kw}}{935.9 \text{ kJ/kg}} = 10.68 \text{ kg/s}$$

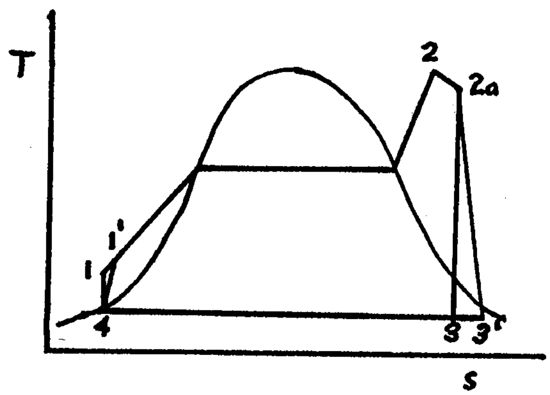
Problem 15.13

A Rankine-cycle power plant produces 100 MW of power and is characterized by a steam generator outlet condition of 10 MPa and 500°C and a condenser pressure of 7.5 kPa. The condensate leaving the condenser is subcooled by 3.3°C. Because of frictional and nonadiabatic effects in the piping leading to the turbine, the turbine inlet conditions are 9.75 MPa and 475°C. The pump discharge is 10.5 MPa, and the turbine and pump internal efficiencies are 85%. Determine (a) the cycle thermal efficiency; (b) the steam flow rate required; (c) the heat transfer from the steam pipe connecting the boiler and turbine.

Given: 100 MW Rankine-cycle power plant with 33°C condenser subcooling, losses between steam generator and turbine 25 kPa and 25°C, and turbine and pump efficiencies of 85%.

Find: The thermal efficiency, steam flow rate, and heat transfer from high pressure steam pipe.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Determining the enthalpies using Appendixes A.5, A.6 and A.7, or using SATSTM.TK and SHTSTM.TK.

h_2 = 3376.5 kJ/kg $\qquad$ h_4 = 182.45 kJ/kg

h_{2a} = 3315.1 kJ/kg $\qquad$ h_1 = 193.05 kJ/kg

h_3 = 2035 kJ/kg $\qquad$ h_1' = 194.9 kJ/kg

h_3' = 2227 kJ/kg

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_{2a} - h_3') - (h_1' - h_4)}{(h_2 - h_1')}$$

$$= \frac{(3315.1 - 2227) - (194.9 - 182.45)}{(3376.5 - 194.9)}$$

(a) $\eta_{th} = 0.338$

$$\dot{W}_{net} = \dot{m}_s\, w_{net}$$

(b) $\dot{m}_s = \dfrac{\dot{W}_{net}}{w_{net}} = \dfrac{100\ 000\ \text{kW}}{1075.65\ \text{kJ/kg}} = 92.97\ \text{kg/s}$

The heat transfer from the steam pipe is.

$$\dot{Q}_{loss} = \dot{m}_s\,(h_2 - h_{2a}) = (92.97\ \text{kg/s})(3376.5 - 3315.1\ \text{kJ/kg})$$

$$\dot{Q}_{loss} = 5708\ \text{kW}$$

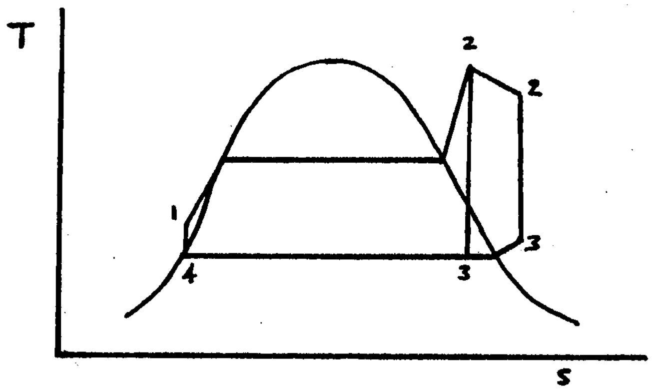
Problem 15.17

Find the decrease in cycle efficiency for Problem 15.16.

Given: Rankine cycle operating between 6.0 MPa and 480°C and 15 kPa, is throttled to turbine inlet pressure of 2.2 MPa at reduced loads.

Find: Decrease in cycle efficiency.

Sketch and Given Data:



Assumptions:
1) The turbine may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.

Analysis: Determine the ideal cycle enthalpies and cycle thermal efficiencies following the procedure in Example 15.1 or using STMCYCLE.TK.

For p_2 = 6.0 MPa	For p_2 = 2.2 MPa
h_2 = 3375.8 kJ/kg	h_2 = 3375.8 kJ/kg
h_3 = 2209.9 kJ/kg	h_3 = 2356.1 kJ/kg
h_4 = 226.29 kJ/kg	h_4 = 226.29 kJ/kg
h_1 = 232.36 kJ/kg	h_1 = 232.36 kJ/kg
η_{th} = 0.369	η_{th} = 0.323

Efficiency decreases 12.5%

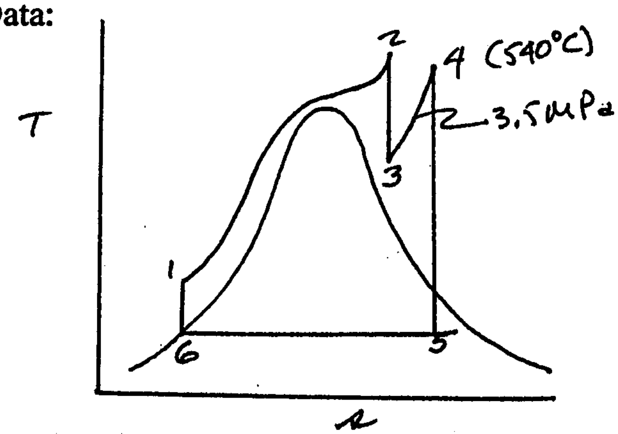
Problem 15.21

The supercritical power plant in Problem 15.20 has a reheat stage added at 3.5 MPa with a reheat temperature of 540°C. All other conditions are the same. Determine (a) the quality of steam entering the condenser; (b) the cycle efficiency.

Given: Reheat Rankine cycle with turbine inlet of 25 MPa and 580°C, reheat of 3.5 MPa and 540°C, and exhaust of 7.0 kPa.

Find: The quality of the exit steam and the cycle efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.

Analysis: Determining the enthalpies for the cycle using Appendices A.6 and A.7 or using SATSTM.TK or SHTSTM.TK.

h_1 = 188.22 kJ/kg $\quad$ h_4 = 3541.2 kJ/kg $\quad$ s_4 = 7.2681 kJ/kg-K

h_2 = 3436.3 kJ/kg $\quad$ h_5 = 2258.1 kJ/kg $\quad$ (a) x = 0.869

h_3 = 2893.8 kJ/kg $\quad$ h_6 = 163.04 kJ/kg

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_2 - h_3) + (h_4 - h_5) - (h_1 - h_6)}{(h_2 - h_1) + (h_4 - h_3)}$$

(b) η_{th} = 0.462

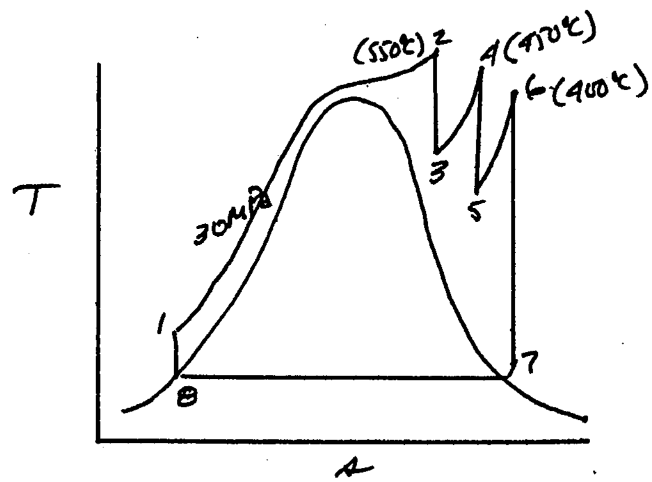
Problem 15.25

A supercritical reheat Rankine cycle has two stages of reheat. The steam entering the high-pressure turbine is 30 kPa and 550°C. The steam expands to 5 MPa and is reheated to 450°C, reenters and expands to 1000 kPa, and is reheated to 400°C. It reenters the turbine and exhausts at 7.5 kPa. Determine (a) the quality or degrees of superheat of the steam entering the condenser; (b) the net work; (c) the cycle thermal efficiency.

Given: Reheat Rankine cycle with inlet steam at 30 MPa and 550°C, reheat to 5 MPa and 450°C, reheat to 1000 kPa and 400°C, and exhaust to 7.5 kPa.

Find: Quality or superheat of exhaust, net work, and cycle thermal efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal reheat Rankine cycle.

Analysis: Determining the enthalpies for the cycle using Appendices A.6 and A.7 or using SATSTM.TK and SHTSTM.TK.

$h_8 = 168.5$ kJ/kg

$h_1 = 198.7$ kJ/kg

$h_2 = 3287.6$ kJ/kg $\qquad s_2 = 6.0485$ kJ/kg-K

$h_3 = 2835.4$ kJ/kg $\qquad s_3 = s_2$

$h_4 = 3317.8$ kJ/kg $\qquad s_4 = 6.8188$ kJ/kg-K

$h_5 = 2888.4$ kJ/kg $\qquad s_5 = s_4$

$h_6 = 3263.9$ kJ/kg $\qquad s_6 = 7.4633$ kJ/kg-K

$h_7 = 2328.0$ kJ/kg $\qquad s_7 = s_6 \qquad$ (a) $\quad x = 0.897$

The net work is.

$$w_{net} = (h_2 - h_3) + (h_4 - h_5) + (h_6 - h_7)$$

(b) $\quad w_{net} = 1817.5$ kJ/kg

The thermal efficiency is.

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{net}}{(h_2 - h_1) + (h_4 - h_3) + (h_6 - h_5)}$$

(c) $$\eta_{th} = \frac{1817.5 \text{ kJ/kg}}{3946.8 \text{ kJ/kg}} = 0.4605$$

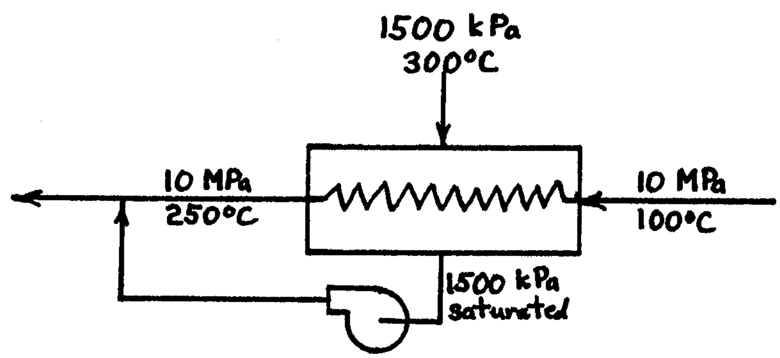
Problem 15.29

In some cycles drain pumps receive the condensate from the shell of the closed feedwater heater and pump it back into the outlet piping from the tube side of the heater. Consider the following situation: Extraction steam enters the shell side of a heater at 1500 kPa and 300°C and condenses to a saturated liquid. The feedwater enters the tube side at 10 MPa and 100°C and leaves at 10 MPa and 250°C. A drain pump with an isentropic efficiency of 80% returns the condensate to the discharge line from the heater. Determine the temperature of the water in the discharge line after it receives the drain pump return.

Given: Feed heater with drain pump.

Find: Water outlet temperature after mixing.

Sketch and Given Data:



Assumptions:
1) The heater is adiabatic.
2) The liquid enthalpies will be based on h_f at the fluid temperature.

Analysis: Determine the enthalpies using Appendices A.5, A.6 and A.7 or SATSTM.TK and SHTSTM.TK.

h_{stm} = 3038.3 kJ/kg

$h_{feed_{in}}$ = 419.6 kJ/kg (h$_f$ at T = 100°C)

$h_{feed_{out}}$ = 1086.0 kJ/kg (h$_f$ at T = 250°C)

h_{drain} = 844.9 kJ/kg (h$_f$ at p = 1500 kPa)

h_{pump} = 844.9 + (0.001154)(10 000 - 1500) = 854.7 kJ/kg

Writing the first law equation for the feedwater heater based on 1 kg of feedwater being heated.

$$1\ h_{feed_{in}} + y\ h_{stm} = 1\ h_{feed_{out}} + y\ h_{drain}$$

$$y = \frac{(h_{feed_{out}} - h_{feed_{in}})}{(h_{stm} - h_{drain})} = \frac{(1086.0 - 419.6)}{(3038.3 - 844.9)} = 0.304\ kg_{stm}/kg_{feed}$$

Writing the first law equation for the mixing process.

$$1\ h_{feed_{out}} + 0.304\ h_{pump} = (1 + 0.304)\ h_{mix}$$

$$h_{mix} = \frac{(1)(1086.0) + (0.304)(854.7)}{1.304} = 1032.1\ kJ/kg$$

From Appendix A.5 or SATSTM.TK.

$$T_{mix} = 239°C$$

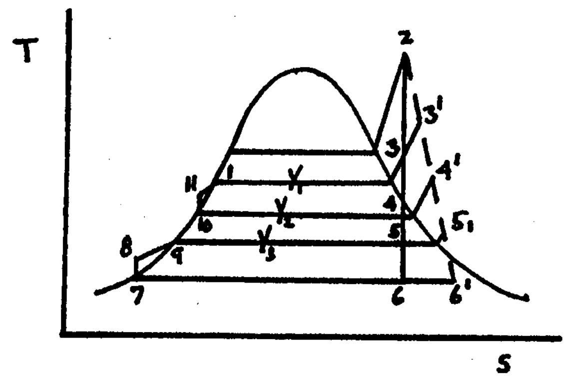
Problem 15.33

A steam power plant produces 1000 MW of electricity while operating on a three-stage regenerative cycle. The steam enters the turbine at 14 MPa and 580°C. Extractions for heating occur at 2.5 MPa, 700 kPa and 150 kPa. The turbine exhausts at 15 kPa and has an internal efficiency of 92%. Determine (a) the T-s diagram; (b) the mass flow rate; (c) the heat supplied; (d) the fuel flow rate, if the energy release is 35 000 kJ/kg fuel; (e) the mass fractions y_1, y_2, y_3; (f) the cycle efficiency.

Given: Three-stage regenerative steam power plant with given steam conditions and 92% turbine efficiency produces 1000 MW.

Find: T-s diagram, mass flow rate, heat supplied, fuel flow rate, bleed steam fractions, and cycle efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The middle heater is open; the other two are closed with pumped forward drains and the feedwater leaving at the saturation temperature of the extraction steam.
4) The pumps are 100% efficient.
5) The drain pump work will be neglected.

Analysis: Determine the enthalpies using Appendices A.5, A.6 and A.7, or SATSTM.TK and SHTSTM.TK.

h_2 = 3539.7 kJ/kg

h_3 = 3016.1 kJ/kg h_3' = 3058.0 kJ/kg (η_t = 92%)

h_4 = 2740.7 kJ/kg h_4' = 2804.6 kJ/kg (η_t = 92%)

h_5 = 2475.7 kJ/kg h_5' = 2560.8 kJ/kg (η_t = 92%)

$h_6 = 2156.9$ kJ/kg $\quad h_6' = 2267.5$ kJ/kg $\quad (\eta_t = 92\%)$

$h_7 = 226.3$ kJ/kg

$h_8 = 227.0$ kJ/kg

$h_9 = 467.3$ kJ/kg $\quad$ (h_f at 150 kPa)

$h_{10} = 696.8$ kJ/kg $\quad$ (h_f at 700 kPa)

$h_{11} = 711.12$ kJ/kg

$h_1 = 962.4$ kJ/kg $\quad$ (h_f at 2500 kPa)

Solving for y_1, y_2 and y_3 using the First Law equations.

$$y_1\, h_3' = (1 - y_1)\, h_{11} = y_1\, h_1 + (1 - y_1)\, h_1 \qquad y_1 = 0.107$$

$$y_2\, h_4' + (1 - y_1 - y_2)\, h_9 = (1 - y_1)\, h_{10} \qquad y_2 = 0.0877$$

$$y_3\, h_5' + (1 - y_1 - y_2 - y_3)\, h_8 = y_3\, h_9 + (1 - y_1 - y_2 - y_3)\, h_9$$

$$y_3 = 0.0829$$

Solving for the net work and heat supplied.

$$w_{net} = w_t - w_p$$

$$= \left[(h_2 - h_3') + (1 - y_1)(h_3' - h_4') + (1-y_1-y_2)(h_4' - h_5') + (1 - y_1-y_2-y_3)(h_5' - h_6')\right]$$

$$- \left[(h_{11} - h_{10}) + (1 - y_1 - y_2 - y_3)(h_8 - h_7)\right]$$

$$w_{net} = 1101.3 \text{ kJ/kg}$$

$$q_{in} = h_2 - h_1 = 3539.7 - 962.4 = 2577.3 \text{ kJ/kg}$$

(f) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{1101.3 \text{ kJ/kg}}{2577.3 \text{ kJ/kg}} = 0.427$$

(b) $$\dot{m}_s = \frac{\dot{W}_{net}}{w_{net}} = \frac{1\ 000\ 000 \text{ kW}}{1101.3 \text{ kJ/kg}} = 908.0 \text{ kg/s}$$

(c) $\dot{Q}_{in} = \dot{m}_s \, q_{in} = (908.0 \text{ kg/s})(2577.3 \text{ kJ/kg}) = 2\ 340\ 234 \text{ kW}$

(d) $\dot{m}_f = \dfrac{\dot{Q}_{in}}{\bar{h}_{RP}} = \dfrac{2\ 340\ 234 \text{ kW}}{35\ 000 \text{ kJ/kg}} = 66.86 \text{ kg/s}$

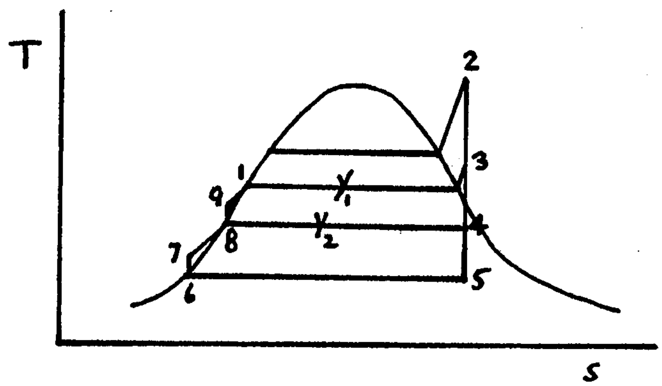
Problem 15.37

A regenerative Rankine cycle, producing 250 MW, has two feedwater heaters, a closed one for the first turbine extraction and an open one for the second turbine extraction. Steam enters the turbine at 7.5 MPa and 500°C and expands to 1500 kPa, where the first extraction stage occurs. The remaining steam expands to 500 kPa, where the second extraction stage occurs. The remainder expands through the turbine and exhausts at 7.5 kPa. The closed feedwater heater drains through a trap to the open heater. Determine (a) the cycle thermal efficiency; (b) the steam flow rate entering the turbine; (c) the steam flow rate to each of the heaters.

Given: 250 MW regenerative Rankine cycle with two feedwater heaters and given steam conditions.

Find: Cycle efficiency, turbine steam flow, and steam flows to heaters.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The closed heater drain temperature is equal to the saturation temperature of the extraction steam.
4) The turbine expansion is isentropic.

Analysis: Determine the cycle enthalpies using Appendices A.5, A.6, and A.7, or SATSTM.TK and SHTSTM.TK.

h_2 = 3406.0 kJ/kg $\qquad$ s_2 = 6.7597 kJ/kg-K

h_3 = 2950.2 kJ/kg $\qquad$ $s_3 = s_2$

h_4 = 2722.7 kJ/kg $\qquad$ $s_4 = s_2$

h_5 = 2107.4 kJ/kg $\qquad$ $s_5 = s_2$

h_6 = 168.5 kJ/kg $\qquad$ h_f at 7.5 kPa

h_7 = 170.0 kJ/kg

h_8 = 639.8 kJ/kg h_f at 500 kPa

h_9 = 647.4 kJ/kg

h_1 = 844.9 kJ/kg h_f at 1500 kPa

Solving for y_1 and y_2 using the first law equations for the heaters.

$$y_1\, h_3 + (1)h_9 = y_1\, h_1 + (1)h_1 \qquad y_1 = 0.0938$$

$$y_2\, h_4 + (1 - y_1 - y_2)h_7 + y_1\, h_1 = (1)\, h_8 \qquad y_2 = 0.1592$$

The net work is.

$$w_{net} = w_t - w_p$$

$$= \left[(h_2 - h_3) + (1 - y_1)(h_3 - h_4) + (1 - y_1 - y_2)(h_4 - h_5)\right]$$

$$- \left[(h_9 - h_8) + (1 - y_1 - y_2)(h_7 - h_6)\right]$$

$$w_{net} = 1112.8 \text{ kJ/kg}$$

The steam flows to the turbine and heaters are.

(b) $\dot{W}_{net} = \dot{m}_t\, w_{net}$ $\dot{m}_t = \dfrac{\dot{W}_{net}}{w_{net}} = \dfrac{250\ 000 \text{ kW}}{1112.8 \text{ kJ/kg}}$

$= 224.7$ kg/s

$$\dot{m}_{htr1} = \dot{m}_t\, y_1 = (224.7 \text{ kg/s})(0.0938) = 21.08 \text{ kg/s}$$

(c) $\dot{m}_{htr2} = \dot{m}_t\, y_2 = (224.7 \text{ kg/s})(0.1591) = 35.75 \text{ kg/s}$

The thermal efficiency is.

(a) $\eta_{th} = \dfrac{W_{net}}{q_{in}} = \dfrac{w_{net}}{(h_2 - h_1)} = \dfrac{1108.2 \text{ kJ/kg}}{(3406.2 - 844.9 \text{ kJ/kg})} = 0.435$

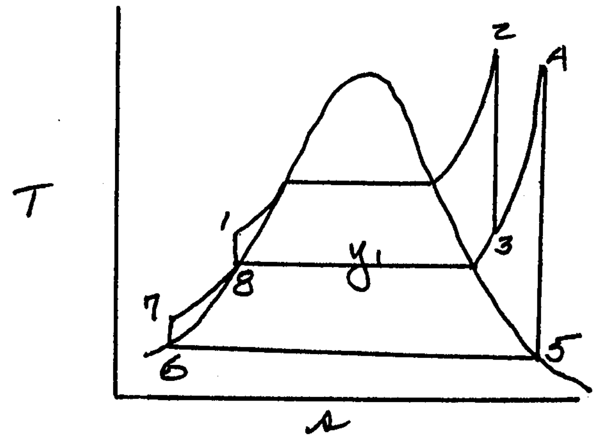
Problem 15.41

A reheat-regenerative Rankine cycle uses steam at 8.4 MPa and 560°C entering the high-pressure turbine. The cycle includes one steam-extraction stage for regenerative feedwater heating, the remainder at this point being reheated to 540°C. The condenser temperature is 35°C. Determine (a) the T-s diagram for the cycle; (b) the optimum extraction pressure; (c) fraction of steam extracted; (d) turbine work in kJ/kg; (e) pump work in kJ/kg; (f) overall thermal efficiency.

Given: Reheat-regenerative Rankine cycle with single extraction.

Find: T-s diagram, optimum extraction pressure, extraction steam fraction, turbine work, pump work, and cycle efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The feed heater is open.
4) The turbine expansion is isentropic.
5) The optimum extraction pressure is when the heater temperature is halfway between the steam generator and condenser saturated temperatures.

Analysis: Determine the optimum extraction pressure.

$$T_{cond} = 35°C$$

$$p_{sg} = 8400 \text{ kPa} \qquad T_{sg} = 298.4°C$$

$$T_{ext} = 25°C + \frac{298.4°C - 25°C}{2} = 161.7°C$$

(b) $p_{ext} = 645.6$ kPa

Determine the cycle enthalpies using Appendices A.5, A.6, and A.7, or using

SATSTM.TK and SHTSTM.TK.

$h_2 = 3541.6$ kJ/kg $\quad s_2 = 6.8786$ kJ/kg-K

$h_3 = 2823.9$ kJ/kg $\quad s_3 = s_2$

$h_4 = 3567.9$ kJ/kg $\quad s_4 = 8.0725$ kJ/kg-K

$h_5 = 2479.1$ kJ/kg $\quad s_5 = s_4$

$h_6 = 146.2$ kJ/kg $\quad h_f$ at 35°C

$h_7 = 146.8$ kJ/kg

$h_8 = 682.7$ kJ/kg $\quad h_f$ at 161.7°C

$h_1 = 690.5$ kJ/kg

Writing first law equation for the heater and solving for y_1.

$y_1\, h_3 + (1 - y_1)\, h_7 = (1)\, h_8$ (c) $y_1 = 0.200$

The turbine and pump work are.

(d) $w_t = (h_2 - h_3) + (1 - y_1)(h_4 - h_5) = 1425.5$ kJ/kg

(e) $w_p = (h_1 - h_8) + (1 - y_1)(h_7 - h_1) = 8.3$ kJ/kg

The thermal efficiency of the cycle is.

(f) $$\eta_{th} = \frac{w_t - w_p}{q_{in}} = \frac{w_t - w_p}{q_{in}} = 0.432$$

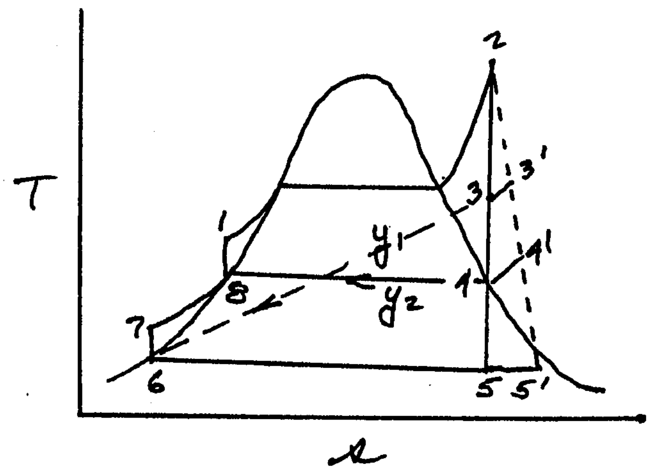
Problem 15.45

A university decides to invest in a cogeneration facility, providing 20 MW of power and steam for heating in the campus buildings. A preliminary design proposal suggests that steam be generated at 2500 kPa and 300°C. In addition a turbine may be purchased that has two extractions stages, the first occurring at 1000 kPa for building heating and the second at 300 kPa for regenerative heating with an open feedwater heater. The condenser pressure is 7.5 kPa. The returns from the buildings may be considered to be saturated at the condenser temperature. The buildings require 3000 kW of heat for the worst-case condition. The turbine's isentropic efficiency is 80% at these steam conditions. The pump efficiency is assumed to be 100%. Determine (a) the steam generator capacity in kg/s of steam produced and in the heat rate required; (b) the mass flow rate of steam extracted for building heating; (c) the cycle's utilization factor.

Given: Regenerative Rankine cycle with high pressure extraction used for heating, and low pressure for feedwater heating.

Find: Steam generator capacity, extraction flow for building heating, and utilization factor.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle enthalpies using Appendices A.5, A.6 and A.7, or SATSTM.TK and SHTSTM.TK.

$h_2 = 3009.8$ kJ/kg $\qquad s_2 = 6.6446$ kJ/kg-K

$h_3 = 2804.4$ kJ/kg $\qquad s_3 = s_2$

$h_3' = 2845.5$ kJ/kg $\quad s_3 = s_2$

$h_4 = 2584.3$ kJ/kg $\qquad s_4 = s_2$

$h_4' = 2669.4$ kJ/kg $\qquad \eta_t = 80\%$

$h_5 = 2071.4$ kJ/kg $\qquad s_5 = s_2$

$h_5' = 2259.1$ kJ/kg $\qquad \eta_t = 80\%$

$h_6 = 168.5$ kJ/kg $\qquad h_f$ at 7.5 kPa

$h_7 = 168.8$ kJ/kg

$h_8 = 561.2$ kJ/kg $\qquad h_f$ at 300 kPa

$h_1 = 563.6$ kJ/kg

Solving for the heating steam flow.

$$\dot{Q}_h = \dot{m}_h(h_3' - h_6) \qquad \dot{m}_h = \dot{m}_s\, y_1$$

(b) $$\dot{m}_s\, y_1 = \frac{3000 \text{ kW}}{(2845.5 - 168.5 \text{ kJ/kg})} = 1.121 \text{ kg/s}$$

The net work and first law equation for the open heater are.

$$w_{net} = w_t - w_p = [(h_2 - h_3') + (1 - y_1)(h_3' - h_4') + (1 - y_1 - y_2)(h_4' - h_5')]$$

$$- [(h_1 - h_8) - (1 - y_2)(h_7 - h_6)]$$

$$y_2\, h_4 + (1 - y_2)\, h_7 = h_8$$

Since the plant must produce 20 MW of power.

$$\dot{W}_{net} = \dot{m}_s\, w_{net}$$

Solving the above simultaneously.

$$y_1 = 0.0371$$

$$y_2 = 0.157$$

(a) $$\dot{m}_s = 30.215 \text{ kg/s}$$

$$\dot{Q}_{in} = \dot{m}_s(h_2 - h_1) = 73\ 692\ \text{kW}$$

The cycle utilization factor is.

(c) $$Y_{cg} = \frac{\dot{W}_{net} + \dot{Q}_h}{\dot{Q}_{in}} = \frac{20\ 000\ \text{kW} + 3000\ \text{kW}}{73\ 692\ \text{kW}} = 0.312$$

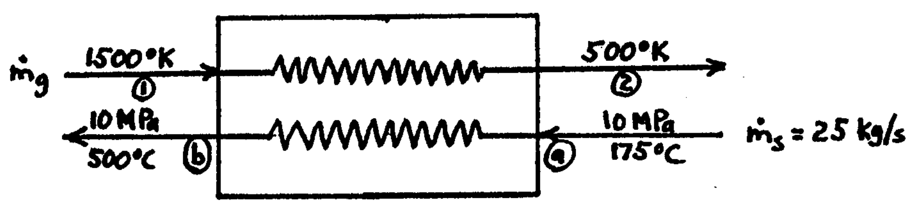
Problem 15.49

A steam generator may be considered to be a constant-pressure combustion chamber followed by a heat exchanger where that heat from the combustion gases is transferred to water, creating steam. Consider such a steam generator where the combustion gases, with properties similar to air enter the heat exchanger at 1500°D and are cooled to 500°K. Twenty-five kg/s of water enters the heat exchanger at 10 MPa and 175°C and leaves as a superheated vapor at 10 MPa and 500°C. T_0 = 300°K and p_0 = 100 kPa. Determine (a) the availability change of the combustion gas in kW; (b) the availability change of the water in kW; (c) the irreversibility rate in kW; (d) the second-law efficiency.

Given: Steam generator producing 25 kg/s of 10 MPa and 175°C steam by combustion gases being cooled from 1500°K to 500°K.

Find: Availability change of the combustion gas and water, the irreversibility rate, and second-law efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) Heat flow to the surroundings and the work is zero.
3) The changes in kinetic and potential energies may be neglected.
4) The combustion gases behave like an ideal gas at ambient conditions.

Analysis: From Appendix A.1, c_p = 1.0047 kJ/kg-K
The change is entropy for a constant pressure process is thus.

$$s_1 - s_2 = c_p \ln\left(\frac{T_2}{T_1}\right) = 1.0047 \ln\left(\frac{500°K}{1500°K}\right) = -1.1038 \text{ kJ/kg-K}$$

From Appendices A.5 and A.7 the steam and water properties are.

h_a = 741.0 kJ/kg $\qquad$ h_b = 3376.5 kJ/kg

$s_a = 2.089$ kJ/kg-K $\qquad$ $s_b = 6.5982$ kJ/kg-K

Solving the first law equation for the gas flow rate.

$$\dot{m}_g\, c_p(T_1 - T_2) = \dot{m}_s(h_b - h_a)$$

$$\dot{m}_g = \frac{(25 \text{ kg/s})(3376.5 - 741.0 \text{ kJ/kg})}{(1.0047 \text{ kJ/kg-K})(1500°K - 500°K)} = 65.58 \text{ kg/s}$$

The change in availability of the combustion gas is.

$$\Psi_2 - \Psi_1 = (h_2 - h_1) - T_0(s_2 - s_1)$$

$$\Psi_2 - \Psi_1 = (1.0047 \text{ kJ/kg-K})(500°K - 1500°K)$$

$$- (300°K)(-1.1038 \text{ kJ/kg-K})$$

$$\Psi_2 - \Psi_1 = -673.56 \text{ kJ/kg}$$

(a) $\quad \dot{m}_g(\Psi_2 - \Psi_1) = (65.58 \text{ kg/s})(-673.56 \text{ kJ/kg}) = -44\ 172 \text{ kW}$

The change in availability of the water is.

$$\Psi_b - \Psi_a = (h_b - h_a) - T_0\,(s_b - s_a)$$

$$\Psi_b - \Psi_a = (3376.5 - 741.0 \text{ kJ/kg}) - (300°K)(6.5982 - 2.089 \text{ kJ/kg-K})$$

$$\Psi_b - \Psi_a = 1282.7 \text{ kJ/kg}$$

(b) $\quad \dot{m}_s(\Psi_b - \Psi_a) = (25 \text{ kg/s})(1282.7 \text{ kJ/kg}) = 32\ 068 \text{ kW}$

The irreversibility rate is.

$$\dot{I} = T_0\left[\dot{m}_g(s_2 - s_1) + \dot{m}_s(s_b - s_a)\right]$$

$$\dot{I} = (300°K)$$

$$\left[(65.58 \text{ kg/s})(-1.1038 \text{ kJ/kg-K}) + (25 \text{ kg/s})(6.5982 - 2.089 \text{ kJ/kg-K})\right]$$

(c) $\quad \dot{I} = 12\ 103 \text{ kW}$

The second law efficiency can be determined by comparing the change in availability of the combustion gases with that for the water.

(d) $$\eta_2 = \frac{32\ 068\ \text{kW}}{44\ 172\ \text{kW}} = 0.726$$

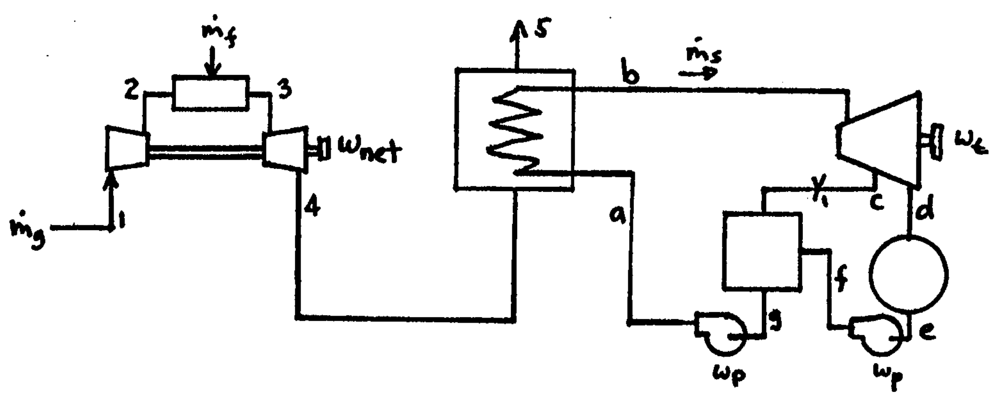
Problem 15.53

A combined gas turbine-steam power plant produces 500 MW of net power. The pressure ratio of the gas turbine unit is 16, with air entering at 300°K and 100 kPa. The maximum inlet temperature to the turbine is 1750°K. The minimum gas temperature from the steam generator is 450°K. Steam is generated at 7.5 MPa and 450°C. The turbine has one open feedwater heater regenerative stage at 500 kPa. The condenser pressure is 10 kPa. Assume the gases have properties similar to air. Determine (a) the air and steam mass flow rates; (b) the cycle efficiency; (c) the availability of that gas leaving the steam generator; (d) the availability of the gas leaving the gas turbine relative to inlet air temperature and pressure. What fraction of this was used in the steam cycle?

Given: 500 MW combined gas turbine-steam power plant.

Find: Air and steam flow rates, cycle efficiency, availability of the gas entering and leaving the steam generator, fraction of availability used in steam cycle.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The expansion and compression processes are isentropic.

Analysis: Determine the net work, heat supplied, and turbine exit temperature for the gas turbine using AIRCYCLE.TK or the procedure in Example 14.1. Using AIRCYCLE.TK

$$w_{net} = -DEL43 - DEL21 = 658.0 \text{ kJ/kg}$$

$$q_{in} = DELh32 = 1281.0 \text{ kJ/kg}$$

$$T_4 = 891.4°K$$

Determining the steam cycle enthalpies using Appendices A.5, A.6, and A.7, or SATSTM.TK and SHTSTM.TK.

h_b = 3282.4 kJ/kg $\qquad$ s_b = 6.5949 kJ/kg-K

h_c = 2652.6 kJ/kg $\qquad$ $s_c = s_b$

h_d = 2088.9 kJ/kg $\qquad$ $s_d = s_b$

h_e = 191.82 kJ/kg $\qquad$ h_f = at 10 kPa

h_f = 192.32 kJ/kg

h_g = 639.8 kJ/kg $\qquad$ h_f at 500 kPa

h_a = 647.5 kJ/kg

Solving for first law equation for the open heater for y_1.

$$y_1\, h_c + (1 - y_1)\, h_f = h_g \qquad y_1 = 0.1819$$

The net work is

$$w_{net} = w_t - w_p = [(h_b - h_c) + (1 - y_1)(h_c - h_d)]$$

$$- [(h_a - h_g + (1 - y_1)(h_f - h_e)]$$

$$w_{net} = 1082.9 \text{ kJ/kg}$$

Solving the first law equation for the steam generator for the steam flow produced per kg of gas flow.

$$m_g\, c_p(T_4 - T_5) = m_s\, (h_b - h_a)$$

$$\frac{m_s}{m_g} = \frac{(1.0047 \text{ kJ/kg-K})(891.4°K - 450°K)}{(3282.4 - 647.5 \text{ kJ/kg})} = 0.1683 \frac{\text{kg steam}}{\text{kg gas}}$$

Solving the equation for total net power for the gas flow rate

$$\dot{W}_{net} = \dot{m}_g\, w_{net_g} + \dot{m}_s\, w_{net_s}$$

$$500\,000 \text{ kW} = \dot{m}_g(658.0 \text{ kJ/kg}) + \dot{m}_g\left(0.1683 \frac{\text{kg steam}}{\text{kg gas}}\right)(1082.4 \text{ kJ/kg})$$

(a)

$$\dot{m}_g = 595.1 \text{ kg/s}$$

$$\dot{m}_s = (0.1683)(595.1 \text{ kJ/kg}) = 100.1 \text{ kg/s}$$

The thermal efficiency is.

(b) $$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{m}_g \, q_{in}} = \frac{500\ 000\ \text{kW}}{(595.1\ \text{kg/s})(1281.0\ \text{kJ/kg})} = 0.656$$

The availability of the gas leaving the steam generator is.

$$\alpha_5 = (h_4 - h_o) - T_0(s_4 - s_0)$$

Using AIR.TK to determine the change in enthalpy and entropy.

$$\alpha_5 = (151.48\ \text{kJ/kg}) - (300°\text{K})(0.4163\ \text{kJ/kg-K})$$

(c) $$\alpha_5 = 26.59\ \text{kJ/kg}$$

Solving for the availability of the gas leaving the gas turbine.

$$\alpha_4 = (622.97\ \text{kJ/kg}) - (300°\text{K})(1.1183\ \text{kJ/kg-K})$$

(d) $$\alpha_4 = 281.48\ \text{kJ/kg}$$

Comparing the change in availability of the gas to the net work produced in the steam cycle per kg of gas.

$$\frac{W_{net}/\text{kg gas}}{\alpha_4 - \alpha_5} = \frac{(0.1683\ \text{kg/kg})(1082.9\ \text{kJ/kg})}{(281.48 - 26.59\ \text{kJ/kg})} = 0.715$$

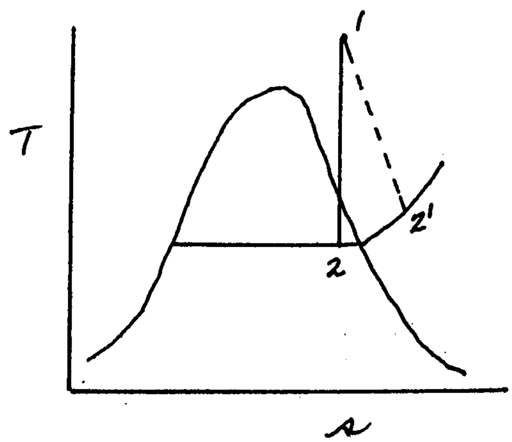
Problem 15.57

Steam enters a turbine at 1.4 MPa and 320°C. The turbine internal efficiency is 70% and the load requirement is 800 kW. The exhaust is to the back pressure system, maintained at 175 kPa. Find the steam flow rate.

Given: Steam turbine expands steam from 1400 kPa and 320°C to 175 kPa. Turbine efficiency is 70%.

Find: Steam flow required to produce 800 kW.

Sketch and Given Data:



Assumptions:
1) The process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the inlet and outlet enthalpies using Appendices A.5, A.6, and A.7 or SATSTM.TK and SHTSTM.TK.

$h_1 = 3084.9$ kJ/kg $\quad s_1 = 7.0288$ kJ/kg-K

$h_2 = 2645.3$ kJ/kg $\quad s_2 = s_1 \quad x = 0.975$

$h_2' = 2777.2$ kJ/kg $\quad \eta_t = 70\%$

The turbine power is

$$\dot{W} = \dot{m}_s\,(h_1 - h_2')$$

$$\dot{m}_s = \frac{\dot{W}}{(h_1 - h_2')} = \frac{800 \text{ KW}}{(3084.9 - 2777.2 \text{ kJ/kg})} = 2.60 \text{ kg/s}$$

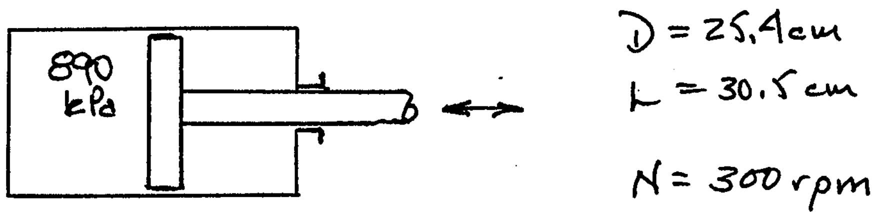
Problem 15.61

Steam is admitted to the cylinder of an engine in such a manner that the average pressure is 840 kPa. The diameter of the piston is 25.4 cm, and the length of the stroke is 30.5 cm. (a) Determine the work that can be done during one revolution, assuming that the steam is admitted successively to each side (top and bottom) of the piston. (b) What is the power produced when the engine is running at 300 rpm?

Given: Double-acting steam reciprocating engine with 25.4 cm diameter and 30.5 cm stroke is supplied by steam at 840 kPa.

Find: Work per revolution and power produced at 300 rpm.

Sketch and Given Data:



Assumptions:
1) The engine is analyzed as a closed system.
2) Friction is negligible.
3) There is no pressure acting on the back of the piston.

Analysis: The work is $w = \int_1^2 p dV$.

For double-acting engine and constant pressure, the work per revolution is.

$$w = 2\ p\ (V_2 - V_1) = (2)(840\ \text{kPa})\left(\frac{\pi}{4}\right)(0.254\ \text{m})^2(0.305\ \text{m})$$

(a) $w = 25.96$ kJ/rev

(b) $\dot{W} = w\ \frac{\text{rev}}{\text{s}} = (25.96\ \text{kJ/rev})\left(\frac{300\ \text{rev/m}}{60\ \text{s/m}}\right) = 129.8\ \text{kW}$

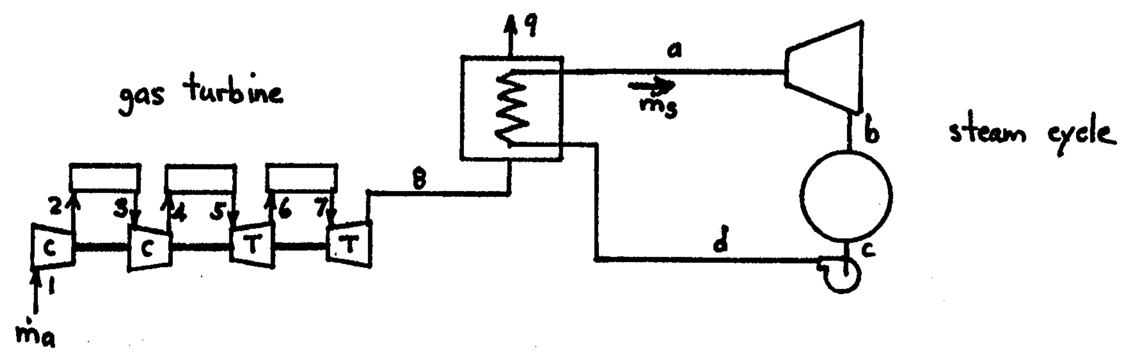
Problem 15.65

A combined gas turbine-steam power plant is to be used for the generation of electric power. The combined unit must produce 600 MW. There are two stages for the compressor with ideal intercooling at the optimum interstage pressure and two stages for the turbine with reheating to the same turbine inlet temperature. The compressor unit receives air at 100 kPa and 290°K and operates with a pressure ratio of 9. The turbine inlet temperature is 1220°K, with reheating occurring at 340 kPa. The turbine exhausts to the steam generator, and the products of combustion are cooled to 150°C. The steam generator produces steam at 5.5 MPa and 450°C. The steam turbine exhausts at 13 kPa. All expansion and compression processes are isentropic. Determine (a) the net gas turbine work per kg air; (b) the net steam turbine work per kg steam; (c) the overall thermal efficiency; (d) the airflow required; (e) the fuel/air ratio if h_{RP} = 43 200 kJ/kg fuel; (f) the fuel flow rate; (g) the cost in dollars per kWh of electricity produced if the fuel costs $0.45/kg; (h) the second-law efficiency.

Given: 600 MW combined gas turbine steam power plant. Gas turbine is intercooled with reheat. Steam cycle is a simple ideal Rankine cycle.

Find: Net steam turbine work, net gas turbine work, thermal efficiency, airflow, fuel/air ratio, fuel flow rate, fuel cost per kWh, and second-law efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: The optimum intercooling pressure is

$$p_2 = p_1\sqrt{p_r} = 100\ \text{kPa}\sqrt{9} = 300\ \text{kPa}$$

Using AIR.TK to determine the change in enthalpy for each process in the gas turbine.

$$h_2 - h_1 = 105.05\ \text{kJ/kg} \qquad s = \text{constant}\ \ T_2 = 394.41°\text{K}$$

$h_3 - h_2 = -105.05$ kJ/kg p = constant

$h_4 - h_3 = 105.05$ kJ/kg s = constant $T_4 = 394.41°K$

$h_5 - h_4 = 905.67$ kJ/kg p = constant

$h_6 - h_5 = -300.69$ kJ/kg s = constant $T_6 = 959.85°K$

$h_7 - h_6 = 300.69$ kJ/kg p = constant

$h_8 - h_7 = -366.94$ kJ/kg s = constant $T_8 = 901.04°K$

$h_9 - h_8 = -509.61$ kJ/kg p = constant

Solving for the fuel added per kg air.

$$r_{f/a_1}\,\bar{h}_{RP} = (1 + r_{f/a_1})(h_5 - h_4)$$

$$r_{f/a_1} = \frac{(h_5 - h_4)}{\bar{h}_{RP} - (h_5 - h_4)} = \frac{905.67 \text{ kJ/kg}}{(43\ 200 - 905.67 \text{ kJ/kg})} = 0.0214$$

$$r_{f/a_2}\,\bar{h}_{RP} = (1 + r_{f/a_1} + r_{f/a_2})(h_7 - h_6)$$

$$r_{f/a_2} = \frac{(1.0214)(300.69 \text{ kJ/kg})}{(43\ 200 - 300.69 \text{ kJ/kg})} = 0.00716$$

(e) $r_{f/a} = r_{f/a_1} + r_{f/a_2} = 0.0214 + 0.00716 = 0.02856$ kg/kg

The net gas turbine work per kg air is.

$$w_{net} = w_t - w_c = [(1.0214)(300.69 \text{ kJ/kg}) + (1.02856)(366.94 \text{ kJ/kg})]$$

$$- [(105.05 \text{ kJ/kg}) + (105.05 \text{ kJ/kg})]$$

(a) $w_{net} = 474.4$ kJ/kg

Analyzing the steam cycle using STMCYCLE.TK.

$h_a = 3310.9$ kJ/kg $h_c = 213.9$ kJ/kg

$h_b = 2175.9$ kJ/kg $h_d = 219.5$ kJ/kg

The net steam cycle work per kg of steam is.

(b) $w_{net} = (h_a - h_b) - (h_d - h_c) = 1129.5 \text{ kJ/kg}$

Solving for the steam flow per kg air using the first law equation about the steam generator.

$$\dot{m}_a(h_8 - h_9) = \dot{m}_s(h_a - h_d)$$

$$\frac{\dot{m}_S}{\dot{m}_a} = \frac{(h_8 - h_9)}{(h_a - h_d)} = 0.165 \ \frac{\text{kg steam}}{\text{kg air}}$$

The thermal efficiency based on 1 kg air is

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(474.4 \text{ kJ/kg}) + (0.165 \text{ kg/kg})(1129.5 \text{ kJ/kg})}{(0.02856 \text{ kg/kg})(43\ 200 \text{ kJ/kg})}$$

(c) $\eta_{th} = 0.536$

The air flow is.

$$\dot{W} = \dot{m}_a\, w_{net}$$

(d) $\dot{m}_a = \dfrac{\dot{W}}{w_{net}} + \dfrac{600\ 000 \text{ kW}}{660.8 \text{ kJ/kg}} = 908.0 \text{ kg/s}$

The fuel flow rate is.

(f) $\dot{m}_f = \dot{m}_a\, r_{a/f} = (908.0 \text{ kg/s})(0.02856 \text{ kg/kg}) = 25.9 \text{ kg/s}$

The fuel cost per kWh is.

(g) $\$/\text{kWh} = \dfrac{(25.9 \text{ kg/s})(\$0.45/\text{kg})(3600 \text{ s/h})}{(600\ 000 \text{ kW})} = 0.0699\ \$/\text{kWh}$

The Carnot cycle efficiency based on T_C = 290°K and T_H = 1220°K.

$$\eta_{carnot} = 1 - \frac{290°K}{1220°K} = 0.762$$

The second-law efficiency is.

(h) $\eta_2 = \dfrac{\eta_{th}}{\eta_{carnot}} = \dfrac{0.535}{0.762} = 0.702$

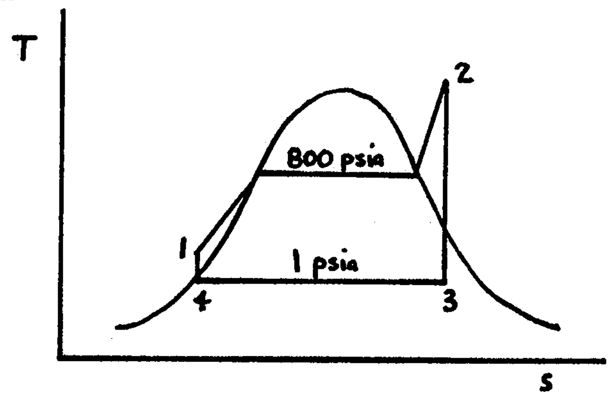
Problem *15.1

In a Rankine cycle, steam enters the turbine at 800 psia and 800°F, which exhausts at 1 psia. Show the cycle on a T-s diagram and find (a) the quality of the steam entering the condenser; (b) the turbine work in Btu/lbm; (c) the pump work in Btu/lbm; (d) the heat supplied in Btu/lbm; (e) the heat rejected in Btu/lbm; (f) the net work of the cycle in Btu/lbm; (g) the thermal efficiency of the cycle.

Given: Rankine cycle with steam expanding from 800 psia and 800°F to 1 psia.

Find: Quality of steam entering condenser, turbine work, pump work, heat rejected, net work, and thermal efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The turbine expansion and pump compression are isentropic.

Analysis: Determine the cycle enthalpies using Appendices A.14, A.15, and A.16, or SATSTM.TK and SHTSTM.TK.

$h_2 = 1399.1$ Btu/lbm $\qquad s_2 = 1.5972$ Btu/lbm-R

$h_3 = 892.1$ Btu/lbm $\qquad s_3 = s_2 \qquad$ (a) $\quad x = 0.794$

$h_4 = 69.58$ Btu/lbm $\qquad h_f$ at 1 psia

$h_1 = 71.97$ Btu/lbm

The turbine work is.

(b) $\quad w_t = h_2 - h_3 = 1399.1 - 892.1 \text{ Btu/lbm} = 507 \text{ Btu/lbm}$

The pump work is.

(c) $w_p = h_1 - h_4 = 71.97 - 69.58 \text{ Btu/lbm} = 2.39 \text{ Btu/lbm}$

The heat supplied is.

(d) $q_{in} = h_2 - h_1 = 1399.1 - 71.97 \text{ Btu/lbm} = 1327.1 \text{ Btu/lbm}$

The heat rejected is.

(e) $q_{out} = h_3 - h_4 = 892.1 - 69.58 \text{ Btu/lbm} = 822.5 \text{ Btu/lbm}$

The net work is.

(f) $w_{net} = w_t - w_p = 507 - 2.39 \text{ Btu/lbm} = 504.6 \text{ Btu/lbm}$

The thermal efficiency is.

(g) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{504.6 \text{ Btu/lbm}}{1327.1 \text{ Btu/lbm}} = 0.380$$

Problem *15.5

A Rankine cycle is characterized by turbine inlet conditions of 1500 psia and 1000°F. The condenser pressure is 1 psia. The heat transfer to the steam in the boiler occurs at the rate of 7.0 x 10^6 Btu/sec. The cooling water in the condenser increases in temperature from 70° to 85°F. Determine (a) the net power produced; (b) the cooling-water flow rate in gal/min; (c) the cycle thermal efficiency.

Given: Rankine cycle operating between 1500 psia and 1000°F, and 1 psia with 7.0 x 10^6 Btu/sec transferred in the boiler.

Find: Net power, cooling water flow, and thermal efficiency.

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.
4) The specified heat of the cooling water is 1.0 Btu/lbm-R.

Analysis: Determine the ideal cycle enthalpies and cycle thermal efficiency following the procedure in Example 15.1 or using STMCYCLE.TK.

h_1 = 74.06 Btu/lbm h_3 = 893.7 Btu/lbm

h_2 = 1490.9 Btu/lbm h_4 = 69.58 Btu/lbm

(c) $$\eta_{th} = 0.4184$$

Using the definition of thermal efficiency, $\eta_{th} = \dfrac{W_{net}}{Q_{in}}$

(a) $$W_{net} = \eta_{th} Q_{in} = (0.4184)(7.0 \times 10^6 \text{ Btu/sec})$$

$$= 2.9288 \times 10^6 \text{ Btu/sec}$$

From the first law equation for the cycle.

$$Q_{out} = Q_{in} - W_{net} = 7.0 \times 10^6 \text{ Btu/sec} - 2.9288 \times 10^6 \text{ Btu/sec}$$

$$Q_{out} = 4.0712 \times 10^6 \text{ Btu/sec}$$

$$Q_{out} = \dot{m}\, c_p\, \Delta T$$

(b) $$\dot{m} = \frac{Q_{out}}{c_p\, \Delta T} = \frac{4.0712 \times 10^6 \text{ Btu/sec}}{(1.0 \text{ Btu/lbm-R})(15°\text{R})} = 271{,}413 \text{ lbm/sec}$$

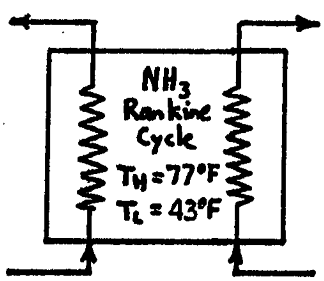
Problem *15.9

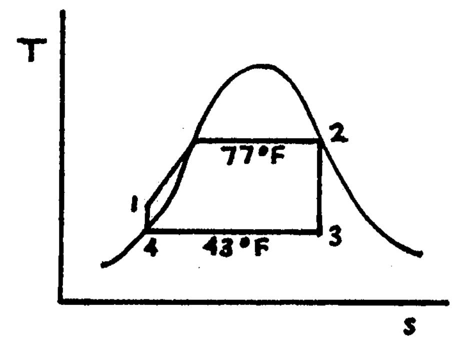
It is possible to construct a Rankine-cycle power plant using warm water near the ocean's surface as a heat source and cold water from the ocean's depth as a heat sink. For a particular plant operating with this configuration, the working substance is ammonia, the surface water is 80°F, and the cold water is 40°F. The ammonia is a saturated vapor entering the turbine and is 3°F less than the seawater temperature entering the heat exchanger and 3°F more than the seawater temperature leaving the turbine. The cycle is to produce 50 MW of power. Determine (a) the cycle thermal efficiency; (b) the cycle efficiency when considering the power requirements of pumps to move the seawater, which amount to 15 MW.

Given: 50 MW Rankine cycle operating between 77°F and 43°F using ammonia.

Find: Thermal efficiency, without and with seawater pump power.

Sketch and Given Data:





Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is an ideal Rankine cycle.

Analysis: Using Appendix A.18.

$h_2 = 630.2$ Btu/lbm $\qquad s_2 = 1.2036$ Btu/lbm-R

$s_3 = s_2 \qquad s_3 = s_f + x\, s_{fg} \qquad x = 0.950 \qquad h_3 = 597.0$ Btu/lbm

$h_4 = 90.15$ Btu/lbm

$$h_1 = h_f + v_f\,(p_1 - p_4) = 90.15 \text{ Btu/lbm}$$

$$+ (0.02543 \text{ ft}^3/\text{lbm})(135.5 - 78.3 \text{ psia})\frac{(144 \text{ in}^2/\text{ft}^3)}{(778.2 \text{ ft-lb}_f/\text{Btu})}$$

$h_1 = 90.42$ Btu/lbm

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{(h_2 - h_3) - (h_1 - h_4)}{(h_2 - h_1)}$$

$$= \frac{(630.2 - 597.0) - (90.42 - 90.05)}{(603.2 - 90.42)}$$

(a) $\eta_{th} = 0.0608$

Considering $\dot{W}_{net} = 50$ MW with an additional 15 MW required to operate the seawater pumps.

(b) $\eta_{cycle} = (0.0608)\left(\frac{50 \text{ MW}}{50 \text{ MW} + 15 \text{ MW}}\right) = 0.0468$

Comment: The small difference in cycle temperatures plus the high power requirements for the seawater pumps results in a low cycle efficiency. However, the "fuel" is free. The question is if the high cost of construction can be repaid by the fuel savings.

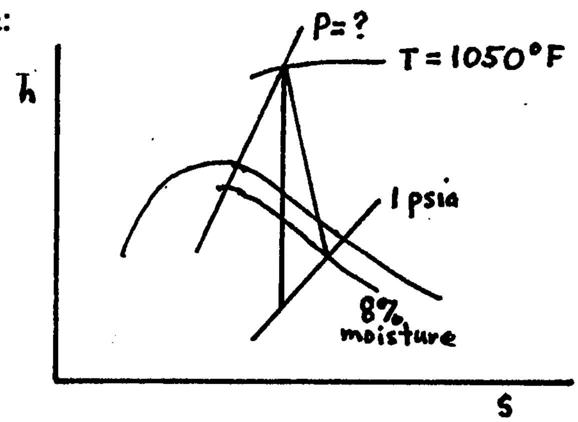
Problem *15.13

A Rankine-cycle power plant is to be designed with a maximum turbine inlet temperature of 1050°F and a minimum condenser pressure of 1 psia. The manufacturer guarantees a turbine isentropic efficiency of 85% and a pump efficiency of 80%. The manufacturer will make this guarantee for the turbine only if the exit steam condition from the turbine is 92% or greater. Determine the steam generator pressure that allows this.

Given: Steam turbine of 85% isentropic efficiency expands steam from 1050°F to 1 psia.

Find: Inlet pressure required for exit quality of 92%.

Sketch and Given Data:



Assumptions:
1) The turbine is analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Solving for the properties of the exhaust steam using Appendix A.15 or SATSTM.TK.

h_{exh} = 1022.9 Btu/lbm $\qquad$ s_{exh} = 1.8303 Btu/lbm-R

Using STMCYCLE.TK, enter the following rule

hexh = h2 - (h2 - h3) *.85

Entering the above value of hexh, and solving.

p2 = 1015 psia

Comment: The problem can also be solved using the Mollier chart, Appendix B.1. Draw a line from the exhaust condition at a slope corresponding to 85% efficiency. Read the pressure at 1050°F (566°C).

Problem *15.17

In the conceptual design stages of a power plant, consideration is given to a steam generator operating at 4000 psia and a maximum temperature of 1100°F. The condenser pressure is 0.7 psia. Should reheat be used in the cycle, and if so, how many stages of reheating would be needed? The steam leaving the turbine should not be superheated.

Given: Power plant with turbine inlet of 4000 psia and 1100°F and exhaust of 0.7 psia with wet steam.

Find: Stages of reheat needed.

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The turbine expansion is isentropic.
4) Maximum moisture permitted is 12%.

Analysis: Using Appendices A.15, and A.16, Appendix B.1 or STMCYCLE.TK a non-reheat cycle would expand steam to 0.7 psia with a quality of 0.731. This is too much moisture.

A single stage of reheat at 800 psia and 1100°F would result in a quality of 0.846. Still too much moisture.

A second stage of reheat at 150 psia and 1100°F would result in a quality of 0.947. Acceptable.

Comment: With typical efficiencies of less than 100%, a single stage of reheat will probably produce an acceptable solution.

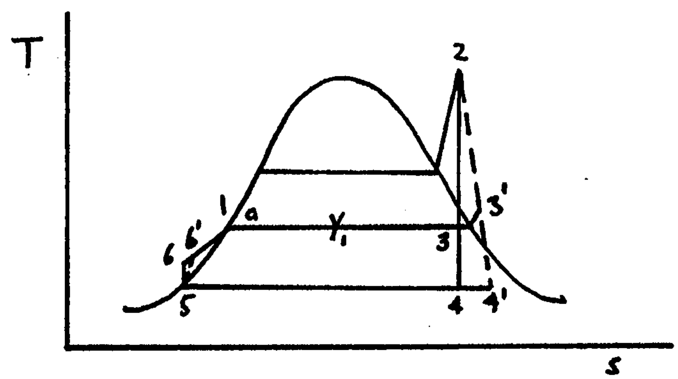
Problem *15.21

Recalculate Problem *15.20, this time including a turbine isentropic efficiency of 85% and a pump efficiency of 80%.

Given: Regenerative Rankine cycle with steam conditions as in problem *15.20, turbine efficiency of 85% and pump efficiency of 80%.

Find: Thermal efficiency, flow to feedwater heater, and net power produced.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) Water leaves the heater as a saturated liquid.

Analysis: From Problem *15.20 the following enthalpies are available.

$$h_2 = 1549.9 \text{ Btu/lbm}$$

$$h_5 = 69.6 \text{ Btu/lbm}$$

$$h_1 = h_a = 298.4 \text{ Btu/lbm}$$

Using the definition of turbine and pump efficiencies, and the enthalpies for points 3, 4, and 6 from Problem *15.20.

$$h_3' = 1549.9 - (0.85)(1549.9 - 1216.6) = 1266.6 \text{ Btu/lbm}$$

$$h_4' = 1549.9 - (0.85)(1549.9 - 915.6) = 1010.7 \text{ Btu/lbm}$$

$$h_6' = 69.6 + \frac{(74.1 - 69.6)}{0.8} = 75.2 \text{ Btu/lbm}$$

Solving for y_1.

$$y_1 = \frac{h_1 - h_6'}{h_3' - h_a} = \frac{(298.4 - 75.2)}{(1266.6 - 298.4)} = 0.2305$$

(b) $\dot{m}_{ex} = \dot{m}_2\, y_1 = (3.6 \times 10^5 \text{ lbm/hr})(0.2305) = 8.30 \times 10^4 \text{ lbm/hr}$

The net power produced is.

$$w_{net} = w_t - w_p = (h_2 - h_3) + (1 - y_1)(h_3' - h_4') - (h_6' - h_5)$$

$$w_{net} = 474.6 \text{ Btu/lbm}$$

(c) $\dot{W}_{net} = \dot{m}_2\, w_{net} = (3.6 \times 10^5 \text{ lbm/hr})(474.6 \text{ Btu/lbm})$

$$= 1.709 \times 10^8 \text{ Btu/hr}$$

The thermal efficiency is.

(a) $$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{net}}{h_2 - h_1} = \frac{474.6}{1549.9 - 298.4} = 0.379$$

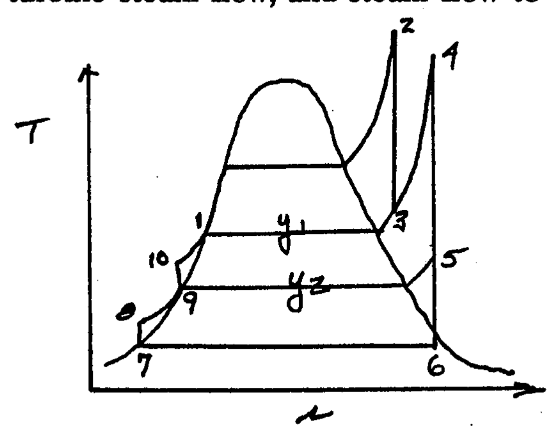
Problem *15.25

A reheat-regenerative Rankine cycle, producing 250 MW, has two feedwater heaters, closed for the first turbine extraction and open for the second turbine extraction. When a fraction steam is extracted for the first stage of feedwater heating, the remainder is reheated to 900°F. Steam enters the turbine at 1000 psia and 1000°F and expands to 200 psia, where the first extraction stage occurs. The remaining steam expands to 50 psia, where the second extraction stage occurs. The remainder expands through the turbine and exhausts at 1 psia. The closed feedwater heater drains through a trap to the open heater. Determine (a) the cycle thermal efficiency; (b) the steam flow rate entering the turbine; (c) the steam flow rate to each of the heaters.

Given: 250 MW reheat-regenerative Rankine cycle with two feedwater heaters are given steam conditions.

Find: Cycle efficiency, turbine steam flow, and steam flow to the heaters.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The feed and drains from the closed heater leave at the saturation temperature of the extraction steam.
4) The turbine expansion is isentropic.

Analysis: Determine the cycle enthalpies using Appendices A.14, A.15, and A.16 or SATSTM.TK and SHTSTM.TK.

h_2 = 1506 Btu/lbm $\quad$ s_2 = 1.6525 Btu/lbm-R

h_3 = 1297.1 Btu/lbm $\quad$ $s_3 = s_2$

h_4 = 1476.8 Btu/lbm $\quad$ s_4 = 1.8047 Btu/lbm-R

h_5 = 1299.6 Btu/lbm $\quad$ $s_5 = s_4$

h_6 = 1008.6 Btu/lbm $\quad$ $s_6 = s_4$

$h_7 = 69.6$ Btu/lbm $\qquad h_f$ at 1 psia

$h_8 = 69.8$ Btu/lbm

$h_9 = 250.1$ Btu/lbm $\qquad h_f$ at 50 psia

$h_{10} = 251.1$ Btu/lbm

$h_1 = 355.6$ Btu/lbm $\qquad h_f$ at 200 psia

Solving for y_1 and y_2 using the First Law equations for the heaters.

$$y_1\, h_3 + (1)\, h_{10} = y_1\, h_1 + (1)\, h_1 \qquad y_1 = 0.1089$$

$$y_2\, h_5 + (1 - y_1 - y_2)\, h_8 + y_1\, h_1 = (1)\, h_9 \qquad y_2 = 0.1213$$

Calculating the net work.

$$w_{net} = w_t - w_p$$

$$= [(h_2 - h_3) + (1 - y_1)(h_4 - h_5) + (1 - y_1 - y_2)(h_5 - h_6)]$$

$$- [(h_{10} - h_9) + (1 - y_1 - y_2)(h_8 - h_7)]$$

$$w_{net} = 587.7 \text{ Btu/lbm}$$

The steam flows to the turbine and heaters are.

(b) $\dot{W}_{net} = \dot{m}_t\, w_{net} \qquad \dot{m}_t = \dfrac{\dot{W}_{net}}{w_{net}}$

$$= \frac{(250\ 000 \text{ kW})(3412 \text{ Btu/kW-hr})}{587.7 \text{ Btu/lbm}}$$

$$= 1.451 \times 10^6 \text{ lbm/hr}$$

(c)

$$\dot{m}_{htr_1} = \dot{m}_t\, y_1 = (1.451 \times 10^6 \text{ lbm/hr})(0.1089) = 1.580 \times 10^5 \text{ lbm/hr}$$

$$\dot{m}_{htr_2} = \dot{m}_t\, y_2 = (1.451 \times 10^6 \text{ lbm/hr})(0.1213) = 1.760 \times 10^5 \text{ lbm/hr}$$

The thermal efficiency is.

(a) $\eta_{th} = \dfrac{w_{net}}{q_{in}} = \dfrac{w_{net}}{(h_2 - h_1) + (1 - y_1)(h_4 - h_3)} = 0.448$

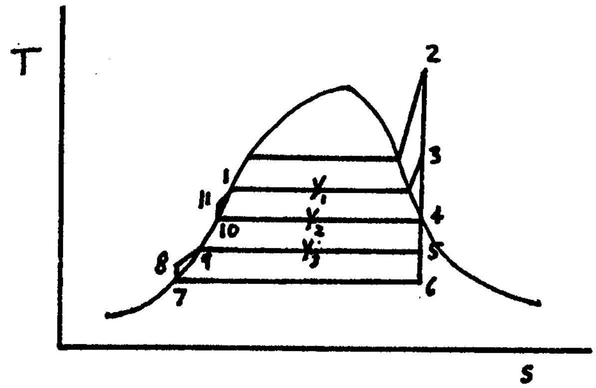
Problem *15.29

In an ideal regenerative cycle, steam is generated at 400 psia and 700°F. Steam is extracted for feedwater heating at 110 30, and 5.99 psia. Condensation occurs at 90°F. Determine (a) the mass fraction extracted at each point; (b) the net work; (c) the cycle efficiency.

Given: Ideal regenerative Rankine cycle with three extractions for feedwater heating.

Find: Extraction mass fractions, net work, and cycle efficiency.

Sketch and Given Data:



Assumptions:

1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The middle heater is open-type; the others are closed.
4) The feedwater and drains leave the closed heaters at the extraction saturation temperature; drains are cascaded.
5) The turbine expansion and compression processes are isentropic.

Analysis: Determine the cycle enthalpies using Appendices A.14, A.15, and A.16, or SATSTM.TK and SHTSTM.TK.

h_2 = 1363.0 Btu/lbm $\quad$ s_2 = 1.6398 Btu/lbm-R

h_3 = 1225.8 Btu/lbm $\quad$ $s_3 = s_2$

h_4 = 1121.9 Btu/lbm $\quad$ $s_4 = s_2$

h_5 = 1015.0 Btu/lbm $\quad$ $s_5 = s_2$

h_6 = 898.2 Btu/lbm $\quad$ $s_6 = s_2$

h_7 = 57.8 Btu/lbm $\quad$ h_f at 90°F

$h_8 = 57.9$ Btu/lbm	$\eta_p = 100\%$
$h_9 = 138.3$ Btu/lbm	h_f at 5.99 psia
$h_{10} = 218.9$ Btu/lbm	h_f at 30 psia
$h_{11} = 220.1$ Btu/lbm	$\eta_p = 100\%$
$h_1 = 305.7$ Btu/lbm	h_f at 110 psia

Solving the first law equation, for the feedwater heaters for y_1, y_2, and y_3.

$$y_1\, h_3 + (1)\, h_{11} = (1)\, h_1 + y_1\, h_1 \qquad y_1 = 0.093$$

$$y_2\, h_4 + (1 - y_1 - y_2)\, h_9 + y_1\, h_1 = (1)\, h_{10} \qquad y_2 = 0.0661$$

$$y_3\, h_5 + (1 - y_1 - y_2)\, h_8 = y_3\, h_9 + (1 - y_1 - y_2)\, h_9 \qquad y_3 = 0.0771$$

The net work is.

$$w_{net} = w_t - w_p$$

$$= [(h_2 - h_3) + (1 - y_1)(h_3 - h_4) + (1 - y_1 - y_2)(h_4 - h_5) + (1 - y_1 - y_2 - y_3)(h_5 - h_6)] - [(h_{11} - h_{10}) + (1 - y_1 - y_2)(h_8 - h_7)]$$

(b) $w_{net} = 409.2$ Btu/lbm

The thermal efficiency is.

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_{net}}{h_2 - h_1} = \frac{409.2 \text{ Btu/lbm}}{1363.0 \text{ Btu/lbm} - 305.7 \text{ Btu/lbm}} = 0.387$$

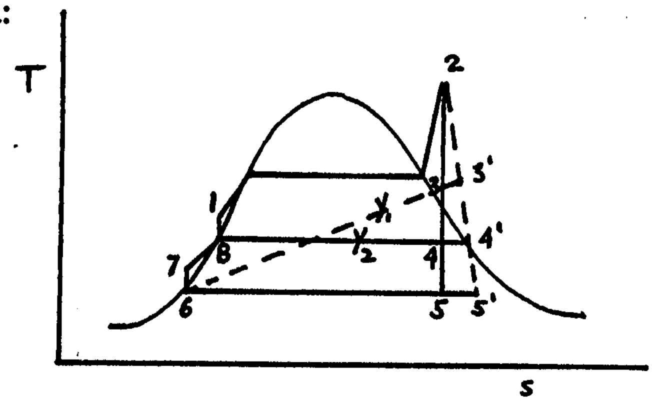
Problem *15.33

A university decides to invest in a cogeneration facility, providing 20 MW of power and steam for heating in the campus buildings. A preliminary design proposal suggests that steam be generated at 400 psia and 550°F. In addition a turbine may be purchased that has two extraction stages, the first occurring at 150 psia for building heating and the second at 50 psia for regenerative heating with an open feedwater heater. The condenser pressure is 1 psia. The returns from the buildings may be considered to be saturated at the condenser temperature. The buildings require 1.08 x 10^7 Btu/hr of heat for the worst-case condition. The turbine's isentropic efficiency is 80% at these steam conditions. The pump efficiency is assumed to be 100%. Determine (a) the steam generator capacity in lbm/sec of steam produced and in the heat rate required; (b) the mass flow rate of steam extracted for building heating; (c) the cycle's utilization factor.

Given: Regenerative Rankine cycle with high pressure extraction used for heating, and low pressure for feedwater heating.

Find: Steam generator capacity, extraction flow for building heating, and utilization factor.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Determine the cycle enthalpies using Appendices A.14, A.15, and A.16, or SATSTM.TK and SHTSTM.TK.

h_2 = 1277.3 Btu/lbm $\qquad$ s_2 = 1.5607 Btu/lbm-R

h_3 = 1187.1 Btu/lbm $\qquad$ $s_3 = s_2$

h_3' = 1205.1 Btu/lbm $\qquad$ η_t = 80%

h_4 = 1101.7 Btu/lbm $\qquad$ $s_4 = s_2$

$h_4' = 1136.8$ Btu/lbm $\qquad \eta_t = 80\%$

$h_5 = 871.6$ Btu/lbm $\qquad s_5 = s_2$

$h_5' = 952.7$ Btu/lbm $\qquad \eta_t = 80\%$

$h_6 = 69.6$ Btu/lbm $\qquad h_f$ at 1 psia

$h_7 = 69.7$ Btu/lbm $\qquad \eta_p = 100\%$

$h_8 = 250.1$ Btu/lbm $\qquad h_f$ at 50 psia

$h_1 = 251.2$ Btu/lbm $\qquad \eta_p = 100\%$

Solving for the heating steam flow.

$$\dot{Q}_h = \dot{m}_h (h_3' - h_6) \qquad \dot{m}_h = \dot{m}_s y_1$$

(b) $$\dot{m}_s y_1 = \frac{1.08 \times 10^7 \text{ Btu/hr}}{(1205.1 - 69.6 \text{ Btu/lbm})} = 9511 \text{ lbm/hr}$$

The net work and first law equation for the open heater are

$$w_{net} = w_t - w_p = [(h_2 - h_3') + (1 - y_1)(h_3' - h_4') + (1 - y_1 - y_2)(h_4' - h_5')]$$
$$- [(h_1 - h_8) - (1 - y_2)(h_7 - h_6)]$$

$$y_2 h_4' + (1 - y_2) h_7 = h_8$$

Since the plant must produce 20 MW of power.

$$\dot{W}_{net} = \dot{m}_s w_{net}$$

Solving the above simultaneously.

$y_1 = 0.03945$

$y_2 = 0.169$

(a) $\dot{m}_s = 241{,}539$ lbm/hr

$$\dot{Q}_{in} = \dot{m}_s(h_2 - h_1) = 2.478 \times 10^8 \text{ Btu/hr}$$

The cycle utilization factor is.

(c) $$Y_{cg} = \frac{\dot{W}_{net} + \dot{Q}_h}{\dot{Q}_{in}} = \frac{(20{,}000 \text{ kW})(3412 \text{ Btu/kW-hr}) + 1.08 \times 10^7 \text{ Btu/hr}}{2.478 \times 10^8 \text{ Btu/hr}}$$

$$= 0.319$$

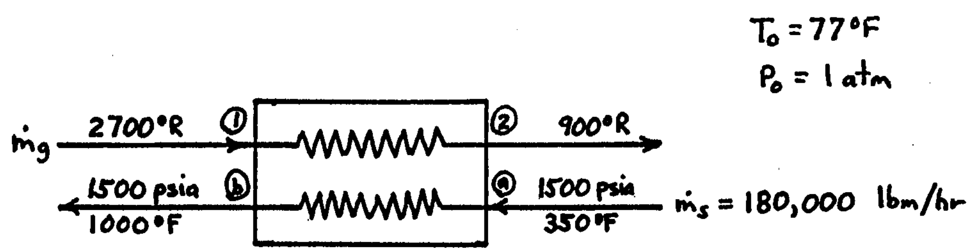
Problem *15.37

A steam generator may be considered to be a constant-pressure combustion chamber followed by a heat exchanger where the heat from the combustion gases is transferred to water, creating steam. Consider such a steam generator where the combustion gases, with properties similar to air, enter the heat exchanger at 2700°R and are cooled to 900°R. At a rate of 180,000 lbm/hr water enters the heat exchanger at 1500 psia and 350°F and leaves as a superheated vapor at 1500 psia and 1000°F. T_0 = 77°F and p_0 = 1 atm. Determine (a) the availability change of the combustion gas in Btu/min; (b) the availability change of the water in Btu/min; (c) the irreversibility rate in Btu/min; (d) the second law efficiency.

Given: Steam generator producing 25 kg/s of 10 MPa and 175°C steam by combustion gases being cooled from 1500°K to 500°K.

Find: Availability change of combustion gas and water, irreversibility rate, and second-law efficiency.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) Heat flow to the surroundings and the work is zero.
3) The changes in kinetic and potential energies may be neglected.
4) The combustion gases behave like an ideal gas at ambient conditions.

Analysis: From Appendix A.1, c_p = 0.24 Btu/lbm-R

The change in entropy for a constant pressure process is thus.

$$s_1 - s_2 = c_p \ln\left(\frac{T_2}{T_1}\right) = 0.24 \ln\left(\frac{900°R}{2700°R}\right) = -0.2637 \text{ Btu/lbm-R}$$

From Appendices A.16 and A.17 the steam and water properties are.

h_a = 323.9 Btu/lbm $\qquad$ h_b = 1490.9 Btu/lbm

s_a = 0.50034 Btu/lbm-R $\qquad$ s_b = 1.6001 Btu/lbm-R

Solving the first law equation for the gas flow rate.

$$\dot{m}_g\, c_p\,(T_1 - T_2) = \dot{m}_s(h_b - h_a)$$

$$\dot{m}_g = \frac{(180{,}000\ \text{lbm/hr})(1490.9 - 323.9\ \text{Btu/lbm})}{(0.24\ \text{Btu/lbm-R})(2700°\text{R} - 900°\text{R})}$$

$$= 486{,}250\ \text{lbm/hr}$$

The change in availability of the combustion gas is.

$$\Psi_2 - \Psi_1 = (h_2 - h_1) - T_0(s_2 - s_1)$$

$$\Psi_2 - \Psi_1 = (0.24\ \text{Btu/lbm-R})(900°\text{R} - 2700°\text{R})$$

$$- (537°\text{R})(- 0.2637\ \text{Btu/lbm-R})$$

$$\Psi_2 - \Psi_1 = -290.39\ \text{Btu/lbm}$$

(a) $$\dot{m}_g(\Psi_2 - \Psi_1) = \frac{(486{,}250\ \text{lbm/hr})}{60\ \text{min/hr}}(-290.39\ \text{Btu/lbm})$$

$$= -2.353 \times 10^6\ \text{Btu/min}$$

The change in availability of the water is.

$$\Psi_b - \Psi_a = (h_b - h_a) - T_0(s_b - s_a)$$

$$\Psi_b - \Psi_a = (1490.9 - 323.9\ \text{Btu/lbm})$$

$$- (537°\text{R})(1.6001 - 0.50034\ \text{Btu/lbm-R})$$

$$\Psi_b - \Psi_a = 576.4\ \text{Btu/lbm}$$

(b) $$\dot{m}_s(\Psi_b - \Psi_a) = \frac{(180{,}000\ \text{Btu/hr})}{60\ \text{min/hr}}(576.4\ \text{Btu/lbm})$$

$$= 1.7292 \times 10^6 \text{ Btu/min}$$

The irreversibility rate is.

$$\dot{I} = T_0 \left[\dot{m}_g(s_2 - s_1) + \dot{m}_s(s_b - s_a)\right]$$

$$\dot{I} = (537°R)\left[\frac{(486{,}250 \text{ lbm/hr})}{60 \text{ min/hr}} (-0.2637 \text{ Btu/lbm-R})\right.$$

$$\left. + \frac{(180{,}000 \text{ lbm/hr})}{60 \text{ min/hr}} (1{,}6001 - 0.50034 \text{ Btu/lbm-R})\right]$$

(c) $\dot{I} = 624{,}100 \text{ Btu/min}$

The second law efficiency can be determined comparing the change in availability of the combustion gases with that for the water.

(d) $$\eta_2 = \frac{1.7292 \times 10^6 \text{ Btu/min}}{2.353 \times 10^6 \text{ Btu/min}} = 0.738$$

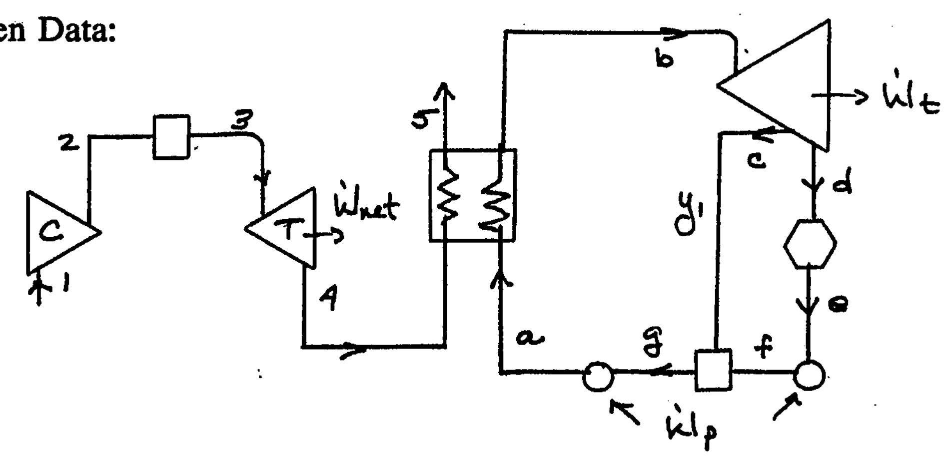
Problem *15.41

A combined gas turbine-steam power plant produces 500 MW of net power. The pressure ratio of the ideal-gas turbine unit is 16, with air entering at 77°F and 1 atm. The maximum inlet temperature to the turbine is 3100°R. The minimum gas temperature from the steam generator is 800°R. Steam is generated at 1000 psia and 900°F. The turbine has one open feedwater heater regenerative stage at 75 pisa. The condenser pressure is 2 psia. Assume the gases have properties similar to air. Determine (a) the air and steam mass flow rates; (b) the cycle efficiency; (c) the availability of the gas leaving the steam generator; (d) the availability of the gas leaving the gas turbine relative to inlet air temperature and pressure. What fraction of this was used in the steam cycle?

Given: 500 MW combined gas turbine-steam power plant.

Find: Air and steam flow rates, cycle efficiency, availability of the gas entering and leaving the steam generator, fraction of availability used in steam cycle.

Sketch and Given Data:



Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The expansion and compression processes are isentropic.

Analysis: Determine the net work, heat supplied, and turbine exit temperature for the gas turbine using AIRCYCLE.TK or the procedure in Example 14.1. Using AIRCYCLE.TK.

$$w_{net} = \text{DEL43 - DEL21} = 276.62 \text{ Btu/lbm}$$

$$q_{in} = \text{DELh32} = 537.77 \text{ Btu/lbm}$$

$$T_4 = 1576.5°\text{R}$$

Determining the steam cycle enthalpies using Appendices A.14, A.15, and A.16, or SATSTM.TK and SHTSTM.TK.

$h_b = 1448.8$ Btu/lbm $\qquad s_b = 1.6121$ Btu/lbm-R

$h_c = 1171.3$ Btu/lbm $\qquad s_c = s_b$

$h_d = 936.0$ Btu/lbm $\qquad s_d = s_b$

$h_e = 94.1$ Btu/lbm $\qquad h_f$ at 2 psia

$h_f = 94.3$ Btu/lbm

$h_g = 277.4$ Btu/lbm $\qquad h_f$ at 75 psia

$h_a = 280.4$ Btu/lbm

Solving the first law equation for the open heater for y_1.

$$y_1\, h_c + (1 - y_1)\, h_f = h_g \qquad y_1 = 0.170$$

The net work is.

$$w_{net} = w_t - w_p = [(h_b - h_c) + (1 - y_1)(h_c - h_d)]$$

$$- [(h_a - h_g) + (1 - y_1)(h_f - h_e)]$$

$$w_{net} = 469.6 \text{ Btu/lbm}$$

Solving for the first law equation for the steam generator for the steam flow produced per kg of gas flow.

$$\dot{m}_g\, c_p\, (T_4 - T_5) = \dot{m}_s(h_b - h_a)$$

$$\frac{\dot{m}_s}{\dot{m}_g} = \frac{(0.24 \text{ Btu/lbm-R})(1576.5°\text{R} - 800°\text{R})}{(1448.8 - 280.4 \text{ Btu/lbm})}$$

$$= 0.1595 \frac{\text{lbm steam}}{\text{lbm gas}}$$

Solving the equation for total net power for the gas flow rate.

$$\dot{W}_{net} = \dot{m}_g\, w_{net_g} + \dot{m}_s\, w_{net_s}$$

$$500\,000 \text{ kW} \left(\frac{3412 \text{ Btu/kW-hr}}{3600 \text{ sec/hr}}\right) = \dot{m}_g(276.62 \text{ Btu/lbm})$$

$$+ \dot{m}_g \left(0.1595 \frac{\text{lbm steam}}{\text{lbm gas}}\right)(469.6 \text{ Btu/lbm})$$

$$\dot{m}_g = 1348.1 \text{ lbm/sec}$$

(a)

$$\dot{m}_S = (0.1595)((1348.1 \text{ lbm/sec}) = 215 \text{ lbm/sec}$$

The thermal efficiency is.

(b) $$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net}}{\dot{m}_g\, q_{in}} = \frac{473{,}889 \text{ Btu/sec}}{(1348.1 \text{ lbm/sec})(537.77 \text{ Btu/lbm})}$$

$$= 0.654$$

The availability of the gas leaving the steam generator is.

$$\alpha_5 = (h_4 - h_0) - T_0(s_4 - s_0)$$

Using AIR.TK to determine the change in enthalpy and entropy.

$$\alpha_5 = (63.485 \text{ Btu/lbm}) - (537°R)(0.09788 \text{ Btu/lbm-R})$$

(c) $$\alpha_5 = 10.92 \text{ Btu/lbm}$$

Solving for the availability of the gas leaving the gas turbine.

$$\alpha_4 = (261.14 \text{ Btu/lbm}) - (537°R)(0.2687 \text{ Btu/lbm-R})$$

(d) $$\alpha_4 = 116.86 \text{ Btu/lbm}$$

Comparing the change in availability of the gas to the net work produced in the steam cycle per kg of gas.

$$\frac{w_{net}/\text{kg gas}}{\alpha_4 - \alpha_5} = \frac{(0.1595 \text{ lbm/lbm})(469.9 \text{ Btu/lbm})}{(116.86 - 10.92 \text{ Btu/lbm})} = 0.707$$

Problem*15.45

Simplify the reheat power plant shown in Figure 15.35 by eliminating all the heaters between the condensate pump and the first heater. Let the condenser operate at 90°F. Assume the high-pressure turbine exhausts at 550 psia. Calculate the mass flows if the power required is 236 MW. Use equipment efficiency guidelines as per actual heat balance discussion.

Given: Reheat-regenerative Rankine cycle producing 236 MW.

Find: Mass flows

Sketch and Given Data: See Figure 15.35

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Using the enthalpies given in Figure 15.35, solve the first-law equations for the seven feedwater heaters for the extraction mass fractions.

$$1316.4\, y_1 + 370 = 336.9\, y_1 = 464.6$$

$$1427\, y_2 + 328.5 + 382.6\, y_1 = 370 + (y_1 + y_2)\, 336.9$$

$$1369\, y_3 + 270.2 + (y_1 + y_2)\, 336.9 = 318.5 + (y_1 + y_2 + y_3)\, 282.6$$

$$1308\, y_4 + (1 - y_1 - y_2 - y_3 - y_4)\, 228.6 + (y_1 + y_2 + y_3)\, 282.6$$

$$= (y_1 + y_2 + y_3 + y_4)\, 272.7 + (1 - y_1 - y_2 - y_3 - y_4) 270.2$$

$$1247\, y_5 + (1 - y_1 - y_2 - y_3 - y_4 - y_5)\, 172 = (1 - y_1 - y_2 - y_3 - y_4)\, 228.6$$

$$1175\, y_6 + (1 - y_1 - y_2 - y_3 - y_5)\, 123.9 = 136\, y_6$$

$$+ (1 - y_1 - y_2 - y_3 - y_4 - y_5)\, 172$$

$$1108\, y_7 + (1 - y_1 - y_2 - y_3 - y_4 - y_5)\, 72.6 + 136\, y_6$$

$$= (1 - y_1 - y_2 - y_3 - y_4 - y_5)\, 123.9 + (y_6 + y_7)\, 84.6$$

The mass fractions are,

$y_1 = 0.09658$ $\quad$ $y_5 = 0.042168$

$y_2 = 0.034021$ $\quad$ $y_6 = 0.035125$

$y_3 = 0.037931$ $\quad y_7 = 0.036369$

$y_4 = 0.03057$

The net work per lbm of inlet steam is.

$$w_{net} = w_t - w_p = [(1461.2 - 1316.4) + (1 - y_1)(1519.2 - 1427)$$
$$+ (1 - y_1 - y_2)(1427 - 1369) + (1 - y_1 - y_2 - y_3)(1369 - 1308)$$
$$+ (1 - y_1 - y_2 - y_3 - y_4)(1308 - 1247)$$
$$+ (1 - y_1 - y_2 - y_3 - y_4 - y_5)(1247 - 1175)$$
$$+ (1 - y_1 - y_2 - y_3 - y_4 - y_5 - y_6)(1175 - 1108)$$
$$+ (1 - y_1 - y_2 - y_3 - y_4 - y_5 - y_6 - y_7)(1108 - 1023.6)]$$
$$- [(1 - y_1 - y_2 - y_3 - y_4 - y_5)\ 0.1 + 7.44)]$$

$$W_{net} = 531.7 \text{ Btu/lbm}$$

From Figure 15.35.

$$\dot{W} = 235{,}090 \text{ kW} + 13{,}730 \text{ kW} + 3200 \text{ kW} + 950 \text{ kW}$$
$$= 252{,}9780 \text{ kW}$$

The inlet steam flow is.

$$\dot{m}_s = \frac{\dot{W}}{w_{net}} = \frac{(252{,}970 \text{ kW})(3412 \text{ Btu/kW-hr})}{531.7 \text{ Btu/lbm}} = 1{,}623{,}347 \text{ lbm/hr}$$

The bleed extraction flows are ($\dot{m}_i = \dot{m}_s\, y_i$).

$\dot{m}_1 = 156{,}783$ lbm/hr $\quad \dot{m}_5 = 68{,}453$ lbm/hr

$\dot{m}_2 = 55{,}228$ lbm/hr $\quad \dot{m}_6 = 57{,}020$ lbm/hr

$\dot{m}_3 = 61{,}575$ lbm/hr $\quad \dot{m}_7 = 58{,}877$ lbm/hr

$\dot{m}_4 = 49{,}626$ lbm/hr

Problem C15.1

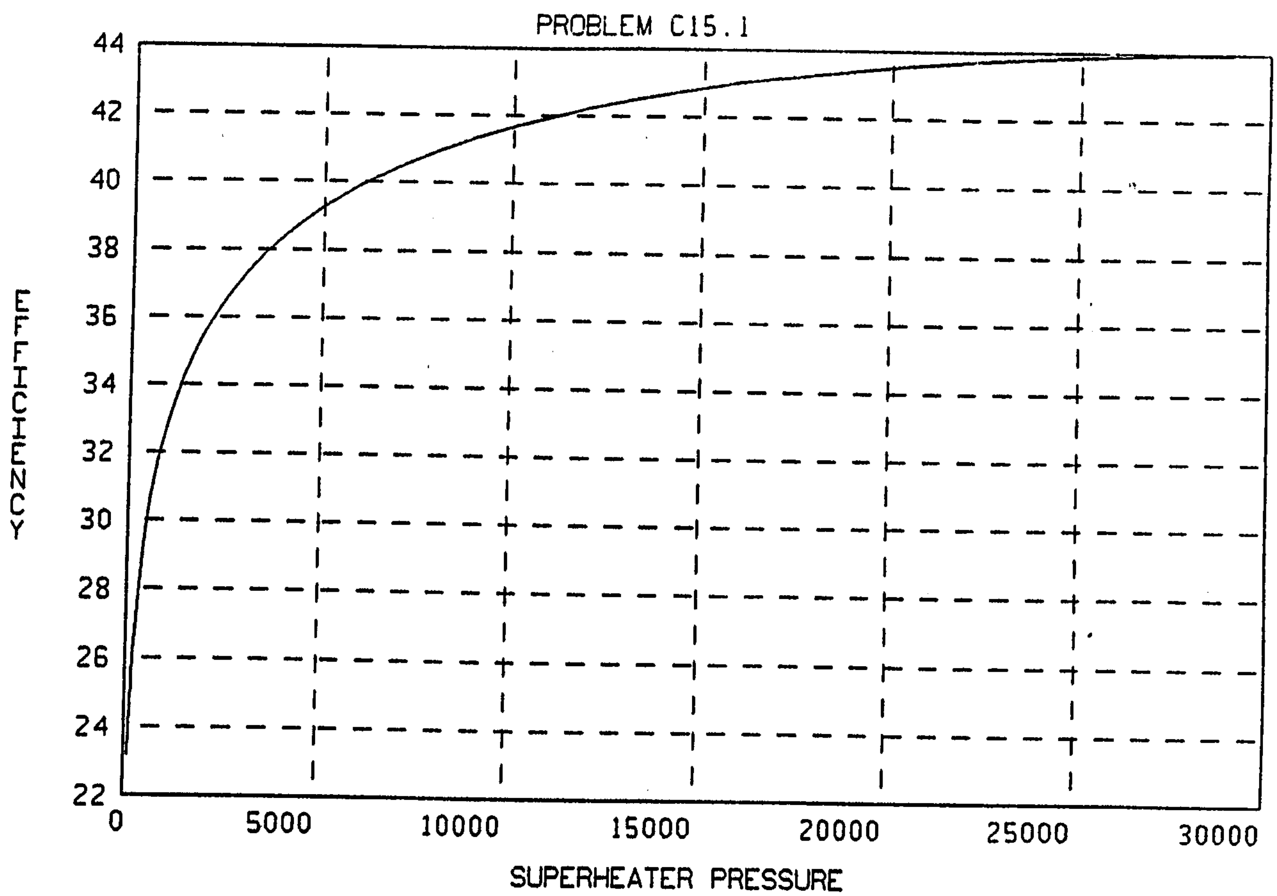
Use STMCYCLE.TK or develop a spreadsheet template or computer program to investigate the effect of varying the steam generator pressure on the thermal efficiency of an ideal Rankine cycle. For a steam generator superheater outlet temperature of 500°C and a condensing temperature of 35°C, vary the steam generator pressure from 100 kPa to 30 MPa. Plot the results.

Given: Ideal Rankine cycle with superheater temperature of 500°C and condensing temperature of 35°C.

Find: Thermal efficiency for range of steam generator pressures.

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.

Analysis: Using STMCYCLE.TK, List Solve for a range of pressures from 100 kPa to 30 MPa and plot the thermal efficiency.



Problem C15.5

Modify STMCYCLE.TK to permit the analysis of an ideal reheat Rankine cycle with a single reheat stage. For steam generator outlet conditions of 7 MPa and 550°C and a condensing temperature of 35°C, use the modified model to determine the reheat pressure that will result in the highest cycle thermal efficiency.

Given: Ideal reheat Rankine cycle with single reheat stage.

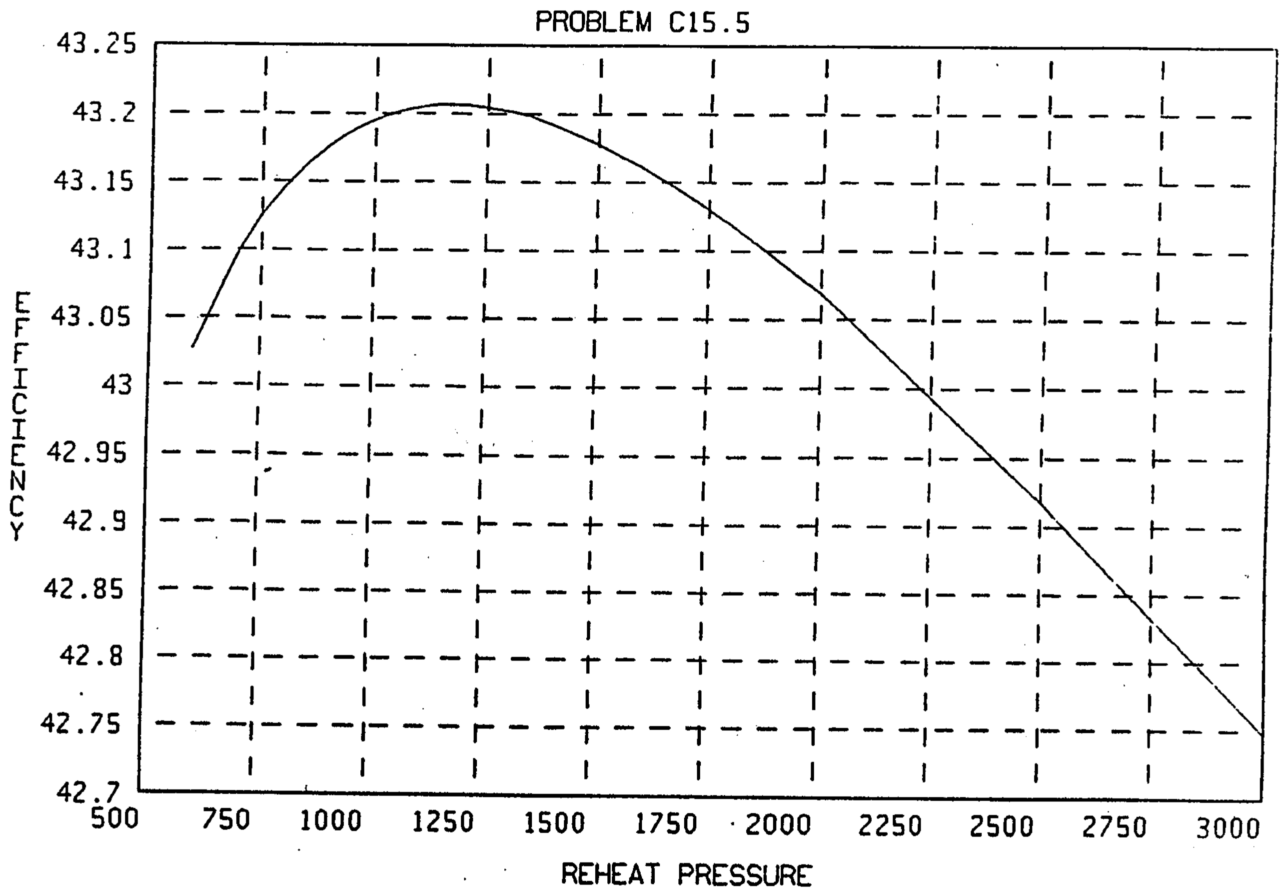
Find: Optimum pressure to reheat steam.

Assumptions:
1) Each process may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) Steam will be reheated to 550°C.

Analysis: Modifying STMCYCLE.TK as follows to add a single reheat stage to the simple Rankine cycle.

```
================ RULE SHEET ================
S Rule-----------------------------------------
  "Cycle Rules
  Wturb=(h2-hbl)+(hrh-h3)
  Wpump=h1-h4
  Wnet=Wturb-Wpump
  Qin=(h2-h1)+(hrh-hbl)
  Eth=(Wnet/Qin)*100
  s3=srh
  sbl=s2
  "Call Superheat Property Functions for Reheater Inlet and Outlet
  vbl=Vsuper(Tbl,Pbl)
  hbl=Hsuper(Tbl,Pbl)
  sbl=Ssuper(Tbl,Pbl)
  vrh=Vsuper(Trh,Prh)
  hrh=Hsuper(Trh,Prh)
  srh=Ssuper(Trh,Prh)
  Prh=Pbl
```

Solving the model with a range at reheat pressures as inputs and plotting the results.



Comment: Optimum reheat pressure of 1200 kPa is 17% of the team generator pressure.

CHAPTER SIXTEEN

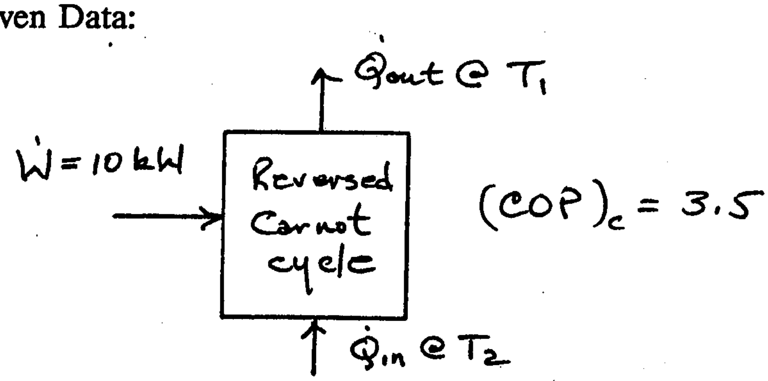
Problem 16.1

A reversed Carnot cycle is used for heating and cooling. The work supplied is 10 kW. If the COP = 3.5 for cooling, determine (a) T_2/T_1; (b) the refrigerating effect (tons); (c) the COP for heating.

Given: A reversed Carnot cycle, the power and COP.

Find: The tons of refrigeration, the $(COP)_h$ and T_2/T_1.

Sketch and Given Data:



Assumptions: 1) Cycle follows Carnot cycle; $T_H = T_1$, $T_C = T_2$.

Analysis: For a reversed Carnot cycle,

$$(COP)_c = \frac{T_C}{T_H - T_C} = \frac{1}{\frac{T_H}{T_C} - 1} = \frac{1}{\frac{T_1}{T_2} - 1} = 3.5$$

$$\frac{T_1}{T_2} = 1.2857 \qquad \text{a)} \quad \frac{T_2}{T_1} = \underline{0.777}$$

$$(COP)_c = 3.5 = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{\dot{Q}_{in}}{10}$$

b) $\dot{Q}_{in} = 35\ \text{kW} = \underline{9.95\ \text{tons}}$

c) $$(COP)_h = \frac{T_H}{T_H - T_C} = \frac{1}{1 - \frac{T_C}{T_H}} = \frac{1}{1 - 0.777} = \underline{4.48}$$

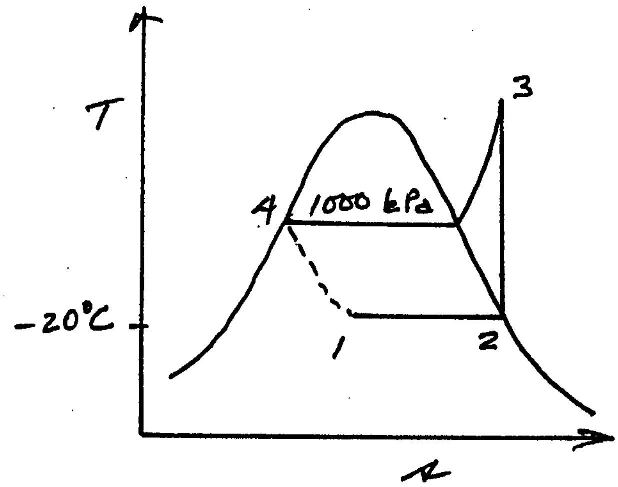
Problem 16.5

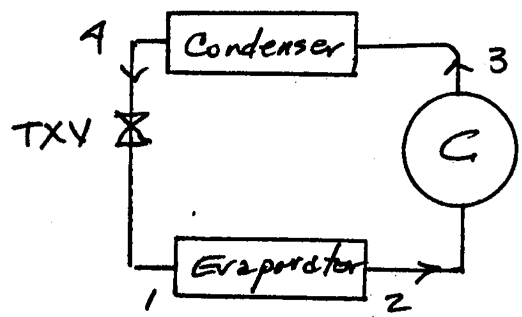
A standard vapor-compression refrigeration system uses R 12 as the refrigerant. The R 12 leaves the evaporator at - 20°C, and the condenser pressure is 1000 kPa. The flow rate is 20 kg/min. Determine (a) the tons of refrigeration; (b) the power required; (c) the COP.

Given: An ideal vapor compression refrigeration system using R 12 and the temperature and pressure limits.

Find: The refrigeration capacity, the compressor power and the COP.

Sketch and Given Data:





Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.
4) The processes are for an ideal vapor compression cycle.

Analysis: Determine the enthalpy values around the cycle.

$h_4 = h_f$ @ 1000 kPa = 76.29 kJ/kg

$h_1 = h_4 = 76.29$ kJ/kg

$h_2 = h_g$ @ -20°C = 160.81 kJ/kg $\qquad s_2 = 0.7082$ kJ/kg-K

$p_3 = 1000$ kPa $\qquad s_3 = s_2 = 0.7082$ kJ/kg-K

$h_3 = 212.15$ kJ/kg

b) $\dot{W}_c = \dot{m}(h_2 - h_3) = \left(\frac{20 \text{ kg/min}}{60 \text{ s/min}}\right)(160.81 - 212.15 \text{ kJ/kg})$

$= \underline{-17.11 \text{ kW}}$

$\dot{Q}_{in} = \dot{m}(h_2 - h_1) = (20/60)(160.81 - 76.29) = 28.17 \text{ kW}$

a) $\text{tons} = \frac{28.17 \text{ kW}}{3.516 \text{ kW/ton}} = \underline{8.01 \text{ tons}}$

c) $\text{COP} = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{28.17}{17.11} = \underline{1.65}$

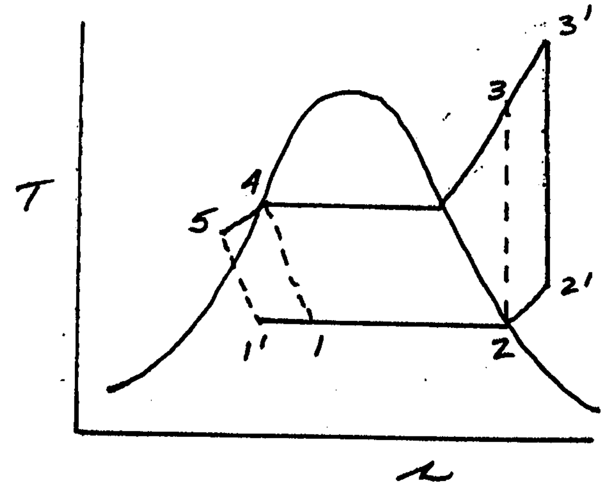
Problem 16.9

In a vapor-compression refrigeration system, the R 12 leaves the evaporator at 150 kPa and 0°C, enters the compressor, and is compressed isentropically to 1.2 MPa. The discharge from the condenser is subcooled by 5°C. The refrigerant flow rate is 40 kg/min. Determine (a) the tons of refrigeration; (b) the COP; (c) the increase in the refrigerating effect compared to the standard cycle.

Given: A vapor compression refrigeration system with evaporator discharge and condenser exit conditions known as is the flow rate.

Find: The tons of refrigeration, COP and refrigerating effect increase compared to the ideal cycle.

Sketch and Given Data:



$P_3 = 1.2$ MPa
$P_2' = 150$ kPa
$T_2' = 0$ °C
$P_2 = 150$ kPa
$T_5 = T_4 - 5$ °C
$\dot{m} = 40$ kg/min

Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the enthalpies around the cycle.

$h_2 = h_g$ @ 150 kPa = 178.61 kJ/kg $s_2 = 0.7082$ kJ/kg-K

$h_2' = 190.66$ $s_2' = 0.7543$ kJ/kg-K

$h_4 = 84.13$ kJ/kg $T_4 = 49.3$°C $T_5 = 44.3$°C $h_1 = 84.13$ kJ/kg

$h_5 = h_f$ @ = 78.97 kJ/kg $h_1' = 78.97$ kJ/kg

$h_3 = 215.54$ kJ/kg $p_3 = 1200$ kPa $s_3 = s_2 = 0.7082$ kJ/kg-K

$h_3' = 231.4$ kJ/kg $p_3' = 1200$ kPa $s_3' = s_2' = 0.7543$ kJ/kg-K

The refrigerating effect is

$$q_{in} = (h_2' - h_1') = (190.66 - 78.97) = 111.69 \text{ kJ/kg}$$

$$\dot{Q}_{in} = \dot{m}\, q_{in} = \left(\frac{40}{60}\,\frac{kg}{s}\right)\left(111.69\,\frac{kJ}{kg}\right) = 74.46 \text{ kW}$$

a) tons of refrigeration $= \dfrac{(74.46 \text{ kW})}{(3.516 \text{ kW/ton})} = \underline{21.18 \text{ tons}}$

$$w_{net} = (h_2' - h_3') = (190.66 - 231.4) = -40.74 \text{ kJ/kg}$$

b) $\text{COP} = \dfrac{q_{in}}{w_{net}} = \dfrac{111.69}{40.74} = \underline{2.74}$

The refrigerating effect for the standard cycle is

$$(q_{in})_{standard} = (h_2 - h_1) = (178.61 - 84.13) = 94.48 \text{ kJ/kg}$$

The increase is

$$\Delta q_{in} = 111.69 - 94.48 = 17.21 \text{ kJ/kg}$$

c) % increase $= \dfrac{17.21}{94.48} = 0.182$ $\underline{\text{or } 18.2\%}$

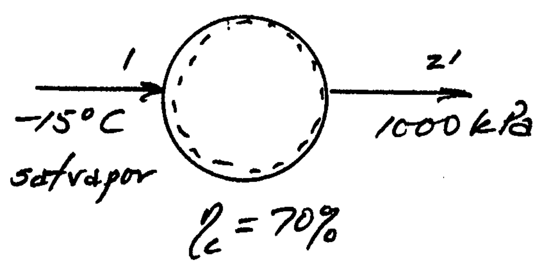
Problem 16.13

Refrigerant 12 enters an adiabatic compressor as a saturated vapor at -15°C and discharges at 1.0 MPa. If the compressor efficiency is 70%, determine the actual work.

Given: An adiabatic compressor with inlet and exit states and the compressor efficiency.

Find: The compressor work.

Sketch and Given Data:



Assumptions:

1) R 12 is a pure substance.
2) The compressor is a steady-state open system.
3) Neglect changes in kinetic and potential energy.
4) The heat flow is zero.

Analysis: Determine the work from a first law analysis.

$$\dot{Q} + \dot{m}\,(h = ke + pe)_1 = \dot{W} + \dot{m}\,(h + ke + pe)'_2$$

Apply assumptions 3 and 4

$$\dot{W} = \dot{m}(h_1 - h'_2)$$

$$w = (h_1 - h'_2)$$

$h_1 = h_g$ @ -15C = 180.85 kJ/kg $\quad s_1 = 0.7046$ kJ/kg-K

$p_2 = 1000$ kPa $\quad s_2 = s_1$

$h_2 = 210.98$ kJ/kg

$$\eta_c = 0.7 = \frac{h_2 - h_1}{h_2' - h_1} = \frac{210.98 - 180.85}{h_2' - 180.85}$$

$$h_2' = 223.89 \text{ kJ/kg}$$

$$w_{net} = (180.85 - 223.89)$$

$$= -43.04 \frac{\text{kJ}}{\text{kg}}$$

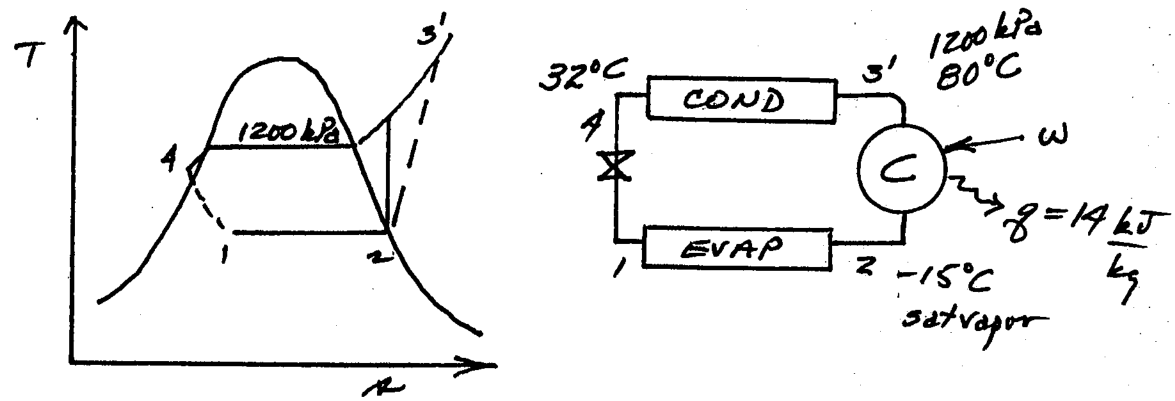
Problem 16.17

A vapor-compression refrigeration system uses R 12 as the refrigerant. The gaseous refrigerant leaves the compressor at 1200 kPa and 80°C. The heat loss during compression is 14 kJ/kg. The refrigerant enters the expansion valve at 32°C. The liquid leaves the evaporator and enters the compressor as a saturated vapor at -15°C. The unit must produce 50 tons of refrigeration. Determine (a) the R 12 flow rate; (b) the compressor power; (c) the COP.

Given: A 50-ton vapor compression refrigeration system uses R 12. The cycle states are given as well as heat loss during compression.

Find: The flow rates of R 12, the power and COP.

Sketch and Given Data:



Assumptions:

1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the enthalpies around the cycle.

$h_2 = 180.85$ kJ/kg $\qquad s_2 = 0.7046$ kJ/kg-K

$h_3' = 230.40$ kJ/kg $\qquad s_3' = 0.7514$ kJ/kg-K

$h_4 = h_f$ @ 32°C $= 66.67$ kJ/kg $\qquad h_1 = 66.57$ kJ/kg

$$\dot{Q}_{in} = \dot{m}(h_2 - h_1)$$

$$(50 \text{ tons})(3.516 \text{ kW/ton}) = (\dot{m} \text{ kg/s})(180.85 - 66.67 \text{ kJ/kg})$$

a) $\dot{m} = \underline{1.540}$ kg/s

Since there is heat loss, perform a first law analysis of the compressor.

$$\dot{Q} + \dot{m}(h + ke + pe)_2 = \dot{W} + \dot{m}(h + ke + pe)_3'$$

Apply assumption 3.

$$\dot{Q} + \dot{m}\ h_2 = \dot{W} + \dot{m}\ h_3'$$

$$(-14\ \text{kJ/kg})(1.54\ \text{kg/s}) + (1.54\ \text{kg/s})(180.85\ \text{kJ/kg})$$

$$= \dot{W} + (1.54\ \text{kg/s})\left(230.4\ \frac{\text{kJ}}{\text{kg}}\right)$$

b) $\dot{W} = \underline{-97.87}\ \text{kW}$

c) $\text{COP} = \dfrac{(50)(3.516)}{(97.87)} = \underline{1.797}$

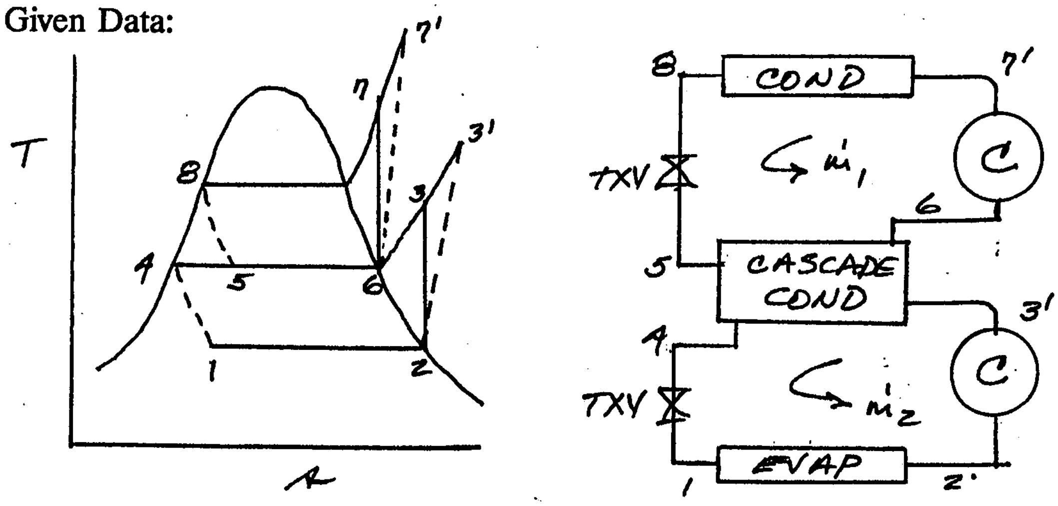
Problem 16.21

The same as Problem 16.20, assuming the isentropic compressor efficiency is 85% for the compressors.

Given: A two-stage cascade refrigeration system per problem 16.20 except the compressors have efficiencies.

Find: The mass flow rates, COP and cascade condenser irreversibility rate.

Sketch and Given Data:



Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Use the property values from Problem 16.20 as appropriate.

$p_3 = 316$ kPa $\quad h_5 = 76.29$ kJ/kg $\quad s_6 = 0.6961 \dfrac{\text{kJ}}{\text{kg-K}}$

$h_1 = 36.76$ kJ/kg $\quad h_6 = 187.84$ kJ/kg $\quad s_5 = 0.2888 \dfrac{\text{kJ}}{\text{kg-K}}$

$h_2 = 174.16$ kJ/kg $\quad h_7 = 208.24$ kJ/kg $\quad s_4 = 0.1445 \dfrac{\text{kJ}}{\text{kg-K}}$

$h_3 = 193.68$ kJ/kg $\quad h_8 = 76.29$ kJ/kg

$h_4 = 36.76$ kJ/kg

Using the compressor efficiency, find h_3' and h_7'.

$$\eta_c = 0.85 = \frac{h_3 - h_2}{h_3' - h_2} = \frac{193.68 - 174.16}{h_3' - 174.16}$$

$$h_3' = 197.12 \text{ kJ/kg} \qquad p_3' = 316 \text{ kPa} \qquad s_3' = 0.7291 \frac{\text{kJ}}{\text{kg-K}}$$

$$\eta_c = 0.85 = \frac{h_7 - h_6}{h_7' - h_6} = \frac{208.24 - 187.84}{h_7' - 187.84}$$

$$h_7' = 232.24 \text{ kJ/kg}$$

From the first law analysis of the evaporator,

$$\dot{Q} = \dot{m}_2(h_2 - h_1)$$

$$(15 \text{ tons})\left(3.516 \frac{\text{kW}}{\text{ton}}\right) = (\dot{m}_2 \text{ kg/s})(174.16 - 36.76 \text{ kJ/kg})$$

a) $\dot{m}_2 = \underline{0.3838}$ kg/s

From a first law analysis of a cascade condenser.

$$\dot{m}_1 h_5 + \dot{m}_2 h_3' = \dot{m}_1 h_6 + \dot{m}_2 h_4$$

a) $$\dot{m}_1 = \frac{\dot{m}_2(h_3' - h_4)}{(h_6 - h_5)} = \frac{(0.3838)(197.12 - 36.76)}{(187.84 - 76.29)} = \underline{0.5517 \text{ kg/s}}$$

The total power is

$$\dot{W}_{total} = \dot{m}_1(h_6 - h_7') + \dot{m}_2(h_2 - h_3')$$

$$\dot{W}_{total} = (0.5517 \text{ kg/s})(187.84 - 232.24 \text{ kJ/kg})$$

$$+ (0.3838)(17416 - 197.12)$$

$$\dot{W}_{total} = -33.3 \text{ kW}$$

b) $$(COP)_c = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{(15)(3.516)}{(33.3)} = \underline{1.58}$$

For an adiabatic, steady open system, the irreversibility rate, $\dot{I}$, is $T_0 \, \Delta\dot{S}_{prod}$

$$\Delta\dot{S}_{prod} = \dot{m}_1(s_6 - s_5) + \dot{m}_2(s_4 - s_3')$$

$$\Delta\dot{S}_{prod} = (0.5517)(0.6961 - 0.2888) + (0.3838)(0.1445 - 0.7291)$$

$$\Delta\dot{S}_{prod} = 0.000338 \text{ kW/K}$$

c) $\dot{I} = (298)(0.000338) = \underline{0.10 \text{ kW}}$

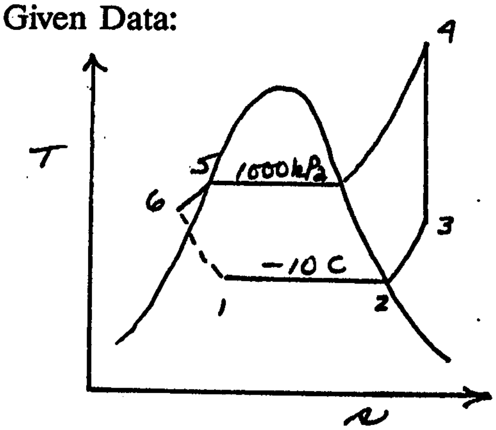
Problem 16.25

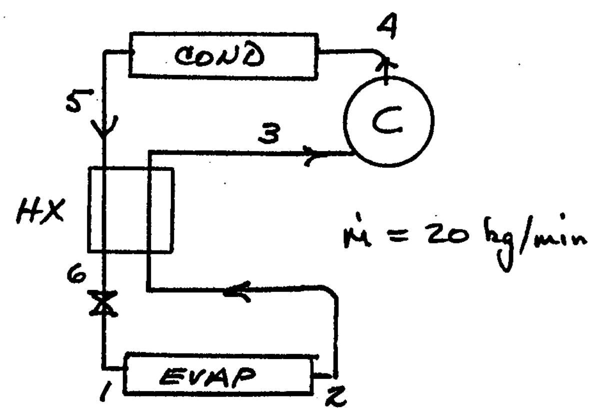
A vapor-compression refrigeration system uses a subcooling-superheating heat exchanger located after the evaporator to subcool the refrigerant entering the expansion valve. The refrigerant leaving the evaporator is superheated in the process. Assume the refrigerant leaves the evaporator as a saturated vapor and the condenser as a saturated liquid and that no pressure drops occur in the heat exchangers. The evaporator temperature is -10°C, the condenser pressure is 1000 kPa, and the flow rate is 20 kg/min. Determine (a) the compressor power; (b) the tons of refrigeration; (c) the COP.

Given: A vapor compression refrigeration system that uses a heat exchanger to subcool the refrigerant entering the expansion valve. System states are noted.

Find: The power required, tons of refrigeration and the COP.

Sketch and Given Data:





Assumptions:
1) The refrigerant is R 12, a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.
4) The refrigerant is superheated 10°C.

Analysis: Determine the enthalpies around the cycle.

h_2 = 183.06 kJ/kg $\qquad$ p_2 = 219.1 kPa

h_5 = 76.29 kJ/kg

$p_3 = p_2$, $\quad T_3 = 0°C$, $\quad h_3 = 189.42$ kJ/kg $\quad s_3 = 0.7251 \dfrac{\text{kJ}}{\text{kg-K}}$

$p_4 = 1000$ kPa, $s_4 = s_3$ $\quad h_4 = 217.72$ kJ/kg-K

Perform a first law analysis on the subcooling-superheating heat exchanger subject to assumption 3 and that $\dot{Q} = 0$ and $\dot{W} = 0$.

$$\dot{m}\, h_5 + \dot{m}\, h_2 = \dot{m}\, h_3 + \dot{m}\, h_6$$

$$h_3 + h_6 = h_2 + h_5$$

$$h_6 = (183.06 + 76.29) - 189.42 = 69.93 \text{ kJ/kg}$$

$$h_1 = h_6$$

The power is

a) $$\dot{W}_{net} = \dot{m}(h_3 - h_4) = \left(\frac{20}{60}\ \frac{kg}{s}\right)(189.42 - 217.72 \text{ kJ/kg})$$

$$= \underline{-9.43 \text{ kW}}$$

b) $$\dot{Q}_{in} = \dot{m}(h_2 - h_1) = \left(\frac{20}{60}\right)(183.06 - 69.93) = \underline{37.71 \text{ kW}}$$

$$= \underline{10.7 \text{ tons}}$$

c) $$COP = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{37.71}{9.43} = \underline{4.0}$$

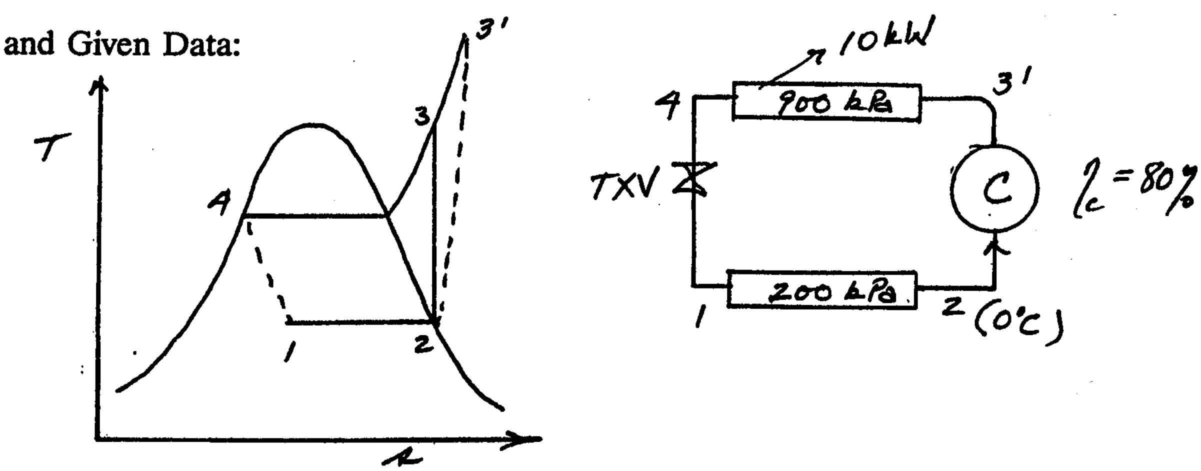
Problem 16.29

A vapor-compression heat pump uses R 12 and provides 10 kW of heating. The evaporator pressure is 200 kPa, and he refrigerant enters the compressor at 0°C. The compressor's isentropic efficiency is 80%, and the condenser pressure is 900 kPa. The electricity to drive the compressor comes from a power plant with an efficiency of 40%. Determine (a) the compressor power; (b) the ratio of heat used in the power plant to produce the electricity to the heat output of the heat pump.

Given: A vapor-compression heat pump provides a specified amount of heat which between known operating conditions.

Find: The compressor power and a comparison between the heat used to generate the electricity to that used in the house.

Sketch and Given Data:



Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the property values around the cycle.

$$h_2 = 189.67 \text{ kJ/kg} \quad s_2 = 0.7320 \text{ kJ/kg-K}$$

$$h_4 = 72.01 \text{ kJ/kg} \quad h_1 = h_4 = 72.01 \text{ kJ/kg}$$

$$s_3 = s_2 \quad p_3 = 900 \text{ kPa} \quad h_3 = 217.95 \text{ kJ/kg}$$

$$\eta_c = 0.80 = \frac{h_3 - h_2}{h_3' - h_2} = \frac{(217.95 - 189.67)}{(h_3' - 189.67)}$$

$$h_3' = 225.02 \text{ kJ/kg}$$

The heat out is

$$\dot{Q}_{out} = \dot{m}(h_4 - h_3')$$

$$(-10\ kW) = (\dot{m}\ kg/s)(72.01 - 225.02\ kJ/kg)$$

$$\dot{m} = 0.06536\ kg/s$$

a) $$\dot{W}_{net} = \dot{m}(h_2 - h_3') = (0.06536)(189.67 - 225.02) = \underline{-2.31\ kW}$$

The power is provided by an electric motor. The power plant producing the electricity has a thermal efficiency of 40%. Hence,

$$\eta_{Th} = 0.40 = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{2.31}{\dot{Q}_{in}}$$

$$\dot{Q}_{in} = 5.775\ kW$$

The ratio of this to the heat out put of the heat pump is

b) $$r = \frac{5.775}{10} = \underline{0.577}$$

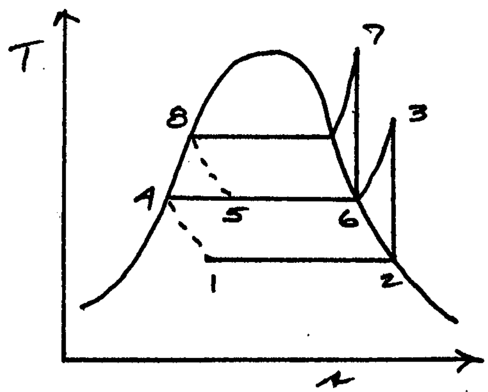
Problem 16.33

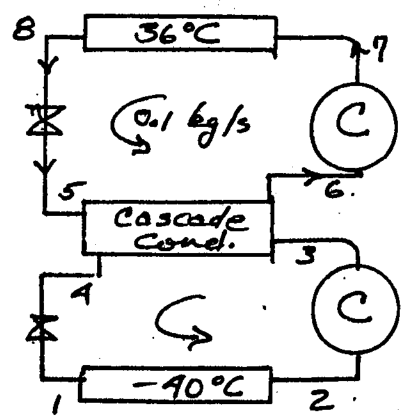
A two-stage cascade refrigeration system uses ammonia as the working substance. The mass flow rate in the high-pressure loop is 0.10 kg/s. The condenser saturated temperature is 36°C, and the evaporator temperature is -40°C. The cascade condenser is direct contact. Determine (a) the cascade condenser pressure for minimum work; (b) the refrigerating effect in tons; (c) the COP; (d) the power required; (e) the second-law efficiency.

Given: A two-stage, cascade refrigeration system uses ammonia. The high pressure mass flow is known as are the cycle states.

Find: The optimum cascade condenser pressure, the tons of refrigeration, the COP, the power and second law efficiency.

Sketch and Given Data:





Assumptions:

1) Ammonia is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the ammonia properties around the cycle.

h_2 = 1389.0 kJ/kg $\qquad$ s_2 = 5.9589 kJ/kg

h_8 = 352.1 kJ/kg $\qquad$ $h_5 = h_8$

p_{sat} @ -40C = 71.77 kPa $\qquad$ p_{sat} @ 36°C = 1389.03 kPa

a) $$p_{opt} = \sqrt{p_2\, p_7} = \sqrt{(71.77)(1389.03)} = \underline{315.7\text{ kPa}}$$

For ease in using the super heat tables, use the values at 1400 kPa for h_7 and at 300 for h_3

$s_3 = s_2$ = 5.9589 kJ/kg-K $\qquad$ h_3 = 1578.4 kJ/kg

$$s_7 = s_6 = 5.4449 \frac{kJ}{kg-K} \qquad h_7 = 1.650.9 \text{ kJ/kg}$$

$$h_4 = 144.3 \text{ kJ/kg} \qquad h_1 = h_4$$

Perform a first law analysis on the cascade condenser applying assumption 3 and $\dot{Q} = 0$, $\dot{W} = 0$.

$$\dot{m}_{hp} h_5 + \dot{m}_{lp} h_3 = \dot{m}_{hp} h_6 + \dot{m}_{lp} h_4$$

$$\dot{m}_{lp} = \dot{m}_{hp} \frac{(h_6 - h_5)}{(h_3 - h_4)} = \frac{(0.1 \text{ kg/s})(1434.0 - 352.1)}{(1578.4 - 144.3)}$$

$$= 0.0754 \text{ kg/s}$$

$$\dot{Q}_{in} = \dot{m}_{lp}(h_2 - h_1) = (0.0754 \text{ kg/s})(1389.0 - 144.3 \text{ kJ/kg})$$

$$= 93.85 \text{ kW}$$

b) $$\text{tons of refrigeration} = \frac{\dot{Q}_{in}}{3.516} = \frac{(93.85 \text{ kW})}{(3.516 \text{ kW/ton})} = \underline{26.69 \text{ tons}}$$

$$\dot{W}_{lp} = \dot{m}_{lp}(h_2 - h_3) = (0.0754)(1389 - 1578.4) = -14.28 \text{ kW}$$

$$\dot{W}_{hp} = \dot{m}_{hp}(h_6 - h_7) = (0.1)(1434.4 - 1650.9) = -21.65 \text{ kW}$$

d) $\dot{W}_{total} = \underline{-35.93 \text{ kW}}$

c) $$COP = \frac{\dot{Q}_{in}}{\dot{W}_{total}} = \frac{93.85}{35.93} = \underline{2.61}$$

The Carnot COP is when the operating limits are between -40C and 36°C. Thus,

$$(COP)_{carnot} = \frac{T_C}{T_H - T_C} = \frac{233}{309 - 233} = 3.06$$

e) $$\eta_2 = \frac{2.61}{3.06} = \underline{0.853}$$

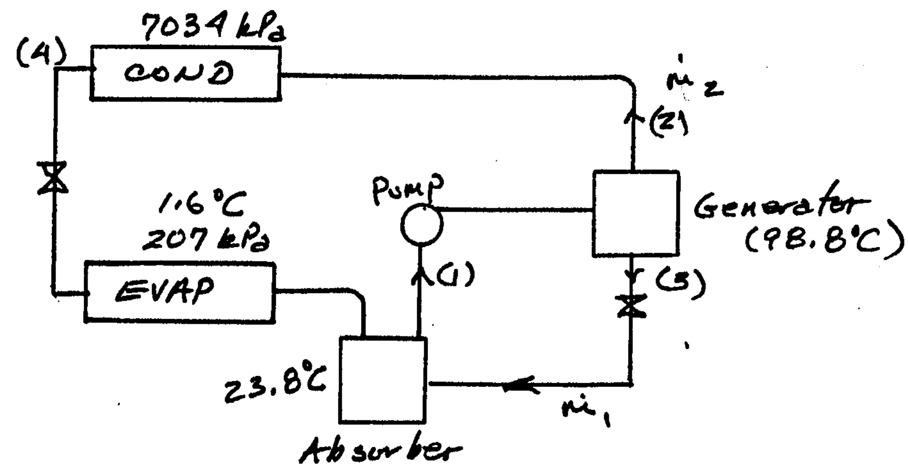
Problem 16.37

A refrigeration unit uses the ammonia-absorption system for cooling. The unit is characterized by the following conditions: generator temperature = 98.8°C, condenser pressure = 7034 kPa, evaporator pressure = 207 kPa, evaporator temperature = 1.6°C, and absorber temperature = 23.8°C. Determine (a) the COP; (b) the heat required per ton of refrigeration; (c) the heat rejected in the condenser.

Given: An ammonia-absorption refrigeration system with the system characteristic temperatures and pressures.

Find: Per ton of refrigeration: the COP, the heat supplied and the heat rejected in the condenser.

Sketch and Given Data:



Assumptions:
1) Each component may be considered a steady-state, open system.
2) Neglect changes in kinetic and potential energy.
3) All states are equilibrium states.

Analysis: From figure B.3(a) find the following properties

State 1	T = 23.8°C	p = 207 kPa	$x_1' = 0.428$	$h_L = -151.1$ kJ/kg
State 2	T = 98.8°C	p = 1034 kPa	$x_2'' = 0.930$	$h_V = 1553.5$ kJ/kg
State 3	T = 98.8°C	p = 1034 kPa	$x_3' = 0.320$	$h_L = 248.8$ kJ/kg
State 4	T = 28.3°C	p = 1034 kPa	$x_4' = x_2'' = 0.930$	$h_L = 81.4$ kJ/kg
State 5	T = 1.6°C	p = 207 kPa	$x_5 = x_4' = x_2'' = 0.930$	

For the purge liquid

$p = 207$ kPa $T = 1.6°C$ $x_5^1 = 0.59$ $h_L = -232.5$ kJ/kg

and for the purge vapor

$p = 207$ kPa $T = -1.1°C$ $x_5^{11} = 0.999^+$ $h_V = 1290.5$ kJ/kg

The ammonia mass leaving the evaporator is

$$(1)(x_5) = m_{pl}\, x_5^1 + (1 - m_{pl})\, x_5^{11}$$

$$0.930 = (0.59)(m_{pl}) + (0.999)(1 - m_{pl})$$

$$m_{pl} = 0.1467$$

$$h_5 = m_{pl}\, h_L + (1 - m_{pl})\, h_V$$

$$h_5 = (0.1467)(-232.5) + (0.8533)(1290.7) = 1067.2 \text{ kJ/kg}$$

$$\dot{m}_2 = \dot{m}_4 = \dot{m}_5 = \frac{(3.526 \text{ kW/ton})}{(h_5 - h_4 \text{ kJ/kg})} = \frac{(3.516)}{(1067.2 - 81.4)}$$

$$\dot{m}_2 = \dot{m}_4 = \dot{m}_5 = 0.003566 \text{ kg/s per ton}$$

A total mass balance is $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$

An ammonia balance is $\dot{m}_1\, x_1 = \dot{m}_2\, x_2 + \dot{m}_3\, x_3$

Solve for $\dot{m}_3$.

$$(0.003566 + \dot{m}_3)(0.428) = (0.003566)(0.930) + (\dot{m}_3)(0.320)$$

$$\dot{m}_3 = 0.01657 \text{ kg/s}$$

$$\dot{m}_1 = (0.003566 + 0.01657) = 0.02014 \text{ kg/s}$$

An energy balance on the generator yields

$$\dot{Q}_H = \dot{m}_2\, h_2 + \dot{m}_3\, h_3 - \dot{m}_1\, h_1$$

$$\dot{Q}_H = (0.003566)(1533.5) + (0.01657)(248.8) - (0.02014(-151.1)$$

b) $\dot{Q}_H = \underline{12.7 \text{ kW/ton}}$

The heat rejected in the condenser is

$$\dot{Q}_C = \dot{m}_2\, h_2 - \dot{m}_4\, h_4$$

c) $\dot{Q}_C = (0.003566)(1553.5) - (0.003566)(81.4) = 5.24$ kW/ton

The COP is

$$COP = \frac{(3.516 \text{ kW/ton})}{(12.7 \text{ kW/ton})} = \underline{0.277}$$

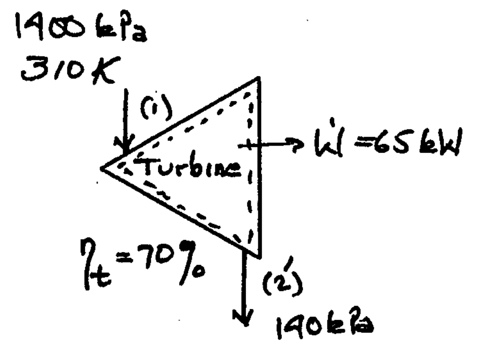
Problem 16.41

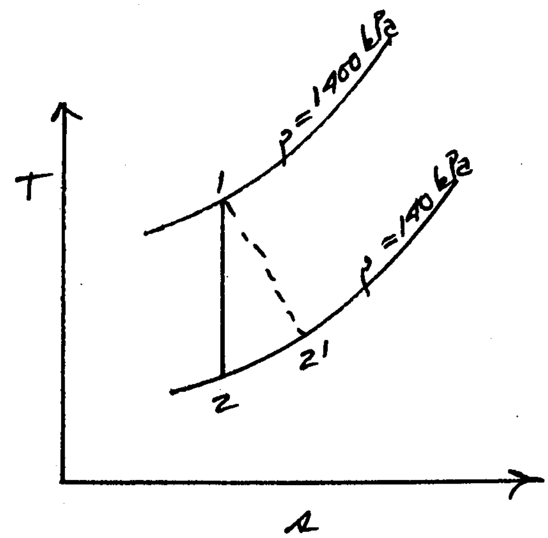
An air turbine receives air at 1400 kPa and 310°K and expands it to 140 kPa. The turbine internal efficiency is 70%, and the power produced is 65 kW. The air exhausting from the turbine will be used for refrigeration. The refrigeration space is to be maintained at 260°K. What is the maximum possible refrigeration in tons?

Given: An air turbine produces power and discharges air at a low temperature, which may be used for cooling. The turbine inlet and exit state, power output and efficiency are given.

Find: The maximum tons of refrigeration possible.

Sketch and Given Data:





Assumptions:
1) Air is an ideal gas.
2) Neglect changes in kinetic and potential energy.
3) The turbine is a steady, open system.
4) The refrigeration space temperature is at 260°K.

Analysis: Determine the actual temperature leaving the turbine and then from a first law analysis the mass flow rate
The turbine internal efficiency is

$$\eta_t = \frac{h_1 - h_2'}{(h_1 - h_2)_s} = \frac{(T_1 - T_2')}{(T_1 - T_2)_s}$$

For an isentropic process

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (310\ \mathrm{K})\left(\frac{140}{1400}\right)^{\frac{0.4}{1.4}} = 160.6\ \mathrm{K}$$

$$0.7 = \frac{(310 - T_2')}{(310 - 160.6)} \qquad T_2' = 205.4 \text{ K}$$

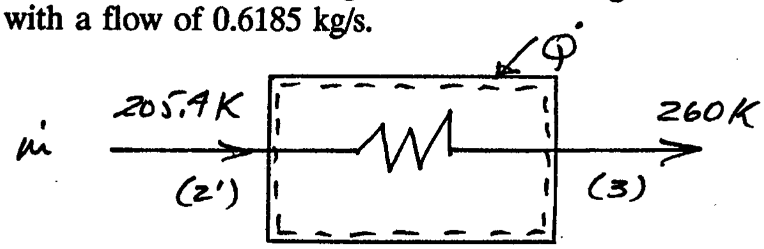
The turbine work is

$$\dot{W} = \dot{m}(h_1 - h_2') = \dot{m}\, c_p(T_1 - T_2')$$

$$(65 \text{ kW}) = (\dot{m} \text{ kg/s})(1.0047 \text{kJ/kg-K})(310 - 205.4 \text{ K})$$

$$\dot{m} = 0.6185 \text{ kg/s}$$

Consider at heat exchanger with air entering at 205.4 K and leaving at 260 K with a flow of 0.6185 kg/s.



$$\dot{Q} = \dot{m}(h_3 - h_2') = \dot{m}\, c_p(T_3 - T_2')$$

$$\dot{Q} = (0.6185 \text{ kg/s})\left(1.0047 \frac{\text{kJ}}{\text{kg-K}}\right)(260 - 205.4 \text{ K}) = 33.93 \text{ kW}$$

$$\dot{Q} = \frac{(33.93 \text{ kW})}{(3.516 \text{ kW/ton})} = \underline{9.65 \text{ tons}}$$

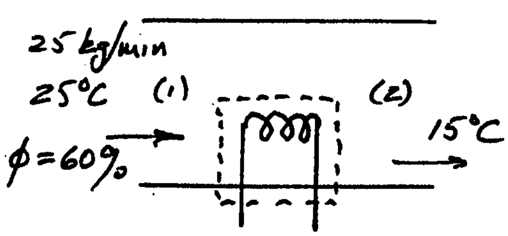
Problem 16.45

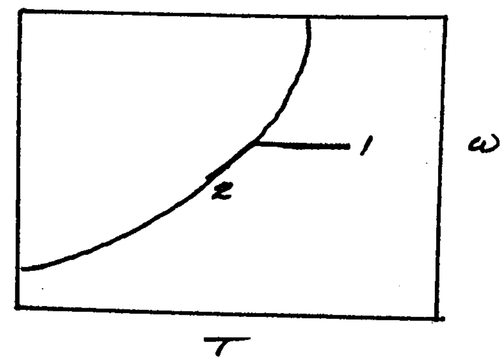
Twenty-five kg/min of air enters a dehumidifier at 25°C, 1 atm, and 60% relative humidity. The air is cooled to 15°C, with water and air exiting separately at this state. Determine (a) the mass flow rate of water leaving; (b) the heat transfer.

Given: An air-vapor mixture enters a dehumidifier at a known state and exits at a known state.

Find: The heat transfer and condensed water flow rate.

Sketch and Given Data:





Assumptions:
1) The pressure is constant and atmospheric.
2) The work is zero.
3) Neglect changes in kinetic and potential energy.
4) The dehumidifier is a steady, open system.

Analysis: Determine the property values at states (1) and (2)

$h_1 = 56.0$ kJ/kg $\qquad \omega_1 = 0.012$ kg vapor/kg air

$h_2 = 42.2$ kJ/kg $\qquad \omega_2 = 0.0108$ kg vapor/kg air

Perform a first law analysis on the dehumidifier.

$$\dot{Q} + \dot{m}_a h_1 = \dot{m}_a h_2 + \dot{m}_w h_f$$

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2)$$

a) $$\dot{m}_w = (25 \text{ kg air/min})\left(0.012 - 0.0108 \ \frac{\text{kg vapor}}{\text{kg air}}\right) = \underline{0.03 \text{ kg/min}}$$

$$\dot{Q} = \dot{m}_a(h_2 - h_1) + \dot{m}_1 h_f$$

$$\dot{Q} = \frac{(25 \text{ kg air/min})(42.2 - 56.0 \text{ kJ/kg air})}{(60 \text{ s/min})}$$

$$+ \frac{\left(0.03 \ \dfrac{\text{kg water}}{\text{min}}\right)\left(61.95 \ \dfrac{\text{kJ}}{\text{kg water}}\right)}{(60 \text{ s/min})}$$

b) $\dot{Q} = \underline{-5.72 \text{ kW}}$

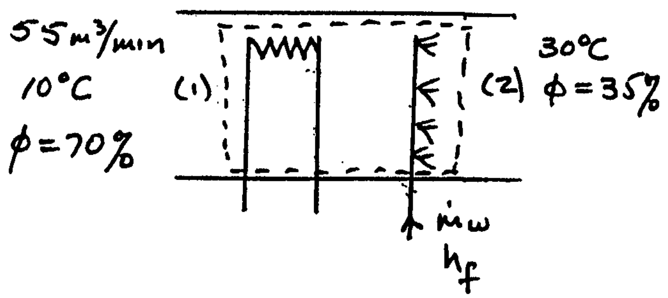
Problem 16.49

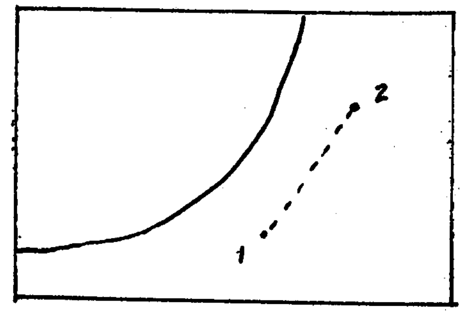
Outside air entering at 55 m³/min, 10°C, and 70% relative humidity is reheated and humidified so the air condition entering the heating system is 30°C and 35% relative humidity. The humidification occurs with water at 15°C. Determine (a) the water flow rate required; (b) the heat transfer in kW.

Given: Air at a known state is heated and humidified to a specified state.

Find: The water required for humidification and the heat required.

Sketch and Given Data:





Assumptions:
1) The pressure is atmospheric.
2) Neglect changes in kinetic and potential energy.
3) The work is zero.
4) The unit is a steady, open system.

Analysis: Determine the properties at states (1) and (2)

$$h_1 = 23.8 \text{ kJ/kg air} \quad \omega_1 = 0.0053 \frac{\text{kg vapor}}{\text{kg air}} \qquad v_1 = 0.81 \text{ m}^3/\text{kg}$$

$$h_2 = 51.0 \text{ kJ/kg air} \quad \omega_2 = 0.008 \frac{\text{kg vapor}}{\text{kg air}}$$

The air mass flow rate is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{(55 \text{ m}^3/\text{min})}{(0.81 \text{ m}^3/\text{kg})} = 67.9 \text{ kg/min} = 1.132 \text{ kg/s}$$

The water flow rate is

$$\dot{m}_1 = \dot{m}_a(\omega_2 - \omega_1) = \left(1.132 \ \frac{\text{kg air}}{\text{s}}\right)\left(0.008 - 0.0053 \ \frac{\text{kg vapor}}{\text{kg air}}\right)$$

a) $\dot{m}_w$ = <u>0.003 kg/s</u>

A first law analysis yields

$$\dot{Q} + \dot{m}_a \, h_1 + \dot{m}_w \, h_f = \dot{m}_a \, h_2$$

$h_f = h_f$ @ 15°C = 61.96 kJ/kg water

$$\dot{Q} = \left(1.132 \ \frac{\text{kg air}}{\text{s}}\right)(51.0 - 23.8)$$

$$- \left(0.003 \ \frac{\text{kg water}}{\text{s}}\right)\left(61.95 \ \frac{\text{kJ}}{\text{kg water}}\right)$$

b) $\dot{Q}$ = <u>30.6 kW</u>

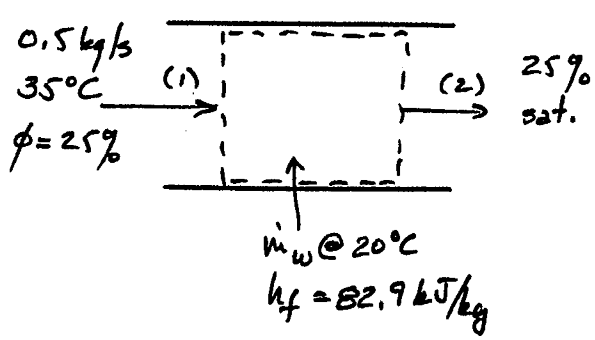
Problem 16.53

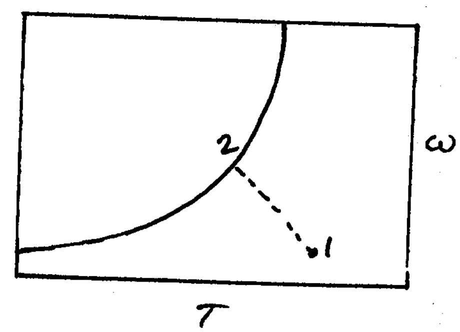
Air at 0.5 kg/s, 35°C, and 25% relative humidity enters an adiabatic evaporative cooler. The cooler receives water at 20°C, and the air leaves saturated at 25°C. Determine the water flow rate.

Given: An adiabatic evaporative cooler receives water and air at known states. The air exit state is known.

Find: The water flow rate.

Sketch and Given Data:





Assumptions:
1) The pressure is atmospheric.
2) The work is zero.
3) Neglect changes in kinetic and potential energy.
4) The cooler is adiabatic and an open, steady system.

Analysis: The humidity ratio at state (1) is $\omega_1 = 0.0085 \frac{\text{kg vapor}}{\text{kg air}}$

and at state (2) $\omega_2 = 0.0202 \frac{\text{kg vapor}}{\text{kg air}}$.

The water flow rate is

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) = (0.5 \text{ kg air/s})\left(0.0202 - 0.0085 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

$\dot{m}_w$ = <u>0.00585 kg water/s</u>

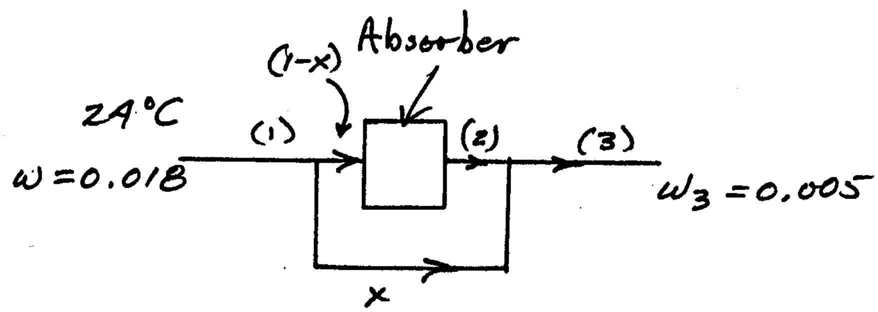
Problem 16.57

Air is to be dehumidified with a silica-gel absorber. The initial air conditions is 24°C with a humidity ratio of 0.018 kg water vapor/kg dry air,it is to leave with a humidity ratio of 0.005. The silica gel reduces the humidity ratio to 0.001, so a portion of the initial air bypasses the silica gel and mixes with the air leaving the gel. Determine the mass fraction bypassed.

Given: Air passes over a silica-gell absorber. A portion of the air by-passes the absorber and mixes with the dried air. The inlet air state, the air leaving the absorber and the final air state are specified.

Find: The fraction of air by-passed.

Sketch and Given Data:



Assumptions:

1) The pressure is atmospheric.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energy.
4) The absorber and mixing chamber are steady, open systems.

Analysis: Let x be the portions of the air stream that is by-passed. A conservation of mass balance for water yields.

$$\dot{m}_a\,\omega_3 = \dot{m}_a(1 - x)\,\omega_2 + \dot{m}_a\,x\,\omega_1$$

$$\omega_3 = (1 - x)\,\omega_2 + x\,\omega_1$$

$$0.005 = (1 - x)(0.001) + x\,(0.018)$$

$x = 0.235$ or <u>23.5%</u>

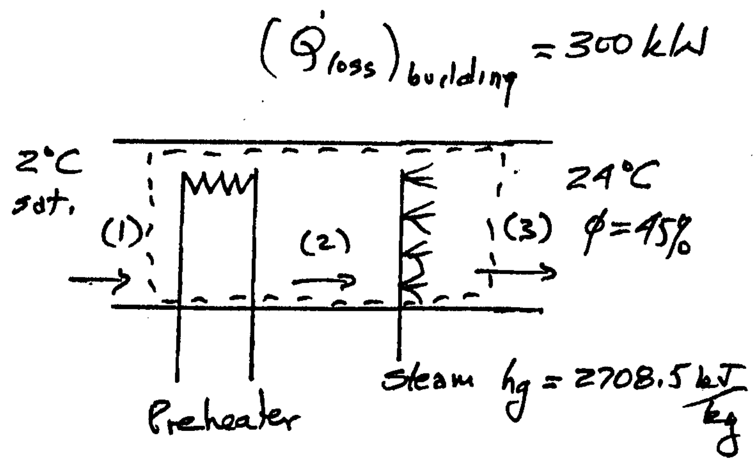
Problem 16.61

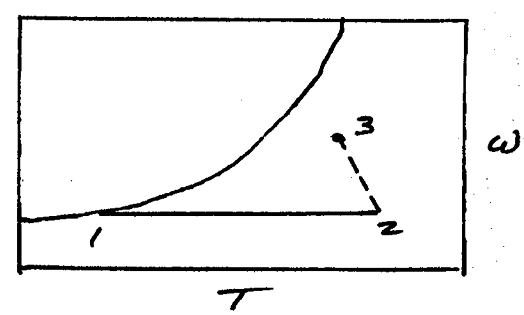
A building has a heat loss of 300 kW. It must be heated by fresh air. The space is to be maintained at 24°C and 45% relative humidity, with an outside temperature of 2°C saturated. Humidification is achieved with 208 kPa saturated steam. Determine (a) the cold-air flow rate in m^3/s; (b) the steam required in kg/s; (c) the hot-air flow rate.

Given: A heating/humidifying air conditioning unit receives air at a known state and discharges it at a known state. The heat supplied is given as is the steam pressure.

Find: The cold and hot air flow rates and the steam flow rate.

Sketch and Given Data:





Assumptions:
1) The pressure is atmospheric.
2) The work is zero.
3) Neglect changes in kinetic and potential energy.
4) Each component may be considered a steady-state, open system.

Analysis: Determine the property values at states (1) and (3)

$$h_1 = 13.0 \text{ kJ/kg} \qquad \omega_1 = .0044\ \frac{\text{kg vapor}}{\text{kg air}} \qquad v_1 = 0.78\ m^3/kg$$

$$h_2 = 46.5 \text{ kJ/kg} \qquad \omega_2 = 0.0085\ \frac{\text{kg vapor}}{\text{kg air}} \qquad v_2 = 0.855\ m^3/kg$$

The total heat added to the air is 300 kW. A first law analysis, after applying assumptions 2 and 3, yields,

$$\dot{Q} + \dot{m}_a h_1 = \dot{m}_a h_2$$

$$\dot{Q} = 300 \text{ kW} = (\dot{m}_a \text{ kg/s})(46.5 - 13.0 \text{ kJ/kg})$$

$$\dot{m}_a = 8.955 \text{ kg/s}$$

a) $\dot{V}_1 = (8.955 \text{ kg/s})(0.78 \text{ m}^3\text{/kg}) = 6.98 \text{ m}^3\text{/s}$

c) $\dot{V}_2 = \dot{m}_a\, v_2 = (8.955)(0.855) = 7.65 \text{ m}^3\text{/s}$

The steam flow rate is

$$\dot{m}_s = \dot{m}_a(\omega_2 - \omega_1) = (8.955 \text{ kg/s})\left(0.0085 - 0.0044 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

b) $\dot{m}_s = \underline{0.0367 \text{ kg/s}}$

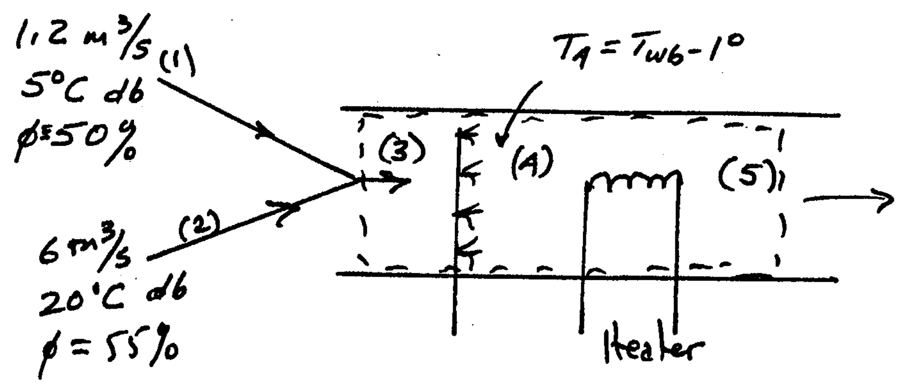
Problem 16.65

A heating system for an office building uses an adiabatic saturation air washer followed by a heating coil. A mixture of 1.2 m³/s of outside air at 5°C dry-bulb and 50% relative humidity and 6 m³/s of return air at 20°C dry-bulb and 55% relative humidity enter the saturator. The mixture leaves with a temperature 1°C less than saturation. The heating coil heats the mixture at 38°C. For the mixture leaving the heating coil, determine (a) the relative humidity; (b) the specific volume; (c) the heat supplied in the coil.

Given: Two air stream mix and then pass through an adiabatic saturator and a heating coil. The mixture states are given.

Find: The mixture relative humidity and specific volume leaving the heating coil and the heat supplied.

Sketch and Given Data:



Assumptions:
1) The pressure is atmospheric.
2) The work is zero.
3) Neglect changes in kinetic and potential energy.
4) Each component may be considered a steady-state, open system.

Analysis: Determine the mixture properties at state 3.

$$h_1 = 12.0 \text{ kJ/kg} \qquad \omega_1 = .0026 \frac{\text{kg vapor}}{\text{kg air}} \qquad v_1 = 0.79 \text{ m}^3\text{/kg}$$

$$h_2 = 40.8 \text{ kJ/kg} \qquad \omega_2 = .008 \frac{\text{kg vapor}}{\text{kg air}} \qquad v_2 = 0.84 \text{ m}^3\text{/kg}$$

Apply the first law for the adiabatic mixing, subject to assumptions 2 and 3, which yields

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$

$$\dot{m}_1 = \frac{\dot{V}_1}{v_1} = \frac{(1.2 \text{ m}^3/\text{s})}{(0.79 \text{ m}^3/\text{kg})} = 1.518 \text{ kg/s}$$

$$\dot{m}_2 = \frac{\dot{V}_2}{v_2} = \frac{(6.0)}{(0.84)} = 7.143 \text{ kg/s}$$

$$(1.518 \text{ kg/s})(12.0 \text{ kJ/kg}) + (7.142 \text{ kg/s})\left(40.8 \frac{\text{kJ}}{\text{kg}}\right) = (8.661 \text{ kg/s})\left(h_3 \frac{\text{kJ}}{\text{kg}}\right)$$

$$h_3 = 35.8 \text{ kJ/kg}$$

The conservation of mass for water yields.

$$\dot{m}_1 \omega_1 + \dot{m}_2 \omega_2 = \dot{m}_3 \omega_3$$

$$\left(1.518 \frac{\text{kg air}}{\text{s}}\right)\left(0.0026 \frac{\text{kg vapor}}{\text{kg air}}\right) + \left(7.143 \frac{\text{kg air}}{\text{s}}\right)\left(0.008 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

$$= \left(8.661 \frac{\text{kg air}}{\text{s}}\right)\left(w_3 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

$$\omega_3 = 0.007 \frac{\text{kg vapor}}{\text{kg air}}$$

For adiabatic saturation, the enthalpy remains constant. Hence, $h_4 = 35.8$ and $\omega_4 = 0.0088 \frac{\text{kg vapor}}{\text{kg air}}$. The heating process occurs at constant vapor pressure, or $\omega_5 = \omega_4$. The enthalpy at state 5 is $h_5 = 60.0$ kJ.kg.

b) $v_5 = \underline{0.89 \text{ m}^3/\text{kg}}$ a) $\phi_5 = \underline{23\%}$

A first law analysis on the heating coil, subject to assumptions 2 and 3, yields

$$\dot{Q} + \dot{m} h_4 = \dot{m} h_5$$

c) $\dot{Q} = \dot{m}(h_5 - h_4) = (8.661 \text{ kg/s})(60.0 - 35.8 \text{ kJ/kg}) = \underline{209.6 \text{ kW}}$

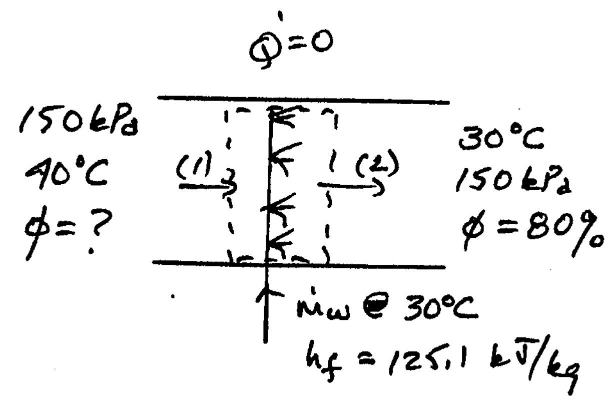
Problem 16.69

An air-water vapor mixture enters and adiabatic device with a pressure of 150 kPa, a temperature of 40°C, and an unknown relative humidity. The air flow rate is 0.2 kg/min. The mixture leaves the device at 30°C, 150 kPa, and 80% relative humidity. Water at 30°C is sprayed into the air for cooling. Determine the water required for 1h of operation.

Given: A steady open system consists of air flowing through an adiabatic container where water is sprayed. The exit state, flow rate and water temperature are known as is the inlet temperature and pressure.

Find: The water needed for one hour's operation.

Sketch and Given Data:



Assumptions:
1) The device is a steady, open system.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energy.

Analysis: Because the system operates at higher than atmospheric pressure, the ideal gas-vapor relationship from Chapter 11 must be used.

The vapor pressure at 30°C is 4.25 kPa and

$$\phi_2 = \frac{p_{v_2}}{p_{g_2}}$$

$$0.8 = \frac{p_{v_2}}{4.25} \qquad p_{v_2} = 3.4 \text{ kPa}$$

$$p_{a_2} = 150 - 3.4 = 146.6 \text{ kPa}$$

$$\omega_2 = 0.622 \frac{p_{v_2}}{p_{a_2}} = (0.622)\left(\frac{3.4}{146.6}\right) = 0.0144 \frac{\text{kg vapor}}{\text{kg air}}$$

The enthalpies of water vapor at 40°C and 30°C are 2574.5 $\frac{\text{kJ}}{\text{kg}}$ and 2556.6 kJ/kg, respectively. The first law on the control, subject to assumptions 2 and 3, yields

$$\dot{m}_a h_{a_1} + \dot{m}_a \omega_1 h_{g_1} + \dot{m}_w h_f = \dot{m}_a h_{a_2} + \dot{m}_a \omega_2 h_{g_2}$$

The enthalpy of an ideal gas is $h = c_p T$, hence

$$\left(0.2 \frac{\text{kg air}}{\text{min}}\right)\left(1.0047 \frac{\text{kJ}}{\text{kg air-K}}\right)(313 \text{ K})$$

$$+ \left(0.2 \frac{\text{kg air}}{\text{min}}\right)\left(\omega_1 \frac{\text{kg vapor}}{\text{kg air}}\right)\left(2574.5 \frac{\text{kJ}}{\text{kg vapor}}\right)$$

$$+ \left(\dot{m}_w \frac{\text{kg water}}{\text{min}}\right)\left(125.1 \frac{\text{kJ}}{\text{kg water}}\right)$$

$$= (0.2 \text{ kg/s})\left(1.0047 \frac{\text{kJ}}{\text{kg air-K}}\right)(303 \text{ K})$$

$$+ \left(0.2 \frac{\text{kg water}}{\text{min}}\right)\left(0.0144 \frac{\text{kg vapor}}{\text{kg air}}\right)\left(2556.6 \frac{\text{kJ}}{\text{kg vapor}}\right)$$

and

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) = \left(0.2 \frac{\text{kg air}}{\text{min}}\right)\left(0.0144 - \omega_1 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

Solve the equations for ω_1,

$$\omega_1 = 0.0104 \frac{\text{kg vapor}}{\text{kg air}}$$

$$\dot{m}_w = \left(0.2 \frac{\text{kg air}}{\text{min}}\right)\left(60 \frac{\text{min}}{\text{h}}\right)\left(0.0144 - 0.0104 \frac{\text{kg vapor}}{\text{kg air}}\right)$$

$$= \underline{0.048 \text{ kg}}$$

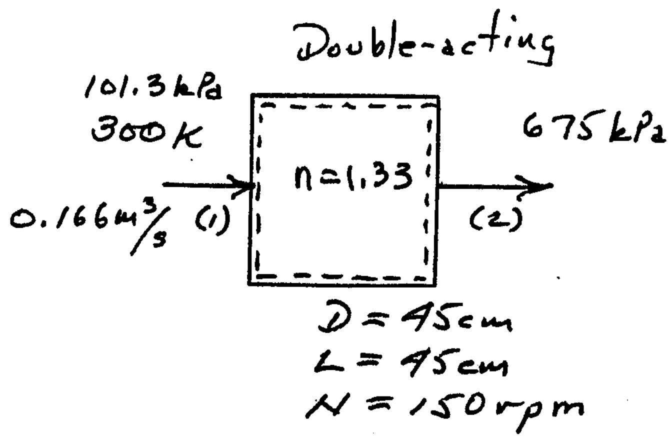
Problem 16.73

Calculate the volumetric efficiency of a single-cylinder, double-acting compressor with a bore and stroke of 0.45 x 0.45 m. The compressor is tested at 150 rpm and found to deliver a gas from 101.3 kPa and 300°K to 375 kPa at a rate of 0.166 m^3/s when n = 1.33 for expansion and compression processes.

Given: The operating conditions of a reciprocating compressor are measured in a test.

Find: The compressor's volumetric efficiency.

Sketch and Given Data:



Assumptions:
1) The compressor is a steady, open system.
2) Neglect changes in kinetic and potential energy.
3) The gas is an ideal gas.
4) The displacement volume of a double-acting compressor is twice the volume of a single-cylinder.

Analysis: The displacement volume per revolution is

$$V_{PD} = 2\frac{\pi}{4}D^2L = \frac{\pi}{2}(0.45\ \text{m})^3 = 0.1431\ \text{m}^3/\text{rev}$$

$$\dot{V}_{PD} = N^*V_{PD} = \left(150\ \frac{\text{rev}}{\text{min}}\right)\left(\frac{1}{60}\ \frac{\text{min}}{\text{s}}\right)\left(0.1431\ \frac{\text{m}^3}{\text{rev}}\right) = 0.3578\ \text{m}^3/\text{s}$$

$$\eta_v = \frac{\dot{V}_{actual}}{\dot{V}_{PD}} = \frac{0.166}{0.3578} = \underline{0.464}\ \text{or}\ 46.4\%$$

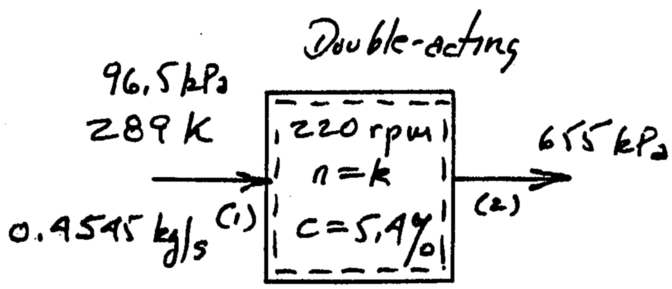
Problem 16.77

A reciprocating double-acting, single-cylinder air compressor operates at 220 rpm with a piston speed of 200 m/s. The air is compressed isentropically from 96.5 kPa and 289°K to 655 kPa. The compressor clearance is 5.4%, and the air flow rate is 0.4545 kg/s. Determine for n - 1.35 (a) the volumetric efficiency; (b) the piston displacement; (c) the power; (d) the bore and stroke if L = D.

Given: A double acting, single cylinder, reciprocating compressor compresses air isentropically between two states. The percent clearance is known, as is the mass flow rate and the polytropic exponent.

Find: The volumetric efficiency, the displacement volume, power required and bore and stroke if L = D.

Sketch and Given Data:



Assumptions:
1) The compressor is a steady, open system.
2) Neglect changes in kinetic and potential energy.
3) Air is an ideal gas.
4) The heat transfer is zero.

Analysis: The volumetric efficiency is

a) $$\eta_v = 1 + c - c\left(\frac{p_2}{p_1}\right)^{1/n} = 1.054 - (0.054)\left(\frac{655}{96.5}\right)^{1/1.35} = \underline{0.831}$$

The total volume flow rate at inlet conditions is

$$\dot{V} = \frac{m\ RT_1}{p_1} = \frac{(0.4545\ \text{kg/s})\left(0.287\ \dfrac{\text{kJ}}{\text{kg-K}}\right)(289\ \text{K})}{(96.5\ \text{kN/m}^2)} = 0.3906\ \text{m}^3/\text{s}$$

The volume flow rate is also

$$\dot{V}_1 = \eta_v \dot{V}_{PD} = (\eta_v)(V_{PD})(N)(2)$$

$$\dot{V}_1 = \left(0.3906 \frac{m^3}{s}\right) = (0.831)(V_{PD})\left(\frac{220}{60} \frac{rev}{s}\right)\left(2 \frac{stroke}{rev}\right)$$

b) $V_{PD} = \underline{0.0641 \text{ m}^3}$

$$V_{PD} = 0.0641 \text{ m}^3 = \frac{\pi}{4} D^2L = \left(\frac{\pi}{4}\right)(D \text{ m})^3$$

d) $D = L = 0.439 \text{ m} = \underline{43.4 \text{ cm}}$

The power is

$$\dot{W} = \frac{n}{n-1} \dot{m} RT_1 \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}\right]$$

$$\dot{W} = \left(\frac{(1.35)}{(0.35)}(0.4545 \text{ kg/s})(0.287 \text{ kJ/kg-K})(289 \text{ K})\right)\left[1 - \left(\frac{655}{96.5}\right)^{\frac{0.35}{1.35}}\right]$$

c) $\dot{W} = \underline{-93.5 \text{ kW}}$

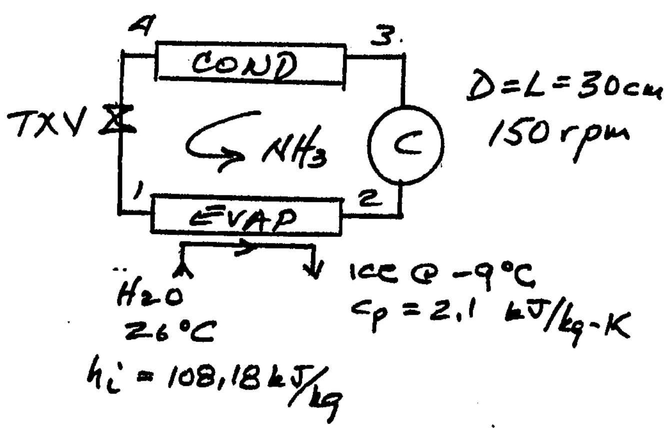
Problem 16.81

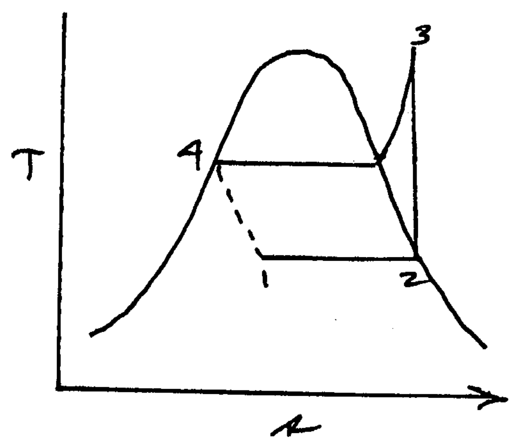
A single-acting compressor with twin cylinders of 30 x 30 cm receives saturated ammonia vapor at 226 kPa and discharges it at 1200 kPa. Saturated liquid ammonia enters the expansion valve. Ice is to be manufactured at -9°C, and the water is a available at 26°C. The compressor runs at 150 rpm, and the volumetric efficiency is 80%. Assuming the specific heat of ice to be 2.1 kJ/kg-K, determine (a) the ammonia flow rate; (b) the mass of ice manufactured; (c) the compressor power.

Given: A double-cylinder refrigeration compressor has known bore and stroke and rpm. The ammonia states around the cycle are known as is the volumetric efficiency. The water temperature, ice temperature and ice specific heat are known.

Find: The ammonia mass flow rate, compressor power and mass of ice manufactured.

Sketch and Given Data:





Assumptions:
1) Ammonia is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.
4) The cycle is an ideal vapor compression cycle.

Analysis: Determine the cycle properties.

$$h_2 = 1424.4\ \frac{kJ}{kg} \qquad s_2 = 5.5600\ \frac{kJ}{kg-K} \qquad v_2 = 0.5296\ m^3/kg$$

$$h_4 = h_f\ @\ 1200\ kPa = 327.9\ \frac{kJ}{kg} \qquad h_1 = h_4$$

$$p_3 = 1200, \qquad s_3 = s_2 \qquad h_3 = 1667.6\ kJ/kg$$

The compressor volume flow rate

$$\dot{V}_2 = \eta_v \, N \, V_{PD}$$

$$V_{PD} = \left(\frac{\pi}{4} D^2 L\right)(2) \qquad N = 150 \text{ rpm}$$

$$\dot{V}_2 = (0.80)\left(\frac{\pi}{4}\right)(0.30 \text{ m})^3(2)\left(\frac{150}{60}\frac{\text{rev}}{\text{s}}\right) = 0.08482 \frac{\text{m}^3}{\text{s}}$$

a) $$\dot{m}_2 = \frac{\dot{V}_2}{v_2} = \frac{(0.08482 \text{ m}^3/\text{s})}{(0.5296 \text{ m}^3/\text{kg})} = \underline{0.160 \text{ kg/s}}$$

c) $$\dot{W} = \dot{m}(h_2 - h_3) = (0.160 \text{ kg/s})\left(1424.4 - 1667.6 \frac{\text{kJ}}{\text{kg}}\right)$$

$$= \underline{-38.9 \text{ kW}}$$

Find the heat received in the evaporator. A first law analysis yields.

$$\dot{Q} = \dot{m}(h_2 - h_1) = (0.16 \text{ kg/s})\left(1424.4 - 327.9 \frac{\text{kJ}}{\text{kg}}\right) = 175.4 \text{ kW}$$

A first law on the evaporator from the water's view is

$$\dot{Q} = \dot{m}_{ice}(h_o - h_i)$$

$$h_o = h_{\substack{water\\0°C}} - h_{ig} - \Delta h_{0\text{-}9°C}$$

$$h_{\substack{water\\0°C}} \approx 0 \qquad h_{ig} = 334.9 \text{ kJ/kg}$$

$$\Delta h = c_p(\Delta T) = -(2.1 \text{ kJ/kg-K})(0-(-9)) = -18.9 \text{ kJ/kg}$$

$$(-175.4 \text{ kW}) = (\dot{m}_{ice} \text{ kg/s})(-334.9 - 18.9 \text{ kJ/kg})$$

b) $$\dot{m}_{ice} = \underline{0.496 \text{ kg/s}}$$

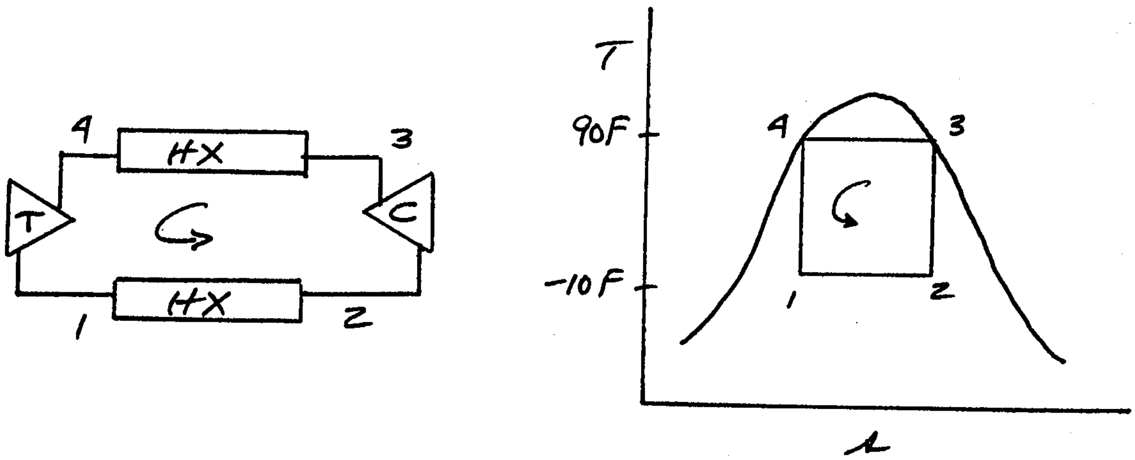
Problem *16.1

A reversed Carnot cycle uses R 12 as the working fluid. The refrigerant enters the condenser as a saturated vapor at 90°F and leaves as a saturated liquid. The evaporator temperature is a constant -10°F. Determine per unit mass (a) the compressor work; (b) the turbine work; (c) the heat input; (d) the COP.

Given: A reversed Carnot cycle uses R 12 and operates between known temperatures.

Find: The compressor and turbine works, the heat input and the COP.

Sketch and Given Data:



Assumptions:
1) R 12 is a pure substance.
2) Cycle processes are illustrated above.

Analysis: From the R 12 tables, find

h_3 = 86.17 Btu/lbm $\quad$ h_4 = 28.71 Btu/lbm

s_3 = 0.16353 Btu/lbm-R $\quad$ s_4 = 0.05900 Btu/lbm-R

The process from 4-1 is isentropic, $s_1 = s_4$

$$0.059 = 0.01462 + x_4(0.15527) \qquad x_4 = 0.286$$

$$h_1 = 6.37 + (0.286)(69.82) = 26.33 \text{ Btu/lbm}$$

The process from 3-2 is isentropic, $s_2 = s_3$

$$0.16353 = 0.01462 + x_2(0.15527) \quad x_2 = 0.959$$

$$h_2 = 6.37 + (0.959)(69.82) = 73.33 \text{ Btu/lbm}$$

From a first law analysis.

a) $$w_c = h_2 - h_3 = (73.33 - 86.17) = -12.84 \text{ Btu/lbm}$$

b) $$w_t = h_4 - h_1 = (28.71 - 26.33) = 2.38 \frac{\text{Btu}}{\text{lbm}}$$

c) $$q_{in} = h_2 - h_1 = (73.33 - 26.33) = 47.0 \frac{\text{Btu}}{\text{lbm}}$$

d) $$(COP)_c = \frac{T_c}{T_H - T_c} = \frac{450}{550 - 450} = \underline{4.5}$$

Or the $(COP)_c$ may be found from heat and work term.

$$w_{net} = w_t + w_c = 2.38 - 12.84 = -10.46 \text{ Btu/lbm}$$

$$(COP)_c = \frac{47.0}{10.46} = 4.5$$

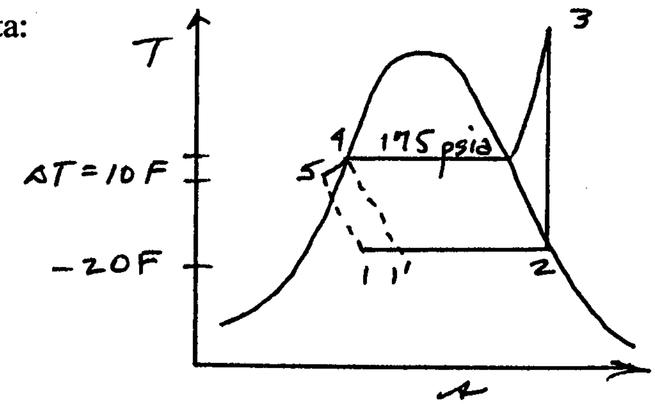
Problem *16.5

A vapor-compression refrigeration system has an evaporator operating at -20°F, a condenser with a pressure of 175 psia, and subcooling of 10°F of the R 12 leaving the condenser. Determine the percentage of increase in refrigerating effect because of the subcooling.

Given: A vapor compression system is ideal except for subcooling of R 12 leaving the condenser.

Find: The percent refrigerating effect increase because of subcooling.

Sketch and Given Data:



Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the enthalpies around the cycle.

$$h_2 = 75.11 \frac{\text{Btu}}{\text{lbm}} \qquad s_2 = 0.17102 \text{ Btu/lbm-R}$$

$$h_4 = h_f \text{ @ 175 psia and } T_4 = 121.2 \text{ F} = 36.27 \text{ Btu/lbm} = h_1'$$

$$T_5 = 111.2 \text{ F} \qquad h_5 = h_f \text{ @ } 111.2 \text{ F} = 33.82 \text{ Btu/lbm} = h_1$$

The refrigerating effect without subcooling is

$$q_{in} = (h_2 - h_1') = (75.11 - 36.27) = 38.84 \text{ Btu/lbm}$$

The refrigerating effect with subcooling is

$$q_{in} = (h_2 - h_1) = (75.11 - 33.82) = 41.29 \text{ Btu/lbm}$$

$$\% \text{ increase in } q_{in} = \frac{41.29 - 38.84}{38.84} = 0.063 \text{ or } \underline{6.3\%}$$

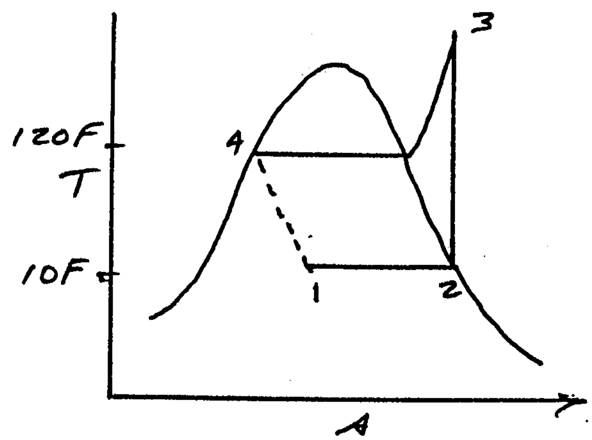
Problem *16.9

In a standard refrigerating cycle the evaporator temperature is -10°F, and the condenser temperature is 120°F. Saturated vapor enters the compressor, and there is no subcooling of the liquid refrigerant. Consider ammonia and R 12, and select the refrigerant that gives the higher COP.

Given: An ideal vapor compression refrigeration system, its operating conditions and two refrigerants, R 12 and ammonia.

Find: Which refrigerant gives the higher COP.

Sketch and Given Data:



Assumptions:

1) R 12 is a pure substance.
2) Ammonia is a pure substance.
3) Each component may be considered a steady-state, open system.
4) Neglect changes in kinetic and potential energy.

Analysis: Determine the COP for R 12.

$$h_2 = 76.196 \frac{\text{Btu}}{\text{lbm}} \qquad s_2 = 0.16989 \text{ Btu/lbm-R}$$

$$h_4 = h_f @ 120 \text{ F} = 36.01 \text{ Btu/lbm} \qquad p_4 = 172.35 \text{ psia} \qquad h_1 = h_4$$

$$p_3 = p_4 \qquad s_3 = s_2 \qquad h_3 = 93.03 \text{ Btu/lbm}$$

$$w_{net} = h_2 - h_3 = (76.196 - 93.03) = -16.83 \text{ Btu/lbm}$$

$$q_{in} = h_2 - h_1 = (76.196 - 36.01) = 40.19 \text{ Btu/lbm}$$

$$(\text{COP})_{R\,12} = \frac{40.19}{16.83} = \underline{2.39}$$

For ammonia

$h_2 = 608.5$ Btu/lbm $\qquad s_2 = 1.3558$ Btu/lbm-R

$$h_4 = 179.0 \ \frac{\text{Btu}}{\text{lbm}} \qquad h_1 = h_4$$

$p_3 = p_4 = 286.4$ psia $\qquad s_3 = s_2 \qquad h_3 = 775.6$

$$w_{net} = (h_2 - h_3) = (608.5 - 775.6) = 167.1 \ \frac{\text{Btu}}{\text{lbm}}$$

$$q_{in} = (h_2 - h_1) = (608.5 - 179.0) = 429.5 \ \frac{\text{Btu}}{\text{lbm}}$$

$$(\text{COP})_{NH_3} = \frac{429.5}{167.1} = \underline{2.57}$$

Ammonia gives the higher COP.

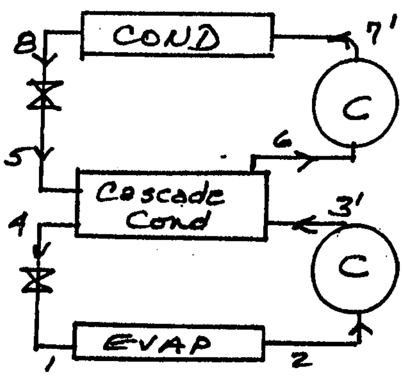
Problem *16.13

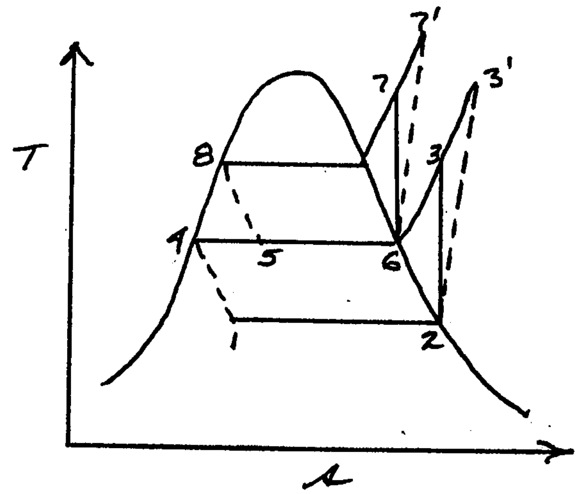
The same as Problem *16.12, assuming the isentropic compressor efficiency is 85% for the compressors.

Given: A two-stage cascade refrigeration system per Problem *16.12 except the compressors have efficiencies.

Find: The mass flow rates, COP and cascade condenser irreversibility rate.

Sketch and Given Data:





Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Use the property values from Problem 16.12* as appropriate.

$$p_3 = 51.7 \text{ psia} \qquad h_5 = 36.27 \text{ Btu/lbm} \quad s_6 = 0.1658 \frac{\text{Btu}}{\text{lbm-R}}$$

$$h_1 = 17.31 \text{ Btu/lbm}$$

$$h_2 = 75.11 \text{ Btu/lbm} \quad h_6 = 81.44 \text{ Btu/lbm} \quad s_5 = 0.0754 \frac{\text{Btu}}{\text{lbm-R}}$$

$$h_3 = 84.05 \frac{\text{Btu}}{\text{lbm}} \qquad h_7 = 90.71 \text{ Btu/lbm} \quad s_4 = 0.0375 \frac{\text{Btu}}{\text{lbm-R}}$$

$$h_4 = 17.31 \frac{\text{Btu}}{\text{lbm}} \qquad h_8 = 36.27 \frac{\text{Btu}}{\text{lbm}}$$

Using the compressor efficiency, find h_3' and h_7'.

$$\eta_c = 0.85 = \frac{h_3 - h_2}{h_3' - h_2} = \frac{84.05 - 75.11}{h_3' - 75.11}$$

$h_3' = 85.63$ Btu/lbm $\quad p_3' = 51.7$ psia $\quad s_3' = 0.1740 \frac{\text{Btu}}{\text{lbm-R}}$

$$\eta_c = 0.85 = \frac{h_7 - h_6}{h_7' - h_6} = \frac{90.71 - 81.44}{h_7' - 81.44}$$

$h_7' = 92.34$ Btu/lbm

From the first law analysis of the evaporator

$$\dot{Q} = \dot{m}_2(h_2 - h_1)$$

$$(15 \text{ tons})(200 \text{ Btu/min-ton}) = (\dot{m}_2 \text{ lbm/min})(75.11 - 17.31 \text{ Btu/lbm})$$

a) $\quad \dot{m}_2 = 51.9$ lbm/min

From a first law analysis of the cascade condenser.

$$\dot{m}_1 h_5 + \dot{m}_2 + h_3' = \dot{m}_1 h_6 + \dot{m}_2 h_4$$

a) $\quad \dot{m}_1 = \frac{\dot{m}_2(h_3' - h_4)}{(h_6 - h_5)} = \frac{(51.9)(85.63 - 17.31)}{(81.44 - 36.27)} = \underline{78.5 \text{ lbm/min}}$

The total power is

$$\dot{W}_{total} = \dot{m}_1(h_6 - h_7') + \dot{m}_2(h_2 - h_3')$$

$$\dot{W}_{total} = (78.5 \text{ lbm/min})(81.44 - 92.34 \text{ Btu/lbm}) + (51.9 \text{ lbm/min})(75.11 - 85.63 \text{ Btu/lbm})$$

$$\dot{W}_{total} = -1401.6 \frac{\text{Btu}}{\text{min}} = \underline{-33.06 \text{ hp}}$$

b) $\quad (COP)_c = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{(15)(200)}{(1401.6)} = \underline{2.14}$

For an adiabatic, steady open system, the irreversibility rate, $\dot{I}$, is $T_o \ \Delta\dot{S}_{prod}$

$$\Delta\dot{S}_{prod} = \dot{m}_1(s_6 - s_5) + \dot{m}_2(s_4 - s_{3'})$$

$$\Delta\dot{S}_{prod} = (78.5)(0.1658 - 0.0754) + (51.9)(0.0375 - 0.1740)$$

$$\Delta\dot{S}_{prod} = 0.01205 \ \frac{Btu}{min\text{-}R}$$

c) $\dot{I} = (537)(0.01205) = 6.47$ Btu/min

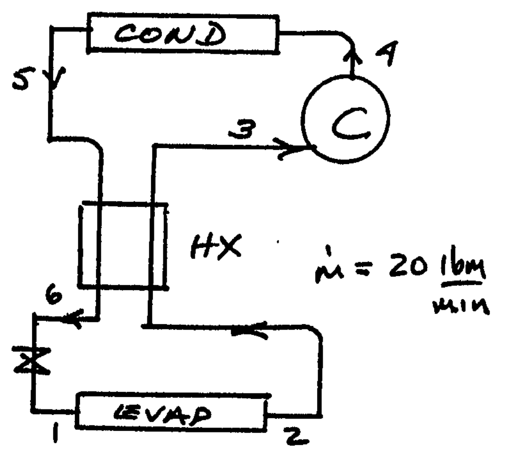
Problem *16.17

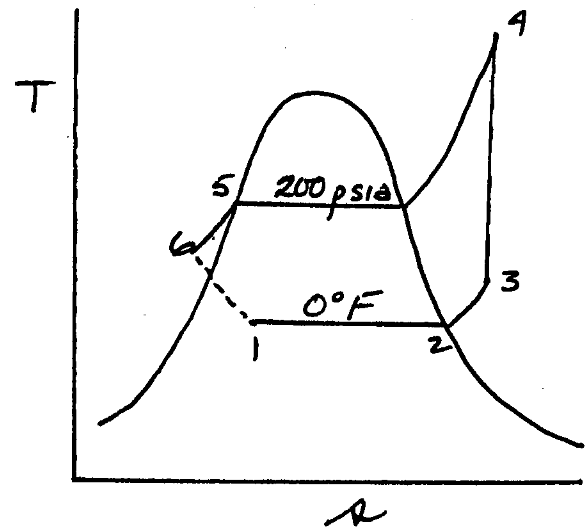
A vapor-compression refrigeration system uses a subcooling-superheating heat exchanger located after the evaporator to subcool the refrigerant entering the expansion valve. The refrigerant leaving the evaporator is superheated in the process. Assume the refrigerant leaves the evaporator as a saturated vapor and the condenser as a saturated liquid and that no pressure drops occur in the heat exchangers. The evaporator temperature is 0°F, the condenser pressure is 200 psia, the flow rate is 20 lbm/min, and 20°F of superheat added. Determine (a) the compressor power; (b) the tons of refrigeration; (c) the COP.

Given: A vapor compression refrigeration system that uses a heat exchanger to subcool the refrigerant entering the expansion valve. System states are noted.

Find: The power required, tons of refrigeration and the COP.

Sketch and Given Data:





Assumptions:
1) The refrigerant is R 12, a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.
4) The refrigerant is superheated 10°C.

Analysis: Determine the enthalpies around the cycle.

$h_2 = 77.27$ Btu/lbm $\quad p_2 = 23.85$ psia

$h_5 = 38.91$ Btu/lbm

$p_3 = p_2, \quad T_3 = 20°F, \quad h_3 = 80.16$ Btu/lbm $\quad s_3 = 0.1750 \dfrac{\text{Btu}}{\text{lbm-R}}$

$p_4 = 200$ psia $\quad s_4 = s_3 \quad h_4 = 97.44$ Btu/lbm

Perform a first law analysis on the subcooling-superheating heat exchanger subject to assumption 3 and that $\dot{Q} = 0$ and $\dot{W} = 0$.

$$\dot{m}\, h_5 + \dot{m}\, h_2 = \dot{m}\, h_3 + \dot{m}\, h_6$$

$$h_3 + h_6 = h_2 + h_5$$

$$h_6 = (77.27 + 38.91) - 80.16 = 36.02 \text{ Btu/lbm}$$

$$h_1 = h_6$$

The power is

a) $\dot{W}_{net} = \dot{m}(h_3 - h_4) = (20 \text{ lbm/min})\left(80.16 - 97.44 \dfrac{\text{Btu}}{\text{lbm}}\right)$

$\dot{W}_{net} = -345.6 \dfrac{\text{Btu}}{\text{min}} = \underline{-8.15 \text{ hp}}$

b) $\dot{Q}_{in} = \dot{m}(h_2 - h_1) = (20)(77.27 - 36.02) = 825 \text{ Btu/min}$

$\dot{Q}_{in} = \underline{4.125 \text{ tons}}$

c) $\text{COP} = \dfrac{\dot{Q}_{in}}{\dot{W}_{net}} = \dfrac{825}{345.6} = \underline{2.39}$

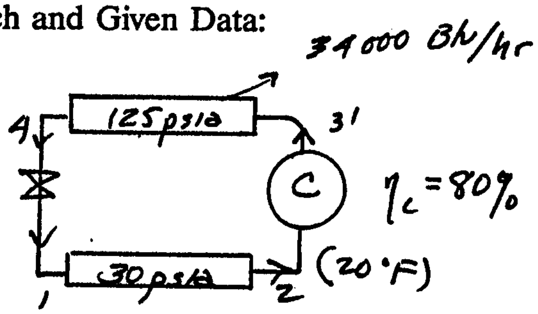
Problem *16.21

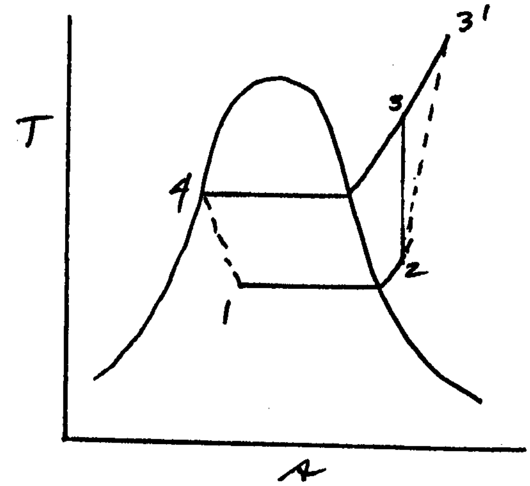
A vapor-compression heat pump uses R 12 and provides 34,000 Btu/hr of heating. The evaporator pressure is 30 psia, and the refrigerant enters the compressor at 20°F. The compressor's isentropic efficiency is 80%, and the condenser pressure is 125 psia. The electricity to drive the compressor comes from a power plant with an efficiency of 40%. Determine (a) the compressor power; (b) the ratio of heat used in the power plant to produce the electricity to the heat output of the heat pump.

Given: A vapor-compression heat pump provides a specified amount of heat which between known operating conditions.

Find: The compressor power and a comparison between the heat used to generate the electricity to that used in the house.

Sketch and Given Data:





Assumptions:

1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the property values around the cycle.

$h_2 = 79.77$ Btu/lbm $\qquad s_2 = 0.1706$ Btu/lbm-R

$h_4 = 30.22$ Btu/lbm $\qquad h_1 = h_4 = 30.22$ Btu/lbm

$s_3 = s_2 \qquad p_3 = 125$ psia $\qquad h_3 = 90.88$ Btu/lbm

$$\eta_c = 0.80 = \frac{h_3 - h_2}{h_3' - h_2} = \frac{(90.88 - 79.77)}{(h_3' - 79.77)}$$

$h_3' = 93.66$ Btu/lbm

The heat out is

$$\dot{Q}_{out} = \dot{m}(h_4 - h_3')$$

$$(-34\ 000\ \text{Btu/hr}) = (\dot{m}\ \text{lbm/hr})(30.22\ -93.66\ \text{Btu/lbm})$$

$$\dot{m} = 535.9\ \frac{\text{lbm}}{\text{hr}} = 8.93\ \text{lbm/min}$$

a) $$\dot{W}_{net} = \dot{m}(h_2 - h_3') = (8.93)(79.77 - 93.66) = -124.0\ \text{Btu/min}$$

$$\dot{W}_{net} = \underline{-2.92\ \text{hp}}$$

The power is provided by an electric motor. The power plant producing the electricity has a thermal efficiency os 40%. Hence,

$$\eta_{Th} = 0.40 = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{124.0}{\dot{Q}_{in}}$$

$$\dot{Q}_{in} = 310\ \text{Btu/min}$$

The ratio of this to the heat output of the heat pump is

b) $$r = \frac{(310\ \text{Btu/min})}{566.7\ \text{Btu/min}} = \underline{0.547}$$

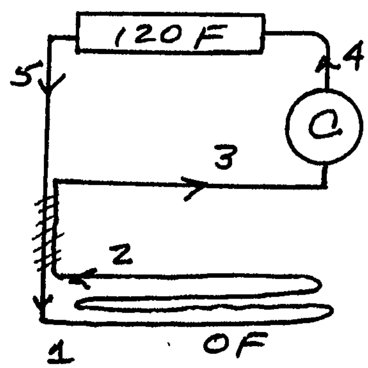
Problem *16.25

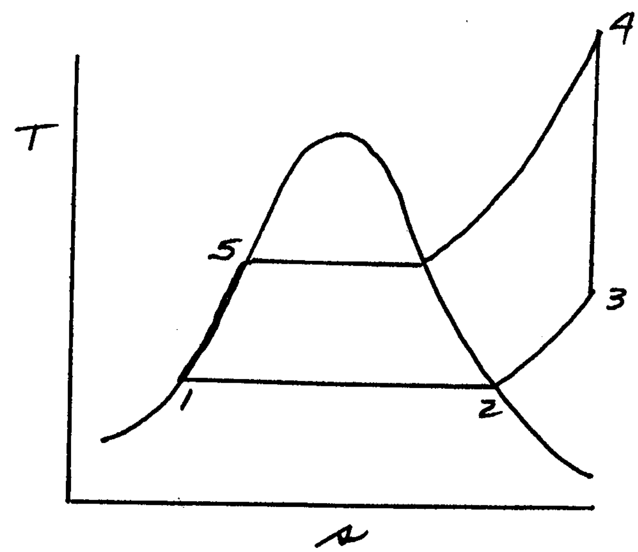
A capillary tube vapor-compression refrigeration system operates on R 12 with an evaporator temperature of 0°F and a condenser temperature of 120°F. The system provides 1 ton of cooling. Determine (a) the mass flow rate; (b) the power; (c) the COP; (d) the temperature of R 12 entering the compressor.

Given: A capillary tube refrigeration system with saturated evaporator and condenser temperatures given. The units' tonnage is specified.

Find: The refrigerant flow rate, the power, the COP and the R 12 temperature entering the compressor.

Sketch and Given Data:





Assumptions:
1) R 12 is a pure substance.
2) Each component may be considered a steady-state, open system.
3) Neglect changes in kinetic and potential energy.

Analysis: Determine the enthalpy values around the cycle.

$$h_5 = h_f \text{ @ } 120°F = 36.01 \text{ Btu/lbm}$$

$$h_1 = h_f \text{ @ } 0°F = 8.52 \frac{\text{Btu}}{\text{lbm}} \qquad h_2 = h_g \text{ @ } 0°F = 77.27 \text{ Btu/lbm}$$

$$p_2 = 23.85 \text{ psia} \qquad p_3 = p_2$$

Perform a first law on subcooling/superheating tubing which yields:

$$\dot{m}\, h_5 + \dot{m}\, h_2 = \dot{m}\, h_1 + \dot{m}\, h_3$$

$$h_3 = h_5 + h_2 - h_1 = 36.01 + 77.27 - 8.52 = 104.76\ \frac{\text{Btu}}{\text{lbm}}$$

$s_3 = 0.2191$ Btu/lbm-R   d) $T_3 = \underline{182.1\text{ F}}$

The process 3-4 is isentropic, $s_4 = s_3$ and $p_4 = 172.3$ psia

$h_4 = 127.1$ Btu/lbm

A first law analysis of the evaporator yields

$$\dot{Q} = \dot{m}(h_2 - h_1)$$

$$(1\text{ tons})(200\text{ Btu/min-ton}) = \left(\dot{m}\ \frac{\text{lbm}}{\text{min}}\right)(77.27 - 8.52\text{ Btu/lbm})$$

a) $\dot{m} = \underline{2.91\text{ lbm/min}}$

b) $\dot{W} = \dot{m}(h_3 - h_4) = (2.91)(104.76 - 127.1) = -65.0\ \frac{\text{Btu}}{\text{min}}$

$\dot{W} = -1.53$ hp

c) $\text{COP} = \frac{\dot{Q}_{in}}{\dot{W}_{net}} = \frac{(200)}{(65.0)} = \underline{3.07}$

Problem *16.29

Using the psychrometric chart, determine (a) the specific enthalpy and specific volume for air with a relative humidity of 60% and a dry-bulb temperature of 100°F; (b) the humidity ratio and the relative humidity, given a wet-bulb temperature of 75°F and a specific volume of 14.5 ft³/lbm; (c) the wet- and dry-bulb temperature, given a relative humidity of 70% and a humidity ratio of 0.018 lbm vapor/lbm air.

Given: Various states of an air-vapor mixture.

Find: Property values from the psychrometric chart.

Assumptions: 1) The pressure is atmospheric.

Analysis: a) $\phi = 60\%,$ $T_{db} = 100°F$

$$h = 52.0 \text{ Btu/lbm air} \qquad v = 14.67 \text{ ft}^3\text{/lbm air}$$

b) $T_{wb} = 75°F,$ $v = 14.5 \text{ ft}^3\text{/lbm}$

$$\omega = 0.0115 \frac{\text{ft}^3}{\text{lbm}} \qquad \phi = 24.2\%$$

c) $\phi = 70\%,$ $\omega = 0.018$ lbm vapor/lbm air

$$T_{wb} = 76.5°F \qquad T_{db} = 84.4°F$$

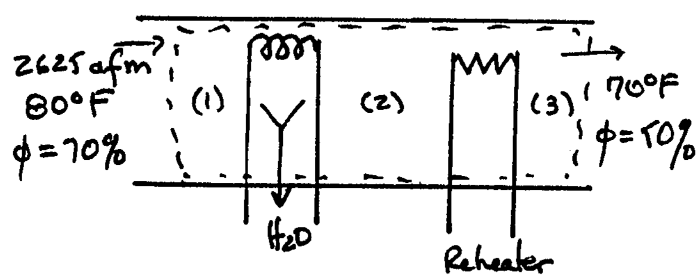
Problem *16.33

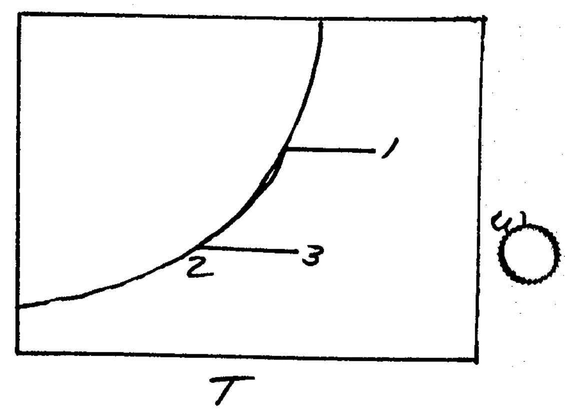
An air conditioning system dehumidifies and then reheats the air. The system operates with 2625 ft^3/min of air entering the dehumidifier at 80°F and 70% relative humidity. The air leaves the reheater at 70°F and 50% relative humidity. Determine (a) the temperature of the air leaving the dehumidifier before it is reheated; (b) the flow rate of the condensed water; (c) the tons of cooling required; (d) the reheat in Btu/min.

Given: An air conditioning system receives a given volume flow of air, dehumidifies it and reheats it to specified states.

Find: The air temperature before reheating, the water flow rate, the tons of cooling required and the reheat required.

Sketch and Given Data:





Assumptions:
1) The pressure is atmospheric.
2) Neglect changes in kinetic and potential energy.
3) The work is zero.
4) Each component may be considered a steady-state, open system.

Analysis: Determine the air properties from the psychrometric chart to be:

$$h_1 = 36.2 \text{ Btu/lbm} \quad \omega_1 = 0.0155 \frac{\text{lbm vapor}}{\text{lbm air}}$$

$$v_1 = 13.95 \text{ ft}^3/\text{lbm air}$$

$$h_3 = 25.4 \frac{\text{Btu}}{\text{lbm}} \quad \omega_3 = 0.0078 \frac{\text{lbm vapor}}{\text{lbm air}}$$

The humidity ratio at (2) is the same as (3)

$\omega_2 = \omega_3 \qquad h_2 = 20.6$ Btu/lbm (a) $\quad T_2 = \underline{50.5°F}$

The air mass flow rate is

$$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{(2625\ \text{ft}^3/\text{min})}{(13.95\ \text{ft}^3/\text{lbm})} = 188.2\ \text{lbm/min}$$

The water flow is

$$\dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) = \left(188.2\ \frac{\text{lbm}}{\text{min}}\right)\left(0.0155 - 0.0078\ \frac{\text{lbm vapor}}{\text{lbm air}}\right)$$

b) $\dot{m}_w = \underline{1.448\ \text{lbm/min}}$

The first law on the dehumidifier yields

$$\dot{Q} + \dot{m}_a h_1 = \dot{m}_a h_2 + \dot{m}_w h_f$$

$$\dot{Q} = \dot{m}_a(h_2 - h_1) + \dot{m}_w h_f \quad \text{where } h_f = h_f\ @\ 70°\text{F} = 37.68\ \frac{\text{Btu}}{\text{lbm}}$$

$$\dot{Q} = (188.2\ \text{lbm/min})\left(20.6 - 36.2\ \frac{\text{Btu}}{\text{lbm air}}\right)$$

$$+ \left(1.448\ \frac{\text{lbm water}}{\text{min}}\right)(37.68\ \text{Btu/lbm water})$$

$$\dot{Q} = -2881\ \text{Btu/min}$$

c) $\dot{Q} = \dfrac{(2881\ \text{Btu/min})}{(200\ \text{Btu/min-ton})} = \underline{14.4\ \text{tons}}$

The first law on the reheater yields

$$\dot{Q} + \dot{m}_a h_2 = \dot{m}_a h_3$$

d) $\dot{Q} = \dot{m}_a(h_3 - h_2) = (188.2\ \text{lbm/min})\left(25.4 - 20.6\ \dfrac{\text{Btu}}{\text{lbm}}\right)$

$$= 903\ \frac{\text{Btu}}{\text{min}}$$

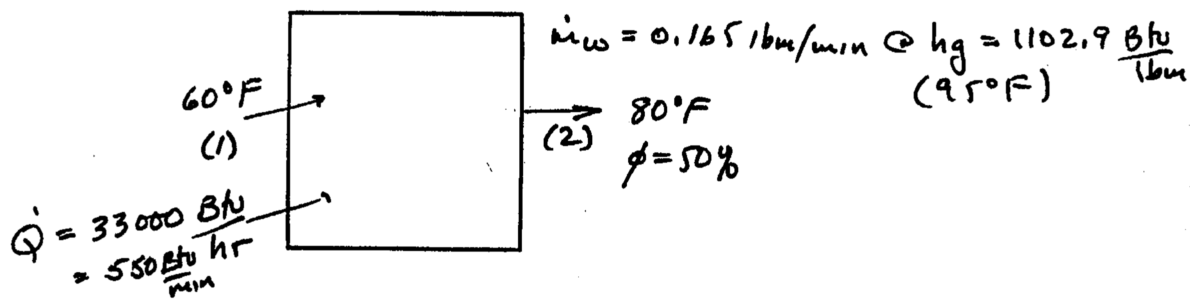
Problem *16.37

An air-conditioned classroom receives air at 60°F. The air leaving via the exit duct is at 80°F and 50% relative humidity. The people in the room may be viewed as adding 0.165 lbm/min of water vapor at 95°F. The heat addition from the people in the room and the lights and surroundings is estimated to be 33,000 Btu/hr. Determine the inlet volume flow rate, relative humidity and humidity ratio.

Given: A classroom receives air at an incompletely defined state, has water vapor and heat input to the air and the air exits at a known state.

Find: The inlet air volume flow rate, the inlet relative humidity and humidity ratio.

Sketch and Given Data:



Assumptions:
1) The pressure is atmospheric.
2) The work is zero.
3) Neglect changes in kinetic and potential energy.
4) The classroom is a steady, open system.

Analysis: The properties at state (2) are

$$h_2 = 31.3 \text{ Btu/lbm air} \qquad \omega_2 = 0.0110 \ \frac{\text{lbm vapor}}{\text{lbm air}}$$

Perform a first law analysis on the classroom

$$\dot{Q} + \dot{m}_a h_1 + \dot{m}_w h_g = \dot{m}_a h_2$$

$$\dot{Q} = \dot{m}_a (h_2 - h_1) - \dot{m}_w h_g$$

$$\dot{m}_w = 0.165 \text{ lbm/min}$$

Use a trial and error solution. Assume a value for state (1), calculate $\dot{m}_a$ from the first law and check the conservation of mass equation for water.

Assume $T_1 = 60°F$, $\phi = 50\%$, $h_1 = 20.4 \dfrac{Btu}{lbm}$, $\omega_1 = 0.0055$

$$\left(550 \frac{Btu}{min}\right) = (\dot{m}_a \ lbm/min)(31.3 - 20.4 \ Btu/lbm)$$

$$- (0.165 \ lbm/min)(1102.9 \ Btu/lbm)$$

$$\dot{m}_a = 67.1 \ lbm/min$$

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) = (67.1)(0.0110 - 0.0055) = 0.369 \ lbm/min$$

This value is too high, hence the initial humidity ratio is higher.
Assume $T = 60°F$, $\phi = 86\%$, $h_1 = 24.8$ Btu/lbm, $w_1 = 0.0096$

$$550 = (\dot{m}_a)(31.3 - 24.8) - (0.165)(1102.9)$$

$$\dot{m}_a = 112.6 \ lbm/min$$

$$\dot{m}_w = (112.6)(0.011 - .0096) = 0.16 \ lbm/min$$

This close enough. Thus

b) $\phi_1 = 86\%$ c) $\omega_1 = 0.0096 \dfrac{lbm \ vapor}{lbm \ air}$

The specific volume is $v_1 = 13.3 \ ft^3/lbm$, thus

a) $$\dot{V}_1 = \dot{m}_a v_1 = \left(112.6 \frac{lbm}{min}\right)\left(13.3 \frac{ft^3}{lbm}\right) = \underline{1497} \ ft^3/min$$

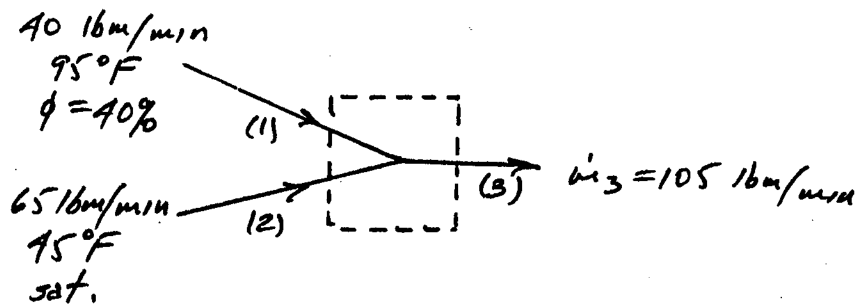
Problem *16.41

Air at 95°F and 40% relative humidity enters an adiabatic mixing chamber with a flow rate of 40 lbm/min and mixes with saturated air at 45°F with a flow rate of 65 lbm/min. Determine the relative humidity and temperature of the exit air.

Given: An adiabatic mixing chamber receives two air streams, creating the exiting third stream. The inlet conditions are specified.

Find: The exit stream's relative humidity and temperature.

Sketch and Given Data:



Assumptions:

1) The pressure is atmospheric.
2) The heat and work are zero.
3) Neglect changes in kinetic and potential energy.
4) The mixing chamber is a steady, open system.

Analysis: Determine the inlet air properties.

$$h_1 = 38.5 \text{ Btu/lbm} \quad \omega_1 = 0.0142 \text{ lbm vapor/lbm air}$$

$$h_2 = 17.7 \text{ Btu/lbm} \quad \omega_2 = 0.0064 \text{ lbm vapor/lbm air}$$

Perform a first law analysis on the mixing chamber and apply assumptions 2 and 3 which yields.

$$\dot{m}_{a_1} h_1 + \dot{m}_{a_2} h_2 = \dot{m}_{a_3} h_3$$

$$(40 \text{ lbm/min})(38.5 \text{ Btu/lbm}) + (65 \text{ lbm/min})\left(17.7 \frac{\text{Btu}}{\text{lbm}}\right)$$

$$= \left(105 \frac{\text{lbm}}{\text{min}}\right)\left(h_3 \frac{\text{Btu}}{\text{lbm}}\right)$$

$$h_3 = 25.6 \frac{\text{Btu}}{\text{lbm}}$$

The conservation of mass applied to water yields.

$$\dot{m}_{a_1} \omega_1 + \dot{m}_{a_2} \omega_2 = \dot{m}_{a_3} w_3$$

$$(40)(0.0142) + (65)(0.0064) = (105)(\omega_3)$$

$$\omega_3 = 0.0094 \text{ lbm vapor/lbm air}$$

From the psychrometric chart knowing h_3 and ω_3 find

$T_3 = \underline{64 \text{ F}}$ $\quad \phi_3 = 73\%$

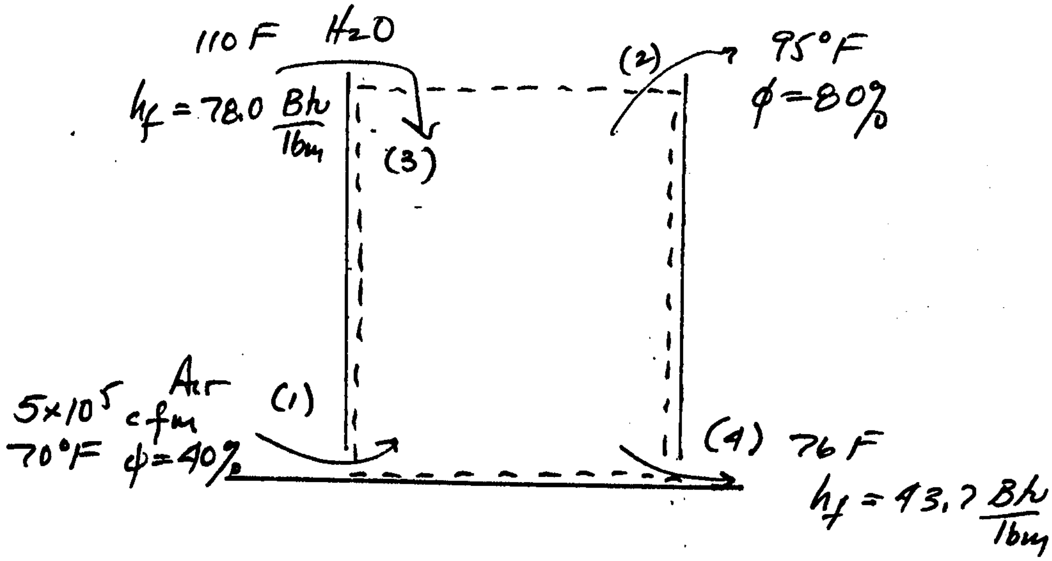
Problem *16.45

A cooling tower receives 5×10^5 ft³/min at atmospheric air at 14.7 psia, 70°F dry-bulb, and 40% relative humidity, and discharges it at 95°F dry-bulb and 80% relative humidity. Water enters at 110°F and leaves at 76°F. Determine (a) the mass flow rate of air entering the cooling tower; (b) the mass flow rate of water entering; (c) the mass flow rate of water evaporated.

Given: A cooling tower cools and water between two states. It receives a known quantity of air enters and leaves at specified conditions.

Find: The air and water mass flow rates entering the cooling tower and the mass flow of water evaporated.

Sketch and Given Data:



Assumptions:
1) The pressure is atmospheric.
2) The cooling tower is a steady, open system.
3) The heat and work are zero.
4) Neglect changes in kinetic and potential energy.

Analysis: Determine the air's properties at states 1 and 2.

$$h_1 = 23.6\ \frac{\text{Btu}}{\text{lbm}} \qquad \omega_1 = 0.0063\ \frac{\text{lbm vapor}}{\text{lbm air}} \qquad v_1 = 13.5\ \frac{\text{ft}^3}{\text{lbm}}$$

$$h_2 = 55.0\ \frac{\text{Btu}}{\text{lbm}} \qquad \omega_2 = 0.0291\ \frac{\text{lbm vapor}}{\text{lbm air}}$$

The air's mass flow rate is

a) $$\dot{m}_a = \frac{\dot{V}_1}{v_1} = \frac{(5\times10^5 \text{ ft}^3/\text{min})}{(13.5 \text{ ft}^3/\text{lbm})} = \underline{37{,}037} \text{ lbm/min}$$

The water evaporated is

$$\dot{m}_e = \dot{m}_a(\omega_2 - \omega_1)$$

$$= \left(37{,}037 \frac{\text{lbm}}{\text{min}}\right)\left(0.0291 - 0.0063 \frac{\text{lbm vapor}}{\text{lbm air}}\right)$$

c) $$\dot{m}_e = \underline{844 \text{ lbm/min}}$$

The first law on the cooling tower, subject to assumptions 3 and 4, yields

$$\dot{m}_a h_1 + \dot{m}_w h_3 = \dot{m}_a h_2 + (\dot{m}_w - \dot{m}_e)h_4$$

$$\left(30\ 037 \frac{\text{lbm air}}{\text{min}}\right)\left(23.6 \frac{\text{Btu}}{\text{lbm air}}\right) + \left(\dot{m}_w \frac{\text{lbm water}}{\text{min}}\right)\left(78.0 \frac{\text{Btu}}{\text{lbm water}}\right)$$

$$= \left(30\ 037 \frac{\text{lbm air}}{\text{min}}\right)\left(55.0 \frac{\text{Btu}}{\text{lbm air}}\right)$$

$$+ \left(\dot{m}_w - 844 \frac{\text{lbm water}}{\text{min}}\right)\left(43.7 \frac{\text{Btu}}{\text{lbm water}}\right)$$

b) $$\dot{m}_w = \underline{32{,}830} \frac{\text{lbm water}}{\text{min}}$$

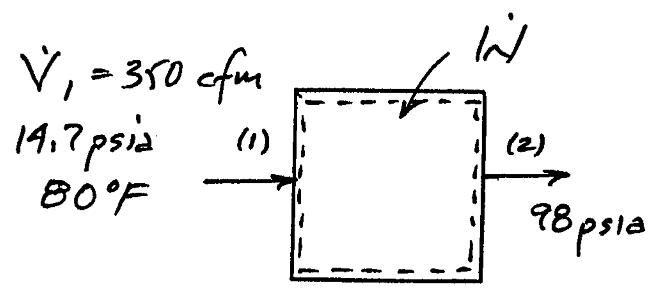
Problem *16.49

A gas compressor handles 350 ft^3/min of a gas at 14.7 psia and 80°F and discharges is at 98 psia. The piston bore and stroke are 18 x 18 in.; the single cylinder is double-acting; the compressor operates at 150 rpm; and n = 1.32. Determine (a) the volumetric efficiency; (b) the clearance percentage.

Given: A single-state, double-acting compressor compresses a specified volume flow rate of a gas from inlet to discharge conditions. The compressor bore and stroke, rpm and the polytropic exponent are given.

Find: The volumetric efficiency and percent clearance.

Sketch and Given Data:



D = L = 18 inches
150 rpm
n = 1.32

Assumptions:
1) The compressor is a steady, open system.
2) The compression and expansion processes are reversible.
3) The gas is an ideal gas.
4) Neglect changes in kinetic and potential energy.

Analysis: Determine the volume flow of the piston displacement.

$$\dot{V}_{PD} = \left(\frac{\pi}{4} D^2 L \frac{ft^3}{stroke}\right)\left(2\ N \frac{strokes}{min}\right)$$

$$\dot{V}_{PD} = \left(\frac{\pi}{4}\right)\left(1.5^3 \frac{ft^3}{stroke}\right)(2)\left(150 \frac{strokes}{min}\right) = 795.2\ ft^3/min$$

a) $$\eta_v = \frac{\dot{V}_{actual}}{\dot{V}_{pd}} = \frac{350}{795.2} = \underline{0.44}$$

$$\eta_v = 1 + c - c\left(\frac{p_2}{p_1}\right)^{1/n}$$

$$0.44 = 1 + c - c\left(\frac{98}{14.7}\right)^{1/1.32}$$

$$0.44 = 1 - 3.208\ c$$

$$c = 0.175 \text{ or } \underline{17.5\%}$$

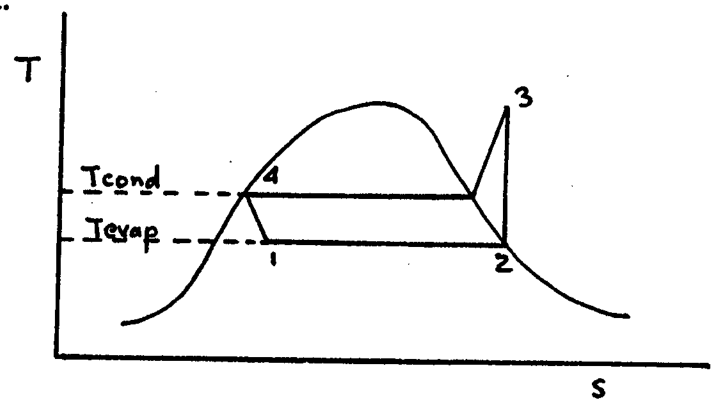
Problem C16.1

Use R12CYCLE.TK to calculate the COP of a standard vapor-compression cycle operating under various evaporating and condensing temperatures. For condensing temperatures of 25°C, 35°C, and 45°C, calculate the COP for evaporating temperatures between -40° and 10°C and plot the results.

Given: Standard vapor-compression refrigeration cycle operating under various evaporating and condensing temperatures.

Find: COP

Sketch and Given Data:

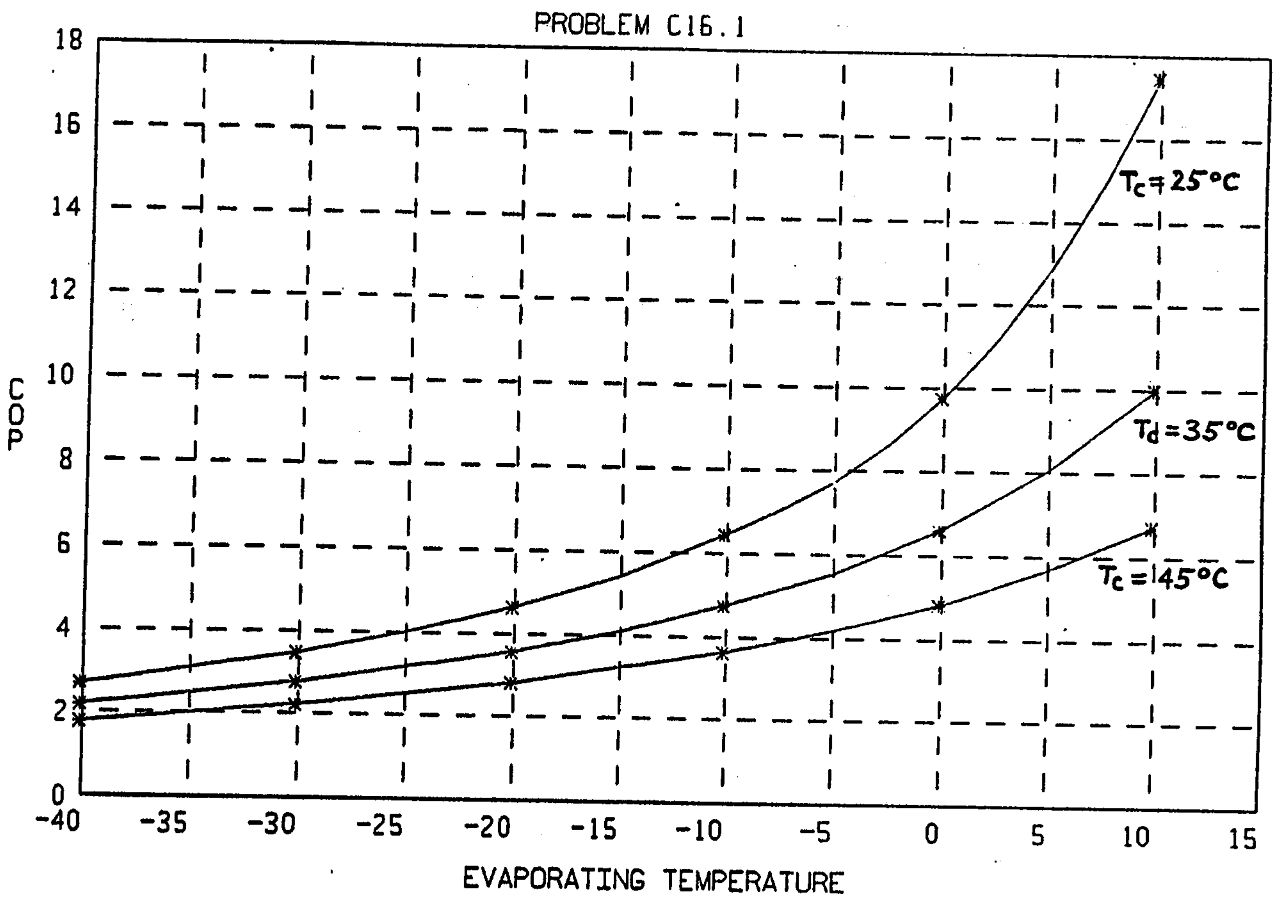


Assumptions:
1) Each component may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is ideal (standard).

Analysis: Using R12CYCLE.TK, enter zero for SHT, SC, DELP12 and DELP34. List Solving with the condensing and evaporating temperatures as inputs, and presenting the results.

PROBLEM C16.1

Tevap	Tcond	COP	Wcomp	Qevap	T3
-40	25	2.7104	40.562	109.94	42.327
-30	25	3.4986	32.74	114.54	37.802
-20	25	4.6477	25.622	119.08	34.191
-10	25	6.467	19.102	123.53	31.309
0	25	9.7581	13.105	127.88	29.012
10	25	17.466	7.5623	132.08	27.167
-40	35	2.1935	45.635	100.1	53.386
-30	35	2.7773	37.699	104.7	48.88
-20	35	3.583	30.488	109.24	45.292
-10	35	4.7583	23.894	113.69	42.432
0	35	6.6181	17.835	118.03	40.155
10	35	9.9843	12.244	122.24	38.328
-40	45	1.7838	50.422	89.945	64.256
-30	45	2.2312	42.375	94.548	59.787
-20	45	2.8252	35.073	99.087	56.235
-10	45	3.6452	28.404	103.54	53.409
0	45	4.8409	22.286	107.88	51.164
10	45	6.734	16.645	112.09	49.364



Problem C16.5

Modify R12CYCLE.TK to include equations to model an ideal reciprocating compressor. Based in a given compressor displacement, the equations should calculate the volumetric efficiency, refrigerant mass flow, compressor power, and refrigeration capacity. For a compressor with 5% clearance and 2 m^3/min displacement, calculate the above variables for evaporating temperatures between -50° and 20°C and for a condensing temperature of 40°C. Plot the results.

Given: Standard vapor-compression cycle with ideal reciprocating compressor.

Find: Performance with various evaporating temperatures.

Assumptions:
1) Each component may be analyzed as a steady-state open system.
2) The changes in kinetic and potential energies may be neglected.
3) The cycle is ideal (standard).
4) The compressor is ideal, with clearance.

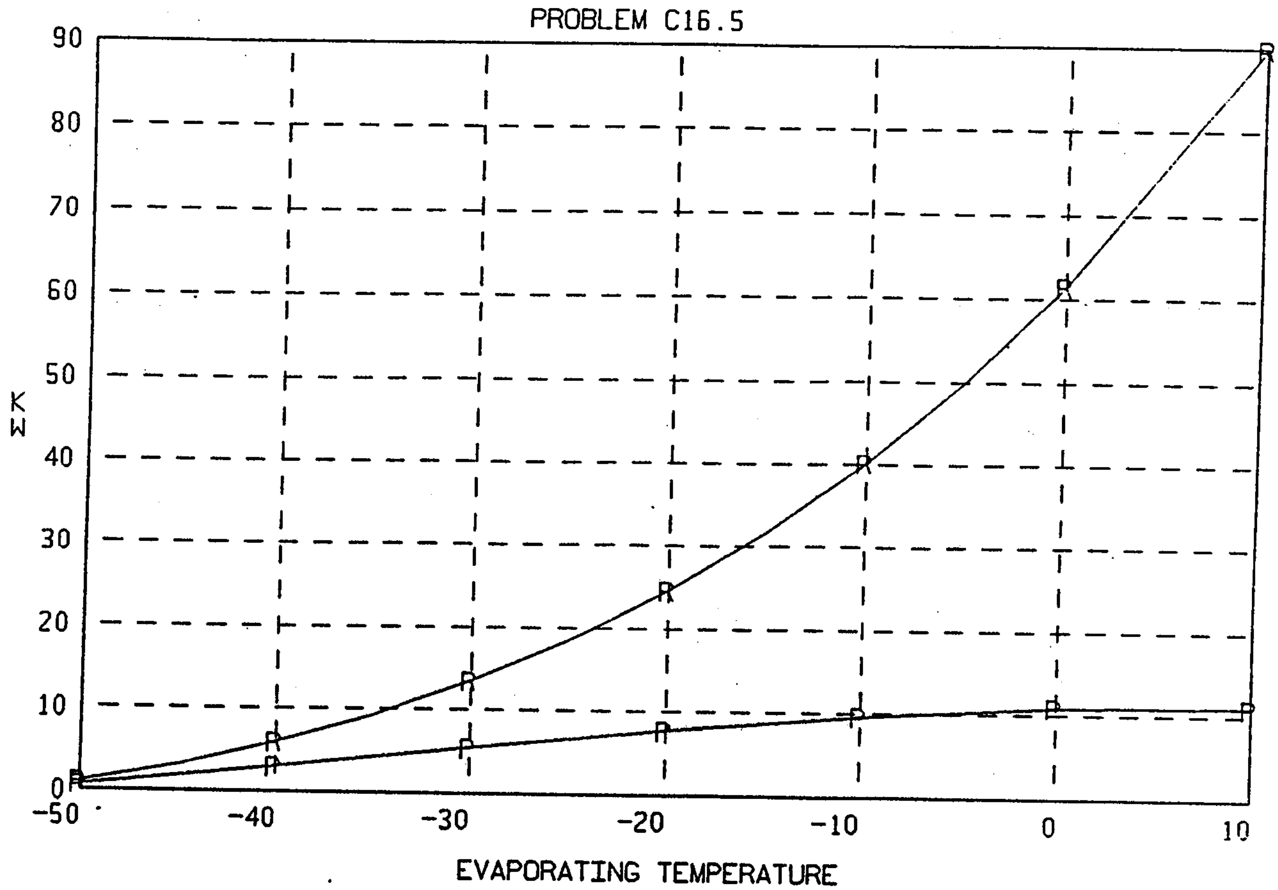
Analysis: Modifying R12CYCLE.TK by adding the following Rules.

```
==================== RULE SHEET ====================
S Rule----------------------------------------------
  "Compressor Rules
  Ev=1+c%-c%*(v2/v3)
  mR=DISPL*Ev/v2
  Pc=mR*Wcomp
  Rc=mR*Qevap
```

List Solving for various evaporator temperatures.

PROBLEM C16.5

Tevap	Ev	mR	Pc	Rc
-50	.12963	.011265	.64215	1.0186
-40	.45294	.062443	3.0013	5.9362
-30	.64701	.13532	5.4225	13.487
-20	.76927	.23554	7.7296	24.545
-10	.84911	.36927	9.6692	40.125
0	.90287	.54338	10.92	61.402
10	.94012	.766	11.092	89.783



Comment: As the evaporating temperature increases, the compressor efficiency increases, R12 specific volume decreases, and thus the mass flow increases dramatically. This results in a significant increase in refrigerating capacity.

CHAPTER SEVENTEEN

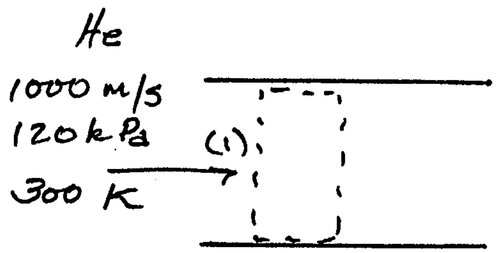
Problem 17.1

Helium is flowing in a pipeline at a velocity of 1000 m/s and with a pressure of 120 kPa and a temperature of 300 K. Determine the stagnation temperature and the isentropic stagnation pressure.

Given: Helium flows at known temperature, pressure and velocity.

Find: The stagnation temperature and the isentropic stagnation pressure.

Sketch and Given Data:



Assumptions:
1) Helium is an ideal gas.
2) Neglect changes in potential energy.

Analysis: From Equation 17.21a

$$T_0 = T + \frac{v^2}{2c_p} = (300\text{K}) + \frac{(1000\text{m/s})^2}{(2)\left(5.1954\frac{\text{kJ}}{\text{kg-K}}\right)\left(1000\frac{\text{J}}{\text{kJ}}\right)}$$

T_0 = <u>396.2K</u>

The reversible adiabatic relationship between T and p yields

$$P_0 = P_1\left(\frac{T_0}{T_1}\right)^{k/k-1} = (120\text{kPa})\left(\frac{396.2}{300}\right)^{\frac{1.666}{0.666}}$$

P_0 = <u>240.6kPa</u>

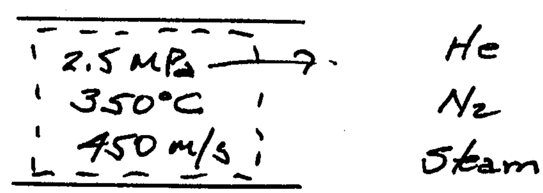
Problem 17.5

Find the isentropic stagnation temperature and pressure for the following fluids flowing through a duct at 2.5 MPa, 350°C, and 450 m/s: (a) helium; (b) nitrogen; (c) steam.

Given: A fluid flows through a duct at known temperature, pressure and velocity.

Find: The isentropic stagnation temperatures and pressures.

Sketch and Given Data:



Assumptions:
1) Helium and nitrogen are ideal gases.
2) Steam is a pure substance.
3) Neglect changes in potential energy.

Analysis: From Equation 17.21:

$$T_o = T + \frac{v^2}{2c_p}$$

and

$$p_o = p\left(\frac{T_o}{T}\right)^{k/k-1}$$

For helium

a)

$$T_o = (623\text{K}) + \frac{(450\text{m/s})^2}{(2)(5195.4\text{J/kg-K})} = \underline{642.5\text{K}}$$

$$p_o = (2500\text{kPa})\left(\frac{642.5}{623}\right)^{\frac{1.666}{0.666}} = \underline{2700\text{kPa}}$$

For nitrogen

b)

$$T_o = 623 + \frac{(450)^2}{(2)(1039.9)} = \underline{720.4K}$$

$$p_o = (2500)\left(\frac{720.4}{623}\right)^{\frac{1.399}{0.399}} = \underline{4160kPa}$$

Steam is not an ideal gas, so the ideal processes are not applicable.

$$h_o = h_1 + \frac{v_1^2}{2}$$

At state 1, $h_1 = 3127.5\frac{kJ}{kg}$ $\quad s_1 = 6.8409kJ/kg\text{-}K$

$$h_o = \left(3127.5\frac{kJ}{kg}\right) + \frac{(450m/s^2)}{(2)(1000J/kJ)} = 228.75\ kJ/kg$$

The entropy remains constant. From the steam tables (using TK Solver) find for h_o and s_o.

c) $\quad T_o = \underline{402.6°C}$ $\qquad p_o = \underline{3559kPa}$

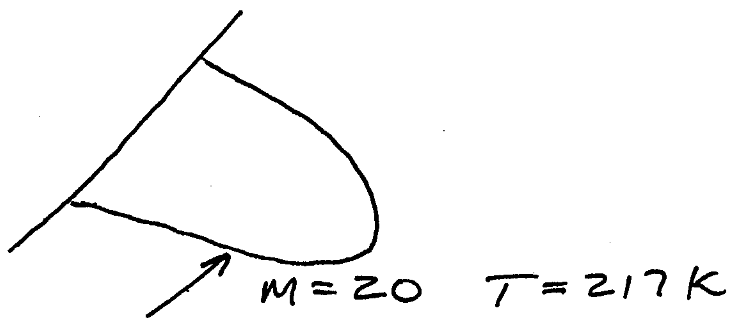
Problem 17.9

A hypersonic aircraft is designed to fly at Mach 20 at an elevation where the atmospheric temperature is 217°K. Determine the stagnation temperature on the leading edge of the aircraft's wing.

Given: An airfoil moves through air at a known temperature with a specified Mach number.

Find: The stagnation temperature.

Sketch and Given Data:



Assumptions: 1) Air is an ideal gas.

Analysis: Equation 17.24 relates Mach number and temperature.

$$\frac{T_o}{T} = 1 + \frac{k-1}{2} M^2$$

$$T_o = (217K)\left[1 + \frac{0.4}{2}(20)^2\right] = 17\ 577K$$

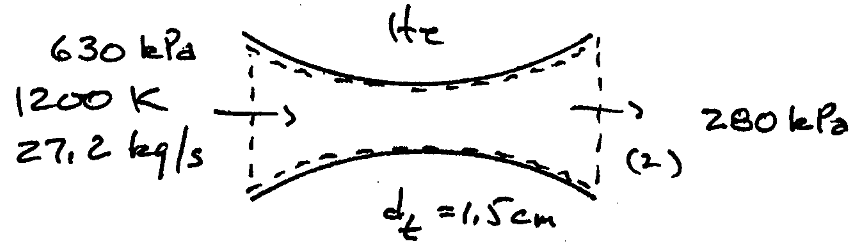
Problem 17.13

At 630 kPa and 1200°K, 27.2 kg/s of helium flows through the inlet nozzles of a gas turbine. The exit pressure is 280 kPa. the throat diameter of each circular nozzle is 1.5 cm. Determine (a) the critical pressure; (b) the minimum number of nozzles required; (c) the force on the nozzles.

Given: Helium flows through nozzles before entering the turbine blades. The inlet and exit states are known as in the nozzle diameter.

Find: The critical pressure, minimum number of nozzles required for the flow and the total force on the nozzle block.

Sketch and Given Data:



Assumptions:
1) Helium is an ideal gas
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: The critical pressure is:

a) $p^* = 0.487\, p_o = (0.487)(630) = \underline{306.8}\text{kPa}$

Find the pressure at the throat from Equation 17.32 or using the isentropic relationships.

$$T^* = \left(\frac{2}{k+1}\right) T_o = \left(\frac{2}{2.666}\right)^{(1200\ K)} = 900.2\ K$$

$$v^* = \frac{RT^*}{p^*} = \frac{(2.077\ kJ/kg\text{-}K)(900.2\ K)}{(306.8\ kN/m^2)} = 6.094\ m^3/kg$$

$$v^* = a^* = (kRT^*)^{½} = \left[(1.666)\left(2077\ \frac{J}{kg\text{-}K}\right)(900.2\ K)\right]^{½}$$

$$v^* = 1764.9\ m/s$$

The mass flow through each nozzle may be calculated.

$$A^* = \frac{\pi}{4}d^2 = \left(\frac{\pi}{4}\right)(0.015\dot{m})^2 = 0.0001767\ m^2$$

$$\dot{m} = \frac{A^*v^*}{v^*} = \frac{(0.0001767\ m^2)(1764.9\ m/s)}{(6.094\ m^3/kg)} = 0.05118\ kg/s$$

$$\dot{m}_{TOTAL} = N\dot{m}$$

$$(27.2\ kg/s) = (N\ nozzles)(0.05118\ kg/s\text{-}nozzle)$$

b) N = 531.5 or 532 nozzles

The exit temperature is

$$T_2 = T_o\left(\frac{p_2}{p_o}\right)^{\frac{k-1}{k}} = (1200\ K)\left(\frac{280}{630}\right)^{\frac{0.666}{1.666}} = 867.7\ K$$

$$v_2 = \sqrt{(2)(h_o - h_2)} = \sqrt{2c_p(T_o - T_2)}$$

$$v_2 = [(2)(5195.4\ J/kg\text{-}K)(1200-867.7\ K)]^{½} = 1858.2\ m/s$$

The force is found from Equation 17.11.

$$F = \dot{m}(v_2 - v_1) = \frac{(27.2\ kg/s)(1858.2 - 0\ m/s)}{(1000\ N/kN)}$$

c) F = 50.5kN

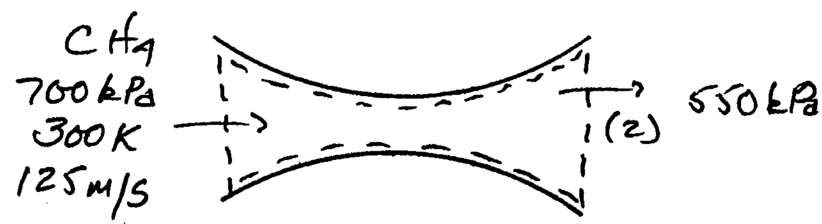
Problem 17.17

Methane flows through an ideal nozzle with the following inlet conditions: static pressure is 700 kPa, static temperature is 300°K, and velocity is 125 m/s. The nozzle discharges into a static pressure of 550 kPa. Determine (a) the exit static temperature; (b) the exit specific volume; (c) the exit velocity.

Given: Methane flows steadily through a nozzle from inlet to exit conditions.

Find: The exit static temperature, specific volume and velocity.

Sketch and Given Data:



Assumptions:
1) Methane is an ideal gas
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: The flow through the nozzle is isentropic.

a) $$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (300\ \text{K})\left(\frac{550}{700}\right)^{\frac{0.321}{1.321}} = \underline{282.9\ \text{K}}$$

b) $$v_2 = \frac{RT_2}{p_2} = \frac{(0.5183\ \text{kJ/kg-K})(282.9\ \text{K})}{(550\ \text{kN/m}^2)} = 0.2666\ \text{m}^3/\text{kg}$$

From a first law analysis on the nozzle.

$$h_1 + \frac{V_1^2}{2} = h_2 + \frac{V_2^2}{2} \text{ and } \Delta h = c_p\Delta T$$

$$\frac{V_2^2}{(2)(1000)} = \frac{(125\ \text{m/s})^2}{(2)(1000\ \text{J/kg})} + \left(2.1347\ \frac{\text{kJ}}{\text{kg-K}}\right)(300 - 282.9\ \text{K})$$

c) $V_2 = \underline{297.7\ \text{m/s}}$

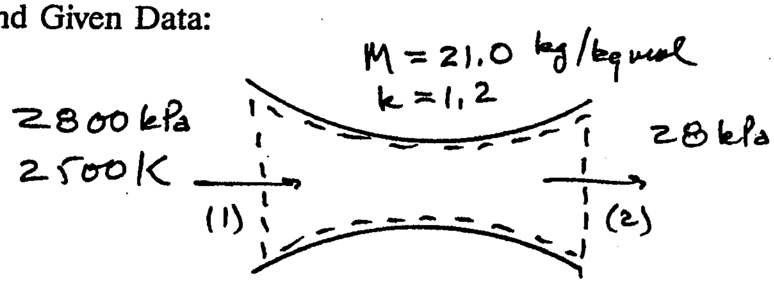
Problem 17.21

An ideal gas in a rocket has the following conditions: nozzle inlet chamber pressure = 2800 kPa, nozzle exit pressure = 28 kPa, k for the gas = 1.2, molecular weight = 21.0, nozzle inlet chamber temperature = 2500°K. Determine (a) the critical pressure ratio; (b) the velocity at the throat; (c) the exit temperature; (d) the exit velocity; (e) the ratio of exit area to throat area.

Given: The gas state entering a rocket nozzle is specified as is the exit state.

Find: The critical pressure ratio, the velocity at the throat, the exit temperature and velocity and the ratio of exit area to throat area.

Sketch and Given Data:



Assumptions:
1) The rocket gas is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: Determine the gas properties.

$$R=\frac{\bar{R}}{M}=\frac{\left(8.3143\frac{kJ}{kgmol-K}\right)}{(21.0kg/kgmol)}=0.3959\frac{kJ}{kg-K}$$

$$k=c_p/c_v=1.2 \quad R=c_p-c_v=0.3959kJ/kg-K$$

$$c_p=2.3754\frac{kJ}{kg-K} \quad c_v=1.9795kJ/kg-K$$

Assume the inlet state has negligible velocity, hence $p_o = p_1$. The critical pressure is:

a)

$$p^* = p_o\left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = (2800 \text{ kPa})\left(\frac{2}{2.2}\right)^{\frac{1.2}{0.2}} = \underline{1580 \text{ kPa}}$$

$$T^* = T_o\left(\frac{2}{k+1}\right) = (2500)\left(\frac{2}{2.2}\right) = 2273 \text{ K}$$

b)

$$v^* = a^* = (kRT)^{½} = \left[(1.2)\left(395.9 \frac{\text{J}}{\text{kg-K}}\right)(2273 \text{ K})\right]^{½} = \underline{1039.2 \text{ m/s}}$$

The exit state properties are:

c)

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (2500 \text{ K})\left(\frac{28}{2800}\right)^{\frac{0.2}{1.2}} = \underline{1160.4 \text{ K}}$$

$$v_2 = \sqrt{2(h_o - h_2)} = \sqrt{2c_p(T_o - T_2)}$$

$$v_2 = \left[(2)\left(2375.4 \frac{\text{J}}{\text{kg-K}}\right)(2500-1160.4 \text{ K})\right]^{½} = \underline{2522.7 \text{ m/s}}$$

d)

$$\frac{A_2}{A_1^*} = \frac{\dot{m}\upsilon_2/v_2}{\dot{m}\upsilon^*/v^*} = \frac{v^*\upsilon_2}{v_2\upsilon^*}$$

$$\upsilon^* = \frac{RT^*}{p^*} = \frac{(0.3959 \text{ kJ/kg-K})(2273 \text{ K})}{(1580 \text{ kN/m}^2)} = 0.5695 \text{ m}^3\text{/kg}$$

$$\upsilon_2 = \frac{RT_2}{p_2} = \frac{(0.3959)(1160.4)}{(28 \text{ kN/m}^2)} = 16.41 \text{ m}^3\text{/kg}$$

e)

$$\frac{A_2}{A^*} = \frac{(1039.2)(16.41)}{(2522.7)(0.5695)} = \underline{11.87}$$

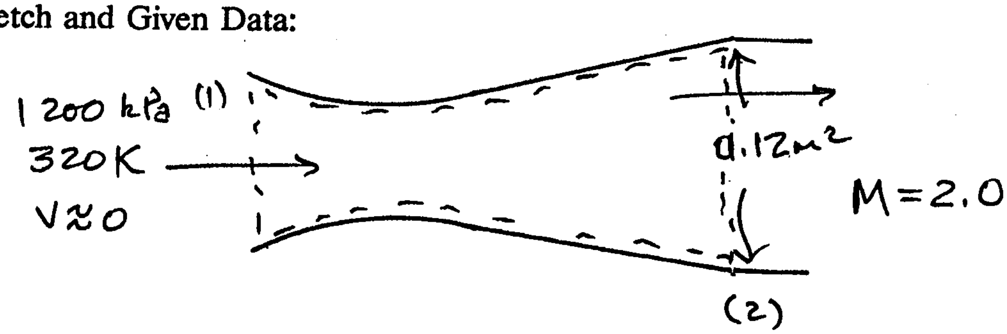
Problem 17.25

A supersonic wind tunnel is created by locating the test section at the exit of a convergent-divergent nozzle. The inlet air is at 1.2 MPa, 320°K, and negligible velocity. The test-seciton area is 0.12 m², and the desired Mach number is 2.0. (a) Determine the air pressure, temperature, and velocity. (b) Discuss the effect of moisture in the air.

Given: A convergent-divergent nozzle is used to create a supersonic wind tunnel. The inlet air state is specified as is the test section area and Mach number.

Find: The air's pressure, temperature and velocity entering the test section. Discuss the effect of moisture in the inlet air.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: Use the isentropic flow relationships (Table 17.2) for M = 2.0.

$$T/T_o = 0.55556 \quad p/p_o = 0.12780 \quad A/A^* = 1.6875$$

$$T_2 = (0.55556)(320K) = \underline{177.8K} = -95.2°C$$

$$p_2 = (0.1278)(1200kPa) = \underline{153.4kPa}$$

$$v_2 = \sqrt{2(h_o - h_2)} = \sqrt{2c_p(T_o - T_2)}$$

$$v_2 = [(2)(1004.7\ J/kg\text{-}K)(320 - 177.8)]^{1/2} = \underline{534.5\ m/s}$$

Comment: 1) Notice the low exit temperature, -95.2°C. Any moisture present would form ice crystals. The crystals can cause sticking of controls and erosion of test materials. Air used in wind tunnels must be dried for these reasons.

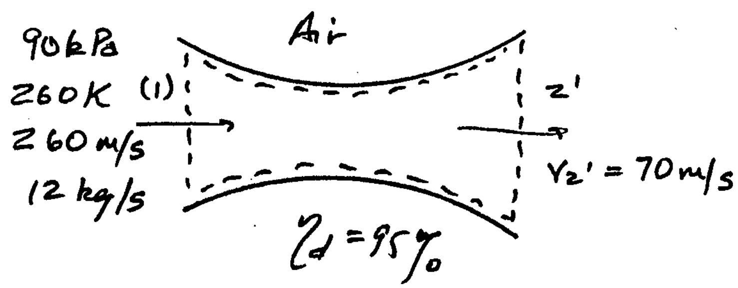
Problem 17.29

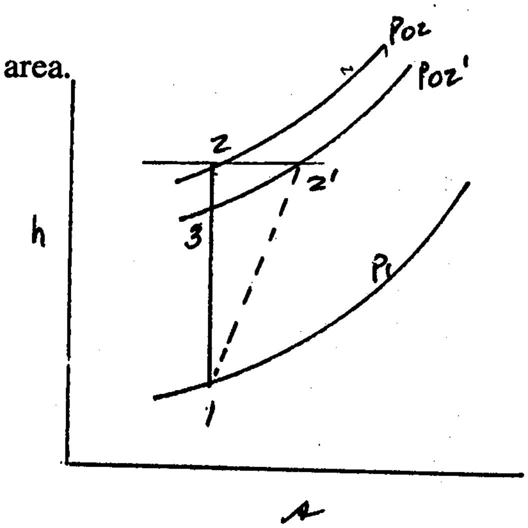
Air enters a diffuser at 90 kPa, 260°K, 260 m/s, and a flow rate of 12 kg/s. The diffuser efficiency is 95%. Determine the diffuser exit temperature, pressure, and area if the exit velocity is 70 m/s.

Given: Air enters a diffuser at known conditions. The diffuser efficiency is specified as is the exit velocity.

Find: The air exit temperature, pressure and area.

Sketch and Given Data:





Assumptions:
1) Air is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The diffuser is a steady, open system.

Analysis: The first law analysis of the yields:

$$ke_1 - ke_{2'} = h_{2'} - h_1$$

$$\frac{(260^2 - 70^2\ m^2/s^2)}{(2)(1000\ J/kJ)} = c_p(T_{2'} - T_1) = \left(1.0047\ \frac{kJ}{kg\text{-}K}\right)(T_{2'} - 260\ K)$$

$$T_{2'} = \underline{291.2\ K}$$

The diffuser efficiency allows one to find T_3.

$$\eta_d = \frac{(h_1 - h_3)_s}{(h_1 - h_{2'})} = \frac{(T_1 - T_3)_s}{(T_1 - T_{2'})}$$

$$0.95 = \frac{(260 - T_3)}{(260 - 291.2)} \qquad T_3 = 289.6\ K$$

Use the isentropic relationships to find $p_3 = p_{02'}$

$$p_3 = p_1\left(\frac{T_3}{T_1}\right)^{\frac{k}{k-1}} = (90\ \text{kPa})\left(\frac{289.6}{260}\right)^{\frac{1.4}{0.4}} = \underline{131.2\ \text{kPa}} = p_{02'}$$

$$v_{2'} = \frac{RT_{2'}}{p_{2'}} = \frac{(0.287\ \text{kJ/kg-K})(291.2\ \text{K})}{(131.2\ \text{kN/m}^2)} = 0.637\ \text{m}^3\text{/kg}$$

From the conservation of mass,

$$A = \frac{\dot{m}v}{V} = \frac{(12\ \text{kg/s})(0.637\ \text{m}^3\text{/kg})}{(70\ \text{m/s})} = \underline{0.1092\ \text{m}^2} = 1092\ \text{cm}^2$$

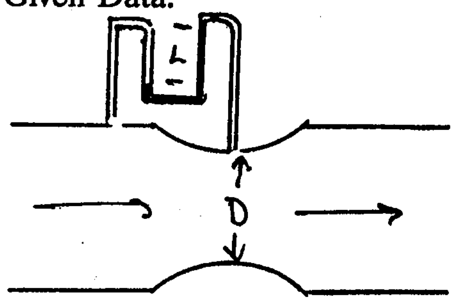
Problem 17.33

A venturi flow meter is used in a plant to measure water flowing through a 30-cm pipe. The throat diameter of the venturi is 23 cm, and the pressure drop is 15 cm of water. Determine the mass flow rate.

Given: A venturi meter is used to measure water flow. The area and pressure drop across the venturi are given.

Find: The mass flow of water.

Sketch and Given Data:



$L = 15 cm\ H_2O$

$D = 23 cm$

Assumptions:
1) Water is a pure substance.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The venture is an open system.

Analysis: Solve for the velocity at the venture throat from Equation 17.52a.

$$v_2 = [v_1^2 + 2\upsilon_1(p_2 - p_1)]^{½}$$

The velocities v_1 and v_2 may be related through the conservation of mass.

$$\dot{m} = \frac{A_1 v_1}{\upsilon_1} = \frac{A_2 v_2}{\upsilon_2} \qquad A = \pi/4D^2$$

$$\frac{D_1^2 v_1}{\upsilon_1} = \frac{D_2^2 v_2}{\upsilon_2} \qquad v_1 = v_2\left(\frac{D_2^2}{D_1^2}\right)\left(\frac{\upsilon_1}{\upsilon_2}\right)$$

The specific volume is constant. Thus:

$$v_1 = (v_2)\left(\frac{23^2}{30^2}\right) = 0.588v_2$$

$$p_2 - p_1 = \rho L g = (1000 \text{ kg/m}^3)(0.15 \text{ m})(9.8 \text{ m/s}^2) = 1470 \text{ N/m}^2$$

υ_1 = 0.001 m³/kg from the steam tables.

$$v_2 = [(0.588v_2)^2 + (2)(\upsilon_1)(\Delta p)]^{1/2}$$

$$v_2^2 = 0.3457v_2^2 + (2)(0.001 \text{ m}^3/\text{kg})(1470 \text{ N/m}^2)$$

$$v_2 = 2.12 \text{ m/s}$$

$$\dot{m} = \frac{(\pi/4)(0.23 \text{ m})^2(2.12 \text{ m/s})}{(0.001 \text{ m}^3/\text{kg})} = \underline{88.1 \text{ kg/s}}$$

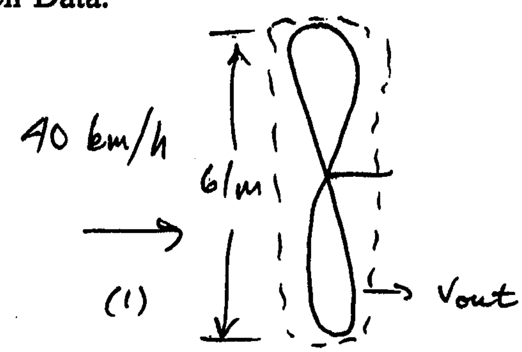
Problem 17.37

For the turbine in Problem 17.36 determine the velocity leaving the blades.

Given: The turbine specifications from Problem 17.36.

Find: The wind velocity leaving the turbine blades.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The heat transfer is zero.
3) Neglect changes in potential energy.
4) The turbine is a steady, open system.

Analysis: The mass flowrate was determined in Problem 17.36 to be 38345 kg/s. The power produced by the turbine is:

$$\dot{W} = \frac{(v_1^2 - v_4^2)Av\rho}{2} = \frac{\dot{m}}{2}(v_1^2 - v_{out}^2)$$

The initial velocity, v_1, is 40 km/h = 11.11 m/s.

$$2000\text{kW} = \frac{(38345\ \text{kg/s})}{2}\frac{(11.11^2 - v_{out}^2\text{m}^2/\text{s}^2)}{(1000\ \text{J/kJ})}$$

v_{out} = <u>4.37 m/s</u>

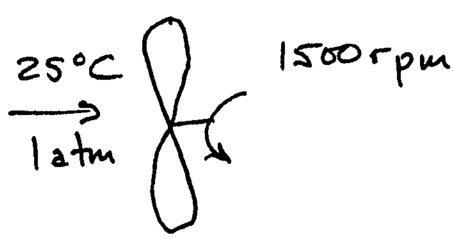
Problem 17.41

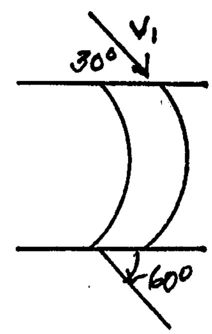
An axial-flow fan operates at 1500 rpm. The blade inlet and exit angles are 30° and 60°, respectively, and guide vanes give the flow entering the first stage an angle of 30°. The ratio of blade tip to hub diameter is 1.375, and the hub diameter is 0.8m. The air enters at 25°C and 1 atm and may be considered incompressible. Determine (a) the discharge velocity diagram; (b) the torque; (c) the power.

Given: An axial flow fan operates at a constant rpm. the blade angles are given as are the various diameters the air state.

Find: The discharge velocity diagram, the torque and the power.

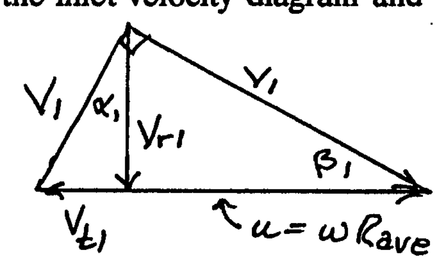
Sketch and Given Data:





Assumptions:
1) Air is an ideal gas.
2) Air may be considered incompressible so the density remains constant.
3) The heat transfer is zero.
4) Neglect changes in potential energy.
5) The fan is a steady, open system.

Analysis: Determine the inlet velocity diagram and then the discharge diagram.



The outside diameter is $D_o = (1.375)(0.8) = 1.1$

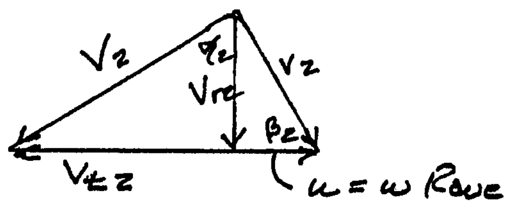
The blade speed u is:

$$u = \left(\frac{0.4 + 0.55}{2}\right)\left(\frac{1500(2\pi)}{60}\right) = 74.6 \text{ m/s}$$

$$\dot{m} = \rho_1 A_1 V_{r_1} = \rho_2 A_2 V_{r_2}$$

$$\rho_1 A_1 = \rho_2 A_2 \text{ (air is incompressible)}$$

$$\therefore V_{r_2} = V_{r_1}$$



$$u = V_{r_1}(\tan\alpha_1 + \cot\beta_1)$$

$$V_{r1} = \frac{u_1}{\tan\alpha_1 + \cot\beta_1} = \frac{(74.6 \text{ m/s})}{(\tan 30^\circ + \cot 30^\circ)} = 32.3 \text{ m/s}$$

$$V_1 = \frac{V_{r_1}}{\cos 30^\circ} = \frac{(32.3 \text{ m/s})}{(\cos 30^\circ)} = 37.3 \text{ m/s}$$

$$V_{t_1} = V_1 \sin 30^\circ = (37.3)\sin 30^\circ = 18.6 \text{ m/s}$$

$$\rho_1 = p_1/RT_1 = \frac{(101 \text{ kN/m}^2}{(0.287 \text{ kJ/kg-K})(298 \text{ K})} = 1.181 \text{ kg/m}^3$$

$$\dot{m} = \rho_1 A_1 V_{r_1}$$

$$A_1 = \pi/4(D_2^2 - D_1^2) = \pi/4(1.1^2 - 0.8^2 \text{m}^2) = 0.447 \text{ m}^2$$

$$\dot{m} = (1.181 \text{ kg/m}^3)(0.447 \text{ m}^2)(32.3 \text{ m/s}) = 17.07 \text{ kg/s}$$

$$\tan\alpha_2 = \frac{V_{t_2}}{V_{r_2}} = \frac{u - V_{r_1}\cot\beta_2}{V_{r_1}} = \frac{(74.6) - (32.3)\cot(60^\circ)}{32.3}$$

$$\alpha_2 = 60^\circ$$

$$\tan(60^\circ) = \frac{V_{t_2}}{32.3} \quad V_{t_2} = 55.9 \text{ m/s}$$

The fan work is:

$$e_p = u_2 V_{t_2} - u_1 V_{t_1} = \frac{(74.6 \text{ m/s})(55.9 - 18.6 \text{ m/s})}{(1000 \text{ J/kJ})} = 2.782 \frac{\text{kJ}}{\text{kg}}$$

The power is:

c) $$E = \dot{m} e_p = (17.07 \text{ kg/s})\left(2.782 \frac{\text{kJ}}{\text{kg}}\right) = \underline{47.5 \text{ kW}}$$

The torque is:

b) $$\tau = \frac{E}{\omega} = \frac{(47500 \text{ W})}{(1500)(2\pi)(60)} = \underline{302.4 \text{ Nm}}$$

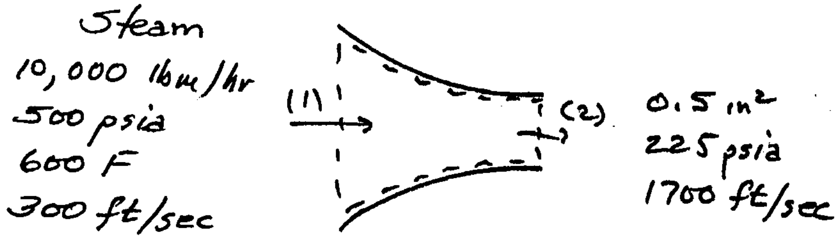
Problem *17.1

A convergent nozzle receives 10,000 lbm/hr of steam at 500 psia, 600°F, and 300 ft/sec and discharges it through an exit area of 0.5 in.^{2} at 225 psia and 1700 ft/sec. Determine the minimum force necessary to hold the nozzle in position.

Given: A convergent nozzle receives a known flowrate of steam at specified pressure, temperature and velocity. The nozzle exit area, pressure and velocity are known.

Find: The minimum force required to hold the nozzle stationary.

Sketch and Given Data:



Assumptions:
1) Steam is a pure substance
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: Assume the steam flows isentropically through the nozzle.
The inlet conditions are:

$$h_1 = 1298.8 \text{ Btu/lbm} \quad s_1 = 1.5588 \frac{\text{Btu}}{\text{lbm}} \quad v_1 = 1.1591 \text{ ft}^3\text{/lbm}$$

$$h_2 = 1220.1 \text{ Btu/lbm} \quad s_2 = s_1 \quad v_2 = 2.1526 \frac{\text{ft}^3}{\text{lbm}}$$

The mass flowrate is:

$$\dot{m} = \frac{A_2 v_2}{\upsilon_2} = \frac{(0.5\ in^2)(1700\ ft/sec)}{(144\ in^2/ft^2)(2.1526\ ft^3/lbm)} = 2.742\ \frac{lbm}{sec}$$

$$A_1 = \frac{\dot{m}\upsilon_1}{v_1} = \frac{(2.742\ lbm/sec)(1.1591\ ft^3/lbm)(144\ in^2/ft^2)}{(300\ ft/sec)}$$

$$A_1 = 1.52\ in^2$$

From Equation 17.11:

$$F = \frac{A_2 v_2^2}{g_c \upsilon_2} - \frac{A_1 v_1^2}{g_c \upsilon_1} = \frac{\dot{m}(v_2 - v_1)}{g_c}$$

$$F = \frac{(2.742\ lbm/sec)(1700\ -\ 300\ ft/sec)}{(32.174\ lbm\text{-}ft/lb_f\ -\ sec^2)} = \underline{119.3\ lb_f}$$

Problem *17.5

Determine the acoustic velocity of R12 at 150 psia and 120°F.

Given: The pressure and temperature of R12.

Find: The acoustic velocity.

Assumptions: 1) R12 is a pure substance.

Analysis: The ideal gas relationships cannot be used for R12. The acoustic velocity may be found from Equation 17.19.

$$a = \left(\frac{1}{\rho\beta_s}\right)^{½} \quad \text{where } \beta_s = -\frac{1}{v}\left(\frac{\partial v}{\partial p}\right)_s$$

Evaluate ρ and β_s from the R12 tables.

$$v_1 = 0.2800 \text{ ft}^3\text{/lbm} \quad s_1 = 0.16628 \frac{\text{Btu}}{\text{lbm-R}} \quad s_1 = \frac{1}{v_1} = 54.45 \frac{\text{kg}}{\text{m}^3}$$

$$p = 148 \text{ psia} \quad s = s_1 \quad v = 0.28381 \text{ ft}^3\text{/lbm}$$

$$p = 152 \text{ psia} \quad s = s_1 \quad v = 0.27637 \text{ ft}^3\text{/lbm}$$

$$\beta_s = -\left(\frac{1}{0.2800 \text{ ft}^3\text{/lbm}}\right)\left(\frac{0.27637 - 0.28581 \text{ ft}^3\text{/lbm}}{152 - 148 \text{ psia}}\right) = +0.006643\frac{1}{\text{psia}}$$

$$a = \left(\frac{v}{\beta_s}\right)^{½} = \left[\frac{(0.2800 \text{ ft}^3\text{/lbm})(144 \text{ in}^2\text{/ft}^2)\left(32.174 \dfrac{\text{lbm-ft}}{\text{lb}_f\text{-sec}^2}\right)}{(0.006643 \text{ in}^2\text{/lb}_f)}\right]^{½}$$

a = <u>441.9ft/sec</u>

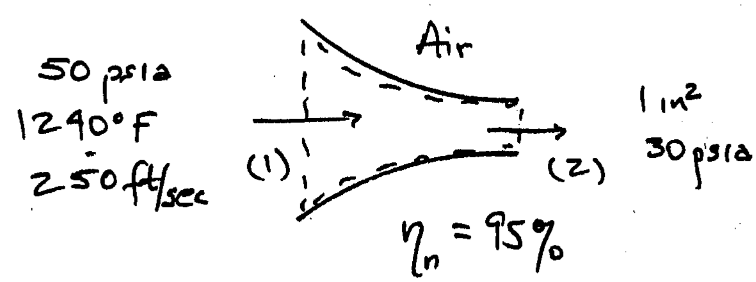
Problem *17.9

A nozzle has a minimum area of 1 in.^{2} and an efficiency of 95%. It receives air at 50 psia, 1240°F, and 250 ft/sec and discharges it at 30 psia. Determine (a) the flow rate; (b) the discharge stagnation enthalpy. (c) Sketch the nozzle shape.

Given: Air flows steadily through a nozzle. The minimum area efficiency are given as well as the inlet state and discharge pressure.

Find: The flow through the nozzle, the discharge stagnation enthalpy and the nozzle shape.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: Determine the air's inlet stagnation state. If p_{exit} is less than the critical pressure, then the nozzle is convergent-divergent. If p_{exit} is greater then p^* the nozzle is convergent.

$$h_o = h_1 + \frac{v^2}{2g_c j} \qquad T_o = T_1 + \frac{v_1^2}{2g_c j c_p}$$

$$T_o = (1700\ R) + \frac{(250\ ft/sec)^2}{(2)\left(32.179\ \frac{lbm\text{-}ft}{lb_f\text{-}sec^2}\right)\left(778.16\ \frac{ft\text{-}lb_f}{Btu}\right)\left(0.24\ \frac{Btu}{lbm\text{-}R}\right)}$$

$$T_o = 1705\ R$$

$$p_o = p_1\left(\frac{T_o}{T_1}\right)^{\frac{k}{k-1}} = (50\text{psia})\left(\frac{1705}{1700}\right)^{\frac{1.4}{0.4}} = 50.5\text{psia}$$

$$p^* = 0.528p_o = 26.67\text{psia}$$

c) Therefore the nozzle is convergent per the sketch shown. The isentropic discharge temperature is:

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} = (1700)\left(\frac{30}{40}\right)^{\frac{0.4}{1.4}} = 1469.1\ R$$

$$\eta_n = \frac{h_o - h_{2'}}{(h_o - h_2)_s} = \frac{T_o - T_{2'}}{T_o - T_2}$$

$$0.95 = \frac{1705 - T_{2'}}{1705 - 1469.1} \qquad T_{2'} = 1480.9\ R$$

$$v_{2'} = \frac{RT_{2'}}{p_2} = \frac{\left(53.34\ \frac{\text{ft-lb}_f}{\text{lbm-R}}\right)(1480.9\ R)}{(30\ \text{lb}_f/\text{in}^2)(144\ \text{in}^2/\text{ft}^2)} = 18.28\ \text{ft}^3/\text{lbm}$$

$$V_{2'} = 223.8\sqrt{h_o - h_{2'}} = (223.8)[(0.24)(1705 - 1480.9)]^{½} = 1641.3\text{ft/sec}$$

a) $$\dot{m} = \frac{A_2V_{2'}}{v_{2'}} = \frac{(1\ \text{in}^2)(1641.3\ \text{ft/sec})}{(144\ \text{in}^2/\text{ft}^2)(18.28\ \text{ft}^3/\text{lbm})} = \underline{0.624}\ \text{lbm/sec}$$

b) The stagnation enthalpy does not change across the nozzle. $h_o = c_pT_o$ = (0.24)(1705) = <u>409.2</u> Btu/lbm

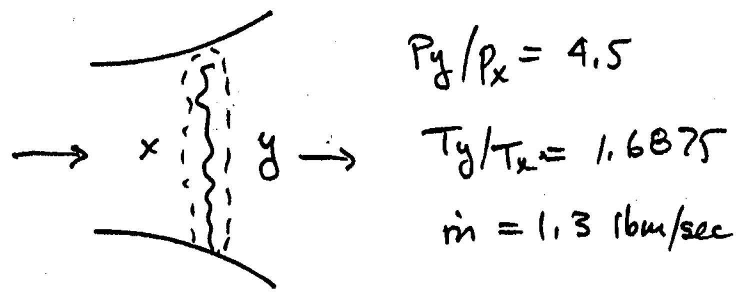
Problem *17.13

Compute the entropy production across the shock wave in Problem *17.12.

Given: The specifications from Problem *17.12.

Find: The entropy production across the shock wave.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.

Analysis: The change of specific entropy across the shock wave is:

$$s_2 - s_1 = s_y - s_x = c_p \ln\left(\frac{T_y}{T_x}\right) - R \ln\left(\frac{p_y}{p_x}\right)$$

$$s_2 - s_1 = (0.24 \text{ Btu/lbm-R})\ln(1.6875) - \frac{\left(53.34 \dfrac{\text{ft-lb}_f}{\text{lbm-R}}\right)}{(778.16 \text{ ft-lb}_f/\text{Btu})}\ln(4.5)$$

$$s_2 - s_1 = 0.0228 \text{ Btu/lbm-R}$$

$$\Delta\dot{S}_{prod} = \dot{m}(s_2 - s_1) = \left(1.3\frac{\text{lbm}}{\text{sec}}\right)\left(0.0228 \frac{\text{Btu}}{\text{lbm-R}}\right) = 0.0296 \frac{\text{Btu}}{\text{sec-R}}$$

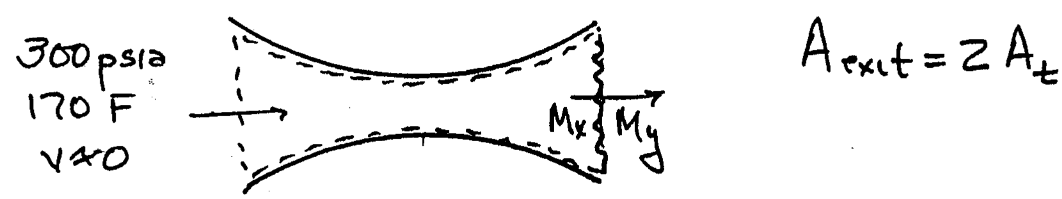
Problem *17.17

Air flows through a convergent-divergent nozzle with inlet conditions of 300 psia, 170°F, and negligible velocity. The exit area is twice the throat area. Determine the exit pressure such that a normal shock wave occurs at the exit plane.

Given: Air flows through a convergent-divergent nozzle from known inlet conditions. The exit area is twice the throat area. A normal shock wave occurs in the exit plane.

Find: The exit pressure.

Sketch and Given Data:



Assumptions:
1) Air is an ideal gas.
2) The heat and work are zero.
3) Neglect changes in potential energy.
4) The nozzle is a steady, open system.
5) The flow is isentropic to the shock wave.

Analysis: $A/A^* = 2.0$. This corresponds to $M = 2.2$ from Table 17.2a. Thus, the Mach number before the shock $M_x = 2.2$. From the normal shock relationships:

$$p_y/p_x = 5.48$$

From the isentropic relationships $p/p_o = 0.09352$

$$p_x = (0.09352)(300 \text{ psia}) = 28.05 \text{ psia}$$

$$p_y = (5.48)(28.05 \text{ psia}) = \underline{153.7 \text{ psia}}$$

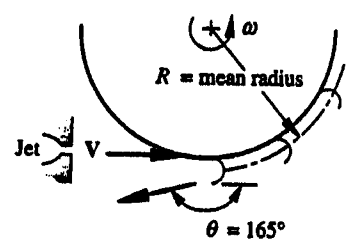
Problem *17.21

A Pelton wheel turbine is shown schematically below, where a jet of water strikes the buckets tangentially and the exit angle is 165°. Derive (a) an expression for the torque and power produced on the rotor; (b) the *u/V* ratio to produce the maximum power.

Given: A Pelton turbine receives a jet of water tangentially. The exit angle for the water is given.

Find: The expression for rotor torque and power and the u/V ratio for maximum power.

Sketch and Given Data:



Assumptions:

1) The turbine operates in a steady-state condition and is an open system.
2) Neglect changes in potential energy.
3) The heat transfer is zero.

Analysis: From Equation 17.74:

$$E = \dot{m}(\omega r_2 V_{t_2} - \omega r_1 V_{t_1})$$

$$\tau = \frac{E}{\omega} = \dot{m}(r_2 V_{t_2} - r_1 V_{t_1})$$

The blade speed, u, is:

$$u = R\omega$$

$$V_{t_1} = V - u \qquad V_{t_2} = (V - u)\cos\theta$$

$$r_1 = r_2 = R$$

The torque becomes:

$$\tau = \dot{m}R[(V-u)\cos\theta - (V - u)]$$

$$\underline{\tau = \dot{m}R(V - u)[1 - \cos\theta)]}$$

a)

$$E = \omega\tau = \dot{m}\omega R(V - u)(1 - \cos\theta)$$

a) $\underline{E = \dot{m}u(V - u)(1 - \cos\theta)}$

Take the derivative of E with respect to u.

$$\frac{dE}{du} = 0 = V - u - u$$

b) $\underline{\frac{u}{V} = \frac{1}{2}}$

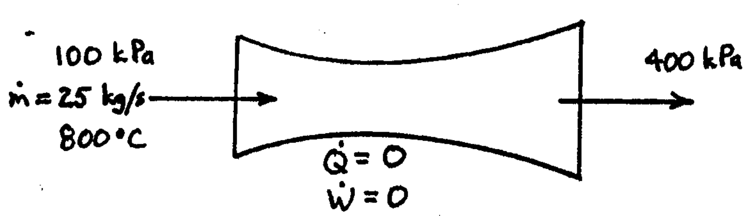
Problem C17.1

Develop TK Solver model, spreadsheet template, or computer program to design a nozzle with a circular cross section to isentropically expand a jet engine's exhaust from 110 kPa and 800°C to 40 kPa. Assume the gas k = 1.33 and R - 0.285 kJ/kg-K. The inlet velocity is negligible, and the flow rate is 25 kg/s. The output should be a table of nozzle area, nozzle diameter, temperature, velocity, Mach number, and pressure in 5-kPa increments.

Given: Isentropic expansion of jet engine exhaust from 110 kPa and 800°C to 40 kPa.

Find: Table of nozzle area, diameter, temperature, velocity, Mach number.

Sketch and Given Data:



Assumptions:
1) The exhaust behaves as an ideal gas.
2) The change in potential energy may be neglected.

Analysis: Using TK Solver, enter the following into the Rule Sheet.

```
============================ RULE SHEET ============================
S Rule--------------------------------------------------------------
* mdot=A*V/v                          "Continuity Equation
* P*v=R*T                             "Perfect Gas Law
* (V^2-V1^2)/(2*1000)=Cp*(T1-T)       "First Law
* T=T1*(P/P1)^((k-1)/k)               "Isentropic Process
* a=(k*1000*R*T)^.5                   "Speed of Sound
* M=V/a                               "Mach Number
* A=PI()*D^2/4
* k=Cp/Cv
* R=Cp-Cv
```

The edited Variable Sheet is.

```
═══════════════════ VARIABLE SHEET ═══════════════════════════════
St Input——— Name—— Output—— Unit——— Comment———————————————
                                      Problem C17.1

              Cp     1.1486   kJ/kg-K  Specific Heat - Pressure
              Cv     .86364   kJ/kg-K  Specific Heat - Volume
   .285       R               kJ/kg-K  Gas Constant
   1.33       k                        Specific Heat Ratio
   800        T1              degC     Inlet Temperature
   110        P1              kPa      Inlet Pressure
   0          V1              m/s      Inlet Velocity
   25         mdot            kg/s     Mass Flow
L             A      .20104   m2       Area
L             v      5.9489   m3/kg    Specific Volume
L  40         P               kPa      Pressure
L             T      834.94   degK     Temperature
L             V      739.76   m/s      Velocity
              a      562.57   m/s      Sonic Velocity
L             M      1.315             Mach Number
L             D      .50594   m        Nozzle Diameter
```

List Solving for pressure from 105 to 40 kPa and displaying the results as a Table.

PROBLEM C17.1

P	A	D	T	V	M
105	.42796	.73817	1060.8	168.2	.26525
100	.3111	.62937	1048.1	240.04	.38083
95	.26153	.57705	1034.8	296.76	.47383
90	.23359	.54536	1021	346.04	.55624
85	.21588	.52428	1006.6	390.86	.63276
80	.20407	.50973	991.62	432.78	.70591
75	.1961	.49969	975.87	472.74	.77729
70	.19093	.49305	959.3	511.41	.84809
65	.18796	.4892	941.82	549.26	.91928
60	.18687	.48779	923.3	586.72	.99176
55	.18755	.48867	903.58	624.13	1.0665
50	.19	.49185	882.47	661.85	1.1444
45	.19438	.49749	859.7	700.26	1.2267
40	.20104	.50594	834.94	739.76	1.315

Problem C17.5

The rotor energy transfer, e, for an ideal impulse turbine can be shown to be

$$e = \frac{2u\,(V_1 \cos \alpha - u)}{g_c}\ \text{ft-lb}_f$$

Using this relationship, develop a TK Solver model, spreadsheet template, or computer program to compute the ideal turbine efficiency. For nozzle angles (α) of 10° and 30°, and blade speeds (u) from 0 to approximately twice the optimum ($V_1 \cos \alpha$), compute the efficiency and plot it versus the blade speed/steam speed ratio (u/V_1).

Given: Ideal impulse turbine with nozzle angles of 10° and 30° operating under varying blade speeds.

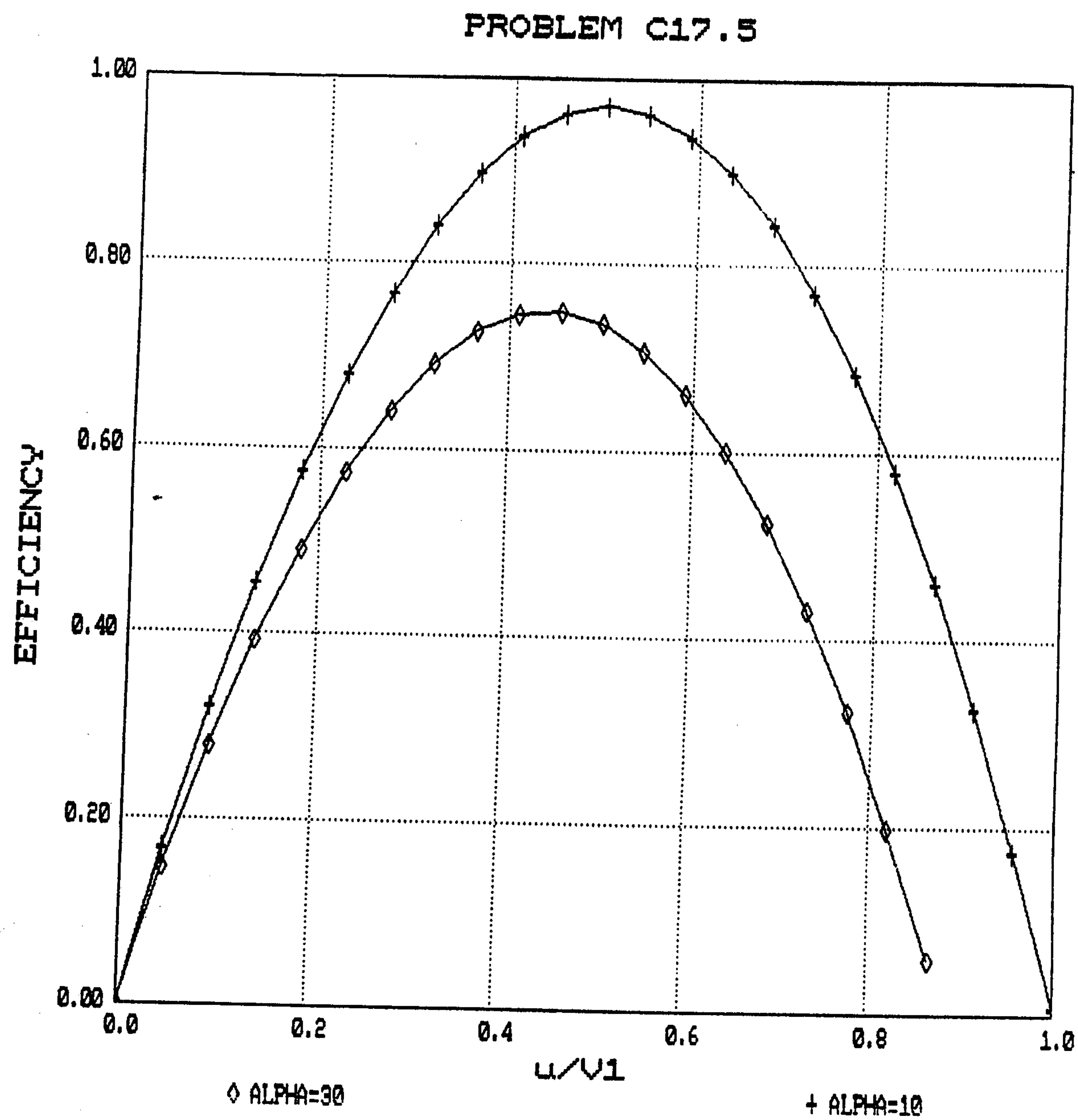
Find: Rotor energy transfer.

Assumptions:
1) The inlet and outlet blade angles are the same.
2) The blade friction is negligible.
3) The nozzle efficiency is 100%.

Analysis: Using a spreadsheet, calculate the nozzle exit velocity (V_1) for Δh = 100 Btu/lbm using equation 17.28b. Entering a range of blade speeds (u) from 0 to approximately the nozzle exit velocity, calculate u/V_1 and the rotor energy transfer (e). The ideal turbine efficiency is calculated from.

$$\text{Efficiency} = \frac{\text{rotor energy tranfer}}{\text{nozzle change in enthalpy}} = \frac{e}{\Delta h}$$

The spreadsheet results are calculated and plotted as follows.


PROBLEM C17.5
1.00
0.80
0.60
0.40
0.20
0.00
EFFICIENCY
0.0
0.2
0.4
0.6
0.8
1.0
u/V1
◊ ALPHA=30
+ ALPHA=10

CHAPTER EIGHTEEN

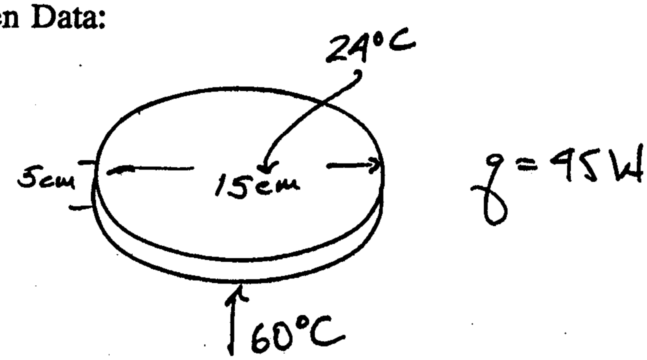
Problem 18.1

An experiment is undertaken to determine the thermal conductivity of an unknown material. The material is 5 cm thick and has a diameter of 15 cm. It is placed on a hot plate of equal diameter where the surface temperature is maintained at 60°C. The outer surface temperature is 24°C, and the power used by the hot plate is 45 W. Determine the thermal conductivity of the material.

Given: A piece of circular material has its surfaces maintained at constant temperatures while the heat transfer is measured.

Find: The material's thermal conductivity.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The properties are uniform.

Analysis: From Fourier's Law, Equation 18.2,

$$q_{\lambda} = \lambda A \frac{(T_h - T_c)}{L}$$

$$(45\ W) = \left(\lambda \frac{W}{m \cdot K}\right)\left(\frac{333-297\ K}{0.05\ m}\right)(\pi/4(0.15\ m)^2)$$

$$\lambda = \underline{3.54\ W/m \cdot K}$$

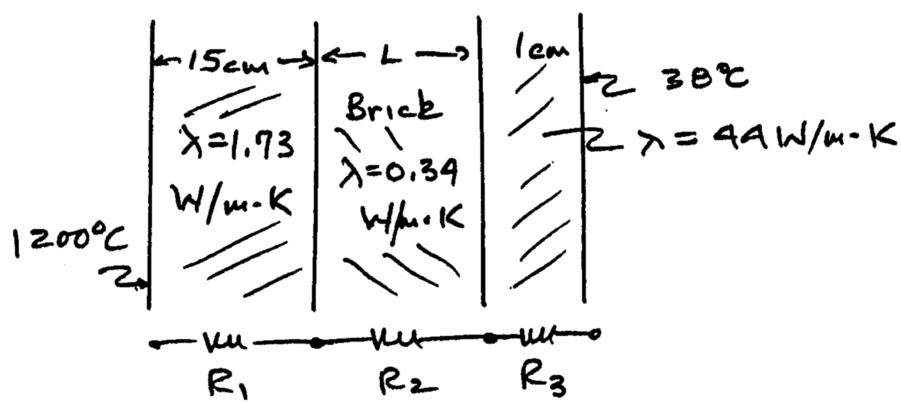
Problem 18.5

The surface of a furnace wall is at a temperature of 1200°C. The outside wall temperature is 38°C. The furnace wall construction has 15 cm of refractory material, λ = 1.73 W/m-K, and the outside wall is 1-cm steel, λ = 44 W/m-K. What thickness of refractory brick must be used between the refractory material and the wall if the heat loss is not to exceed 0.7 kW/m^2? The thermal conductivity of the brick is 0.34 W/m-K.

Given: A furnace wall is a composite of several materials. The thermal conductivity of each material as well as its thickness is known. The temperatures of the outer wall surfaces are specified.

Find: The refractory brick required to limit the heat loss to a specified value.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The properties of each material are uniform.

Analysis: The equation for combined heat transfer

$$q = \frac{\Delta T}{\Sigma R_i}$$

is used to find the unknown resistance.

$$R_1 = \frac{L_1}{\lambda_1} = \frac{(0.15\ \text{m})}{(1.73\ \text{W/m}\cdot\text{K})} = 0.0867\left(\frac{\text{m}^2\cdot\text{K}}{\text{W}}\right)$$

$$R_3 = \frac{L_3}{\lambda_3} = \frac{(0.01\ \text{m})}{(44\ \text{W/m}\cdot\text{K})} = 0.00023\left(\frac{\text{m}^2\cdot\text{K}}{\text{W}}\right)$$

$$700\ \frac{\text{W}}{\text{m}^2} = \frac{(1473\ -\ 311\ \text{K})}{(\sum R_i)\ \frac{\text{m}^2\ \cdot\ \text{K}}{\text{W}}}$$

$$\sum R_i = 1.66\ \frac{\text{m}^2\ \cdot\ \text{K}}{\text{W}} = R_1 + R_2 + R_3$$

$$0.0867 + R_2 + 0.00023 = 1.66$$

$$R_2 = 1.573\frac{\text{m}^2\cdot\text{K}}{\text{W}} = \frac{L_2}{\lambda_2} = \frac{(L_2\ \text{m})}{(0.34\ \text{W/m}\cdot\text{K})}$$

$$L_2 = 0.535\text{m} = 53.5\text{cm}$$

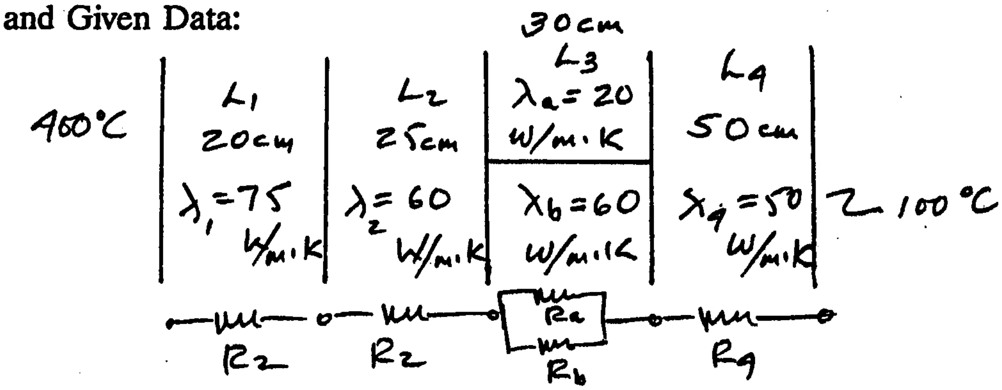
Problem 18.9

For the composite wall illustrated in Figure 18.5, the following values apply: L_1 = 20 cm, λ_1 = 75 W/m-K; L_2 = 25 cm, λ_2 = 60 W/m-K; L_3 = 30 cm, λ_a = 20 W/m-K, λ_b = 60 W/m-K; L_4 = 50 cm, λ_4 = 50 W/m-K. One surface is maintained at 400°C while the other is maintained at 100°C. Determine the heat flow and the temperature at the L_3/L_4 interface.

Given: The composite wall per Figure 18.5 with various lengths and thermal conductivities specified.

Find: The heat flow and the temperature at the L_3/L_4.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The properties of each material are uniform.

Analysis: Determine the resistances per unit area.

$$R_1 = \frac{L_1}{\lambda_1} = \frac{(0.20\ \text{m})}{(75\ \text{W/m-K})} = 0.00267\ \frac{\text{m}^2\text{-K}}{\text{W}}$$

$$R_2 = \frac{L_2}{\lambda_2} = \frac{0.25}{60} = 0.00417\ \frac{\text{m}^2\text{-K}}{\text{W}}$$

$$R_a = \frac{L_3}{\lambda_a} = \frac{0.30}{20} = 0.015\ \frac{\text{m}^2\text{-K}}{\text{W}}$$

$$R_b = \frac{L_3}{\lambda_b} = \frac{0.3}{60} = 0.005\ \frac{\text{m}^2\text{-K}}{\text{W}}$$

$$\frac{1}{R_3} = \frac{1}{R_a} + \frac{1}{R_b} = \frac{1}{0.015} + \frac{1}{0.005}$$

$$R_3 = 0.00375\ \frac{m^2\text{-}K}{W}$$

$$R_4 = \frac{L_4}{\lambda_4} = \frac{0.5}{50} = 0.01\ \frac{m^2\text{-}K}{W}$$

$$\Sigma R_i = 0.00267 + 0.00417 + 0.00375 + 0.01 = 0.0206\ \frac{m^2\text{-}K}{W}$$

$$q = \frac{\Delta T}{\Sigma R_i} = \frac{(673-373\ K)}{\left(0.0206\ \frac{m^2\text{-}K}{W}\right)} = \underline{14\ 563}\ \frac{W}{m^2}$$

$$q = \frac{T_1 - T_3}{R_1 + R_2 + R_3}$$

$$14\ 563 = \frac{(673 - T_3)}{(0.0106)}$$

$$T_3 = 518.6\ K = \underline{245.6\ C}$$

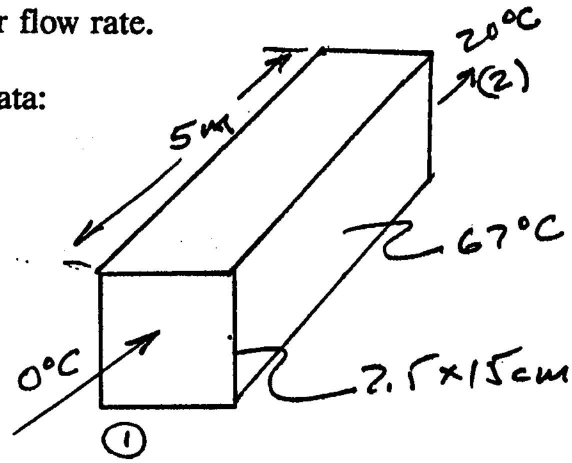
Problem 18.13

Air enters a heating duct with cross-sectional dimensions of 7.5 x 15 cm. The air enters the 5-m-long duct with a temperature of 0°C, and the duct surface is maintained at 67°C. If the air exit temperature is to be 20°C, what is the air flow rate?

Given: Air flows steadily through a constant temperature duct and increases in temperature. The temperatures and dimensions of the duct are specified.

Find: The air flow rate.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The heat transfer is by convection.

Analysis: The air properties are evaluated at the average air temperature of 10°C.

$$\mu = 17.85 \times 10^{-6} \frac{\text{N}\cdot\text{s}}{\text{m}^2} \qquad \nu = 14.8 \times 10^{-6} \text{ m}^2/\text{s}$$

$$P_r = 0.71$$

$$c_p = 1011 \text{ J/kg-K} \qquad \rho = 1.208 \text{ kg/m}^3$$

$$\lambda = 0.0244 \text{ W/m-K}$$

The hydraulic diameter for the duct is

$$D_H = \frac{2\,ab}{a+b} = \frac{(2)(7.5)(15)}{(7.5+15)} = 10 \text{ cm} = 0.1 \text{ m}$$

$$A = (7.5+7.5+15+15)(5)/100 = 2.25 \text{ m}^2$$

The heat transfer may be determined from the first law or by using the equation for convective heat flow.

$$q = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

$$q = \bar{h}A\ (T_s - T_{bulk})$$

The temperatures are known as is the area and specific heat. The mass flow is unknown as is the convective coefficient. However

$$\bar{h} = \frac{(N_u)(\lambda)}{D_H}$$

$$N_u = 0.027\ R_e^{0.8}\ P_r^{1/3} \left(\frac{\mu}{\mu_\rho}\right)^{0.14} \qquad A = (.075)(.15) = .0112\ m^2$$

$$R_e = \frac{v\rho D_H}{\mu} = \frac{\dot{m}D_H}{A\mu} = \frac{(\dot{m})(0.1)}{(.0112)(17.85\times10^{-6})} = (5.0\times10^5)\ \dot{m}$$

$$N_u = (0.027)(5\times10^5\ \dot{m})^{0.8}(0.71)^{1/3} \left(\frac{17.85}{20.1}\right)^{0.14} = 858.5(\dot{m})^{0.8}$$

$$\bar{h} = \frac{(858.5)(\dot{m})^{0.8}(0.0244)}{(0.1)} = 209.5(\dot{m})^{0.8}$$

$$(\dot{m}\ kg/s)(1011\ J/kg\text{-}K)(293-273\ K) = \left[(209.5)(\dot{m})^{0.8}\frac{W}{m^2\cdot K}\right](2.25\ m^2)(340-283\ K)$$

$$20\ 220\ \dot{m} = 26\ 868\ (\dot{m})^{0.8}$$

$$\dot{m} = 4.14\ kg/s$$

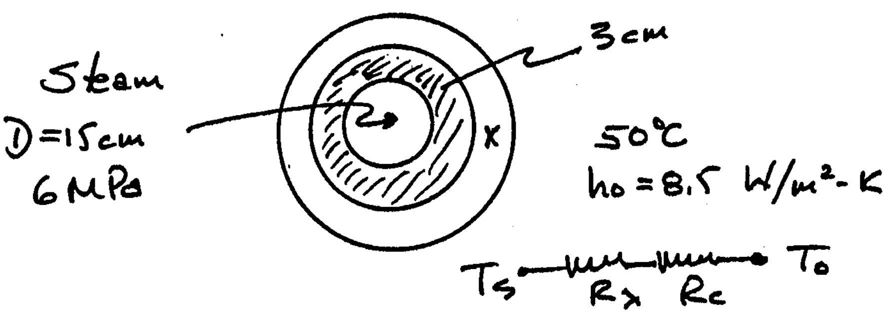
Problem 18.17

A 15-cm-diameter steam line carries saturated steam at 6 MPa and is located in a tunnel with stagnant air with a temperature of 50°C. The outside unit convective coefficient is 8.5 W/m²-K. The steam line is covered with 3 cm of 85% magnesia insulation. It is decided to reduce the heat loss by one-half. How much 85% magnesia insulation is required? Neglect thermal resistance of pipe and inside surface.

Given: A steam pipe is covered with a known amount of insulation. The steam pressure, outside temperature and outside convective coefficient are known.

Find: The additional insulation required to reduce the heat loss by 50%.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The inside surface temperature of the insulation is the saturated steam temperature at 6 MPa.

Analysis: The saturated steam temperature is 275.6°C.

Determine the original heat transfer through the 3 cm of insulation, $\lambda = 0.022$ W/m·K

$$R_\lambda = R_1 = \frac{\ln(d_2/d_1)}{Z\pi\lambda} = \frac{\ln\left(\frac{21}{15}\right)}{(2)(\pi)(0.022\,\text{W/m}\cdot\text{K})} = 2.434\frac{\text{m}\cdot\text{K}}{\text{W}}$$

$$R_c = R_2 = \frac{1}{h_c A} = \frac{1}{\pi d_2 h_c} = \frac{1}{(\pi)(0.21\ \text{m})(8.5\ \text{W/m}^2\text{-K})}$$

$$R_2 = 0.178\ \frac{\text{m}\cdot\text{K}}{\text{W}}$$

$$\Sigma R_j = 2.434 + 0.178 = 2.612$$

$$q = \frac{\Delta T}{\Sigma R_j} = \frac{(548.6-323\ K)}{\left(2.612\ \frac{m\cdot K}{W}\right)} = 86.4\ \frac{W}{m}$$

The new heat transfer is q = 86.4/2 = 43.2 W/m

$$\left(43.2\ \frac{W}{m}\right) = \frac{\Delta T}{\Sigma R_i} = \frac{(548.6-323)}{\Sigma R_i}$$

$$\Sigma R_i = 5.222\ \frac{m\cdot K}{W}$$

$$5.222 = \frac{\ln(d_2/15)}{2\pi(0.022)} + \frac{1}{(\pi)(8.5)(d_2)}$$

Solve for d_2 by trial and error

$$d_2 = 0.304\ m = 30.4\ cm$$

The total insulation required is (30.4 - 15)/2 = 7.7 cm. Of this 3.0 cm was in place, thus 4.7 cm must be added.

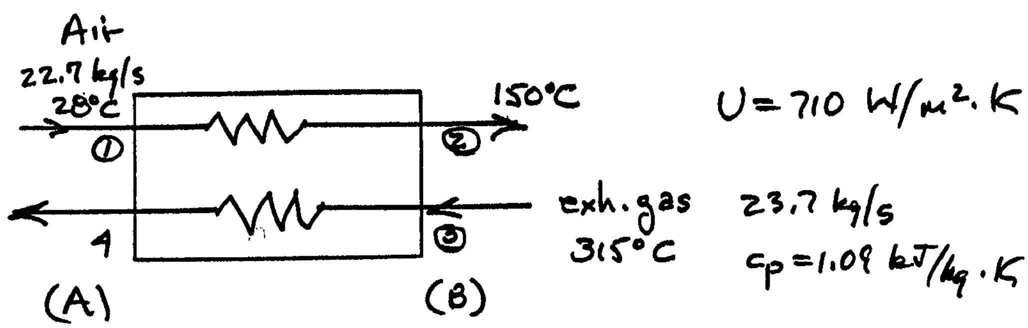
Problem 18.21

A 22.7-kg/s flow of air enters a preheater at 28°C and leaves at 150°C; 23.7 kg/s of exhaust gases, c_p = 1.09 kJ/kg-K, enters at 315°C. The overall coefficient of heat transfer is 710 W/m²-K. Determine (a) the exit exhaust gas temperature; (b) the surface area for parallel flow; (c) the surface area for counterflow; (d) the LMTD.

Given: Air is preheated by exhaust gases. The air and gas flowrates, specific heats and temperatures are given as well as the overall coefficient of heat transfer.

Find: The exhaust gas exit temperature, the LMTD and the surface areas required for parallel and counter flow.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) No heat loss to surroundings

Analysis: Determine the heat transferred from a first law analysis of the air's control volume which yields

$$\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

$$\dot{Q} = (22.7 \text{ kg/s})(1.0047 \text{ kJ/kg-K})(423-301 \text{ K}) = 2782 \text{ kW}$$

The first applied to the gas's control yields

$$\dot{Q} = \dot{m}(h_4 - h_3) = \dot{m}c_p(T_4 - T_3)$$

$$(-2782 \text{ kW}) = (23.7 \text{ kg/s})(1.09 \text{ kJ/kg-K})(T_4 - 588 \text{ K})$$

(a) T_4 = 480.3K = <u>207.3C</u>

For counterflow

$$\Delta T_A = (480.3 - 301) = 179.3$$

$\Delta T_B = (588 - 423) = 165$

(d) $$\text{LMTD} = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{179.3-165}{\ln\left(\frac{179.3}{165}\right)} = \underline{172°K}$$

(c) $$A = \frac{\dot{Q}}{(U)(\text{LMTD})} = \frac{(2782\ \text{kW})}{(0.710\ \text{kW/m}^2\text{-K})(172\text{K})} = \underline{22.78\ \text{m}^2}$$

For parallel flow

28°C ——————————— >150°C

315°C ——————————— >207.3°C

(A) (B)

$\Delta T_A = (588 - 301) = 287$

$\Delta T_B = (480.3 - 423) = 57.3$

(d)

$$\text{LMTD} = \frac{(287-57.3)}{\ln\left(\frac{287}{57.3}\right)} = \underline{142.6°K}$$

$$A = \frac{(2782)}{(0.710)(142.6)} = \underline{27.48\ \text{m}^2}$$

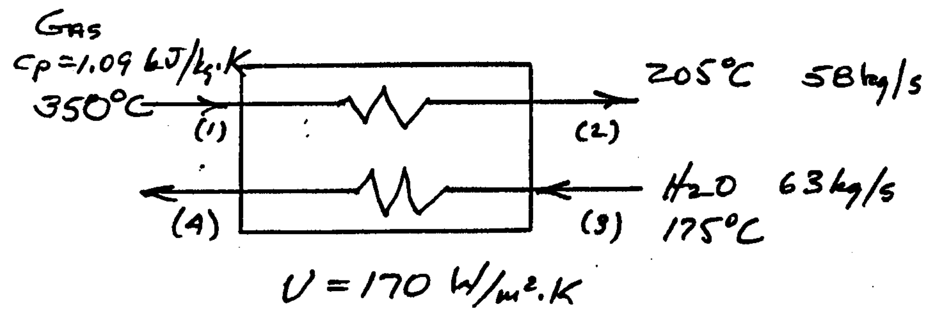
Problem 18.25

A one-shell-pass, six-tube-pass heat exchanger is used as an economizer on a steam generator. The flue gas, c_p = 1.09 kJ/kg-K, enters at 350°C and leaves at 205°C with a flow rate of 58.0 kg/s. The feedwater enters at 175°C with a flow rate of 63 kg/s. A change of operating conditions occurs; the water flow is now 25.2 kg/s, entering at 138°C. The new gas flow rate is 23.8 kg/s, but the gas temperature remains the same. Determine (a) the old surface area required if U - 170 W/m²-K; (b) the effectiveness; (c) the new water outlet temperature.

Given: Water is heated in an economizer by hot flue gases. The gas temperatures and flowrate are given as is the water flow and inlet temperature. Operating conditions change resulting in new flowrates. The overall coefficient of heat transfer is specified.

Find: The surface area of the heat exchanger, its effectiveness and the new outlet temperature of the water.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The heat exchanger is adiabatic
3) U remains constant
4) The flue gas is an ideal gas

Analysis: Determine the heat transferred from a first law analysis of the flue gas's control volume.

$$\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$
$$\dot{Q} = (58\ \text{kg/s})(1.09\ \text{kJ/kg-K})(478 - 623\ \text{K}) = -9167\ \text{kW}$$

Determine the water's outlet temperature

$\dot{Q} = \dot{m}(h_4 - h_3) \qquad h_3 = h_f@175°C = 741.0 \text{ kJ/kg}$

$(9167 \text{ kW}) = (63 \text{ kg/s})(h_4 - 741.0 \text{ kJ/kg})$

$h_4 = 886.5 \qquad T_4 = 207.5°C$

$\Delta T_A = (623 - 480.5) = 142.5°K \qquad \Delta T_B = (478 - 448) = 30°K$

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{142.5 - 30}{\ln\left(\frac{142.5}{30}\right)} = 72.2°K$$

$$P = \frac{480.5 - 448}{623 - 448} = 0.185$$

$$Z = \frac{623 - 478}{480.5 - 448} = 4.5$$

From Figure 18.13 F = 1, therefore $\overline{\Delta T}$ = LMTD

$$\dot{Q} = UA\,\overline{\Delta T}$$

(a) $$A = \frac{(9167 \text{ kW})}{(0.17 \text{ kW/m}^2\text{-K})(72.2 \text{ K})} = \underline{746.9 \text{ m}^2}$$

Determine the effectiveness

$$C_h = \dot{m}c_p = (58 \text{ kg/s})(1.09 \text{ kJ/kg-K}) = 63.22 \text{ kW/K}$$

From table A.23, the average specific heat of water is 4.5 kJ/kg-K.

$$C_c = \dot{m}c_p = (63)(4.5) = 283.5 \text{ kW/K}$$

$$\frac{C_{min}}{C_{max}} = \frac{63.22}{283.5} = 0.22$$

$$\frac{UA}{C_{min}} = \frac{(0.17 \frac{\text{kW}}{\text{m}^2\text{-K}})(746.9 \text{ m}^2)}{(63.22 \text{ kW/K})} = 2.0$$

(b) From Figure 18.8, $\epsilon = \underline{0.80}$

Apply Equation 18.51 to determine the new outlet water temperature

$$\epsilon C_{min}(T_{h_{in}} - T_{c_{in}}) = C_c(T_{c_{out}} - T_{c_{in}})$$

$$(0.80)(23.8\ \text{kg/s})\left(1.09\ \frac{\text{kJ}}{\text{kg-K}}\right)(623-411\ \text{K}) = (25.2\ \text{kg/s})\left(4.36\ \frac{\text{kJ}}{\text{kg-K}}\right)(T_{c_{out}} - 411\ \text{K})$$

(c) $T_{c_{out}}$ = 451.0°K = <u>178°C</u>

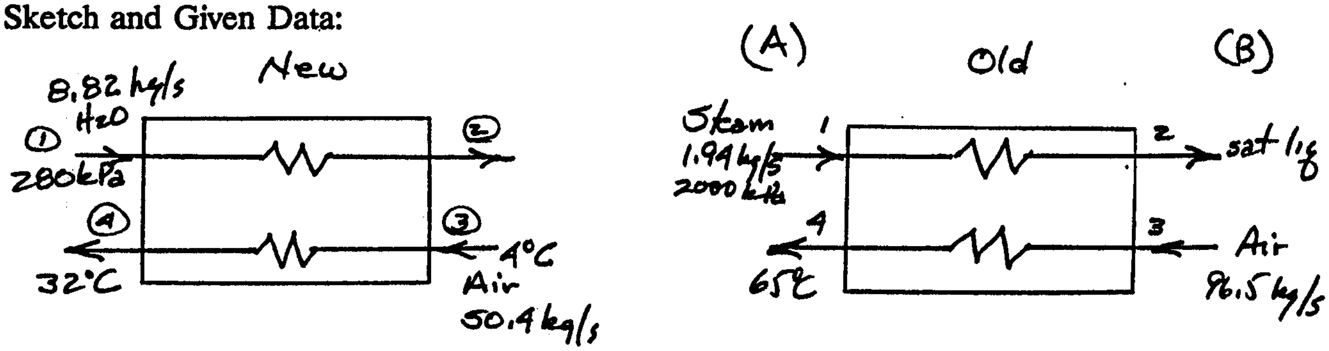
Problem 18.29

A new plant process requires 50.4 kg/s of air to be heated from 4°C to 32°C. Saturated water at 280 kPa is available for heating the air and has a supply capacity of 8.82 kg/s. An old heat exchanger is suggested for use in the new process. Records show the following: dry saturated steam flow with no subcooling, 1.94 kg/s at 2000 kPa; airflow, 96.5 kg/s, exiting at 65°C. Determine (a) the original LMTD; (b) the effectiveness; (c) whether the heat exchanger can be used in the new process.

Given: A heat exchanger is required to heat air between certain temperatures using water as a heat source. An old heat exchanger is available as well as the operating data for a different set of circumstances.

Find: The original LMTD and effectiveness of the heat exchanger. Determine whether or not it can be used in the new application.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The effectiveness remains constant.

Analysis: For the old heat exchanger, find the heat transferred by a first law analysis.

$$\dot{Q} = \dot{m}(h_2 - h_1) = (1.94 \text{ kg/s})(909.0 - 27.99 \text{ kJ/kg}) = -3667.8 \text{ kW}$$

The enthalpy values were found from the steam table. The temperature of the steam is 212.4°C. Determine the air's inlet temperature and from a first law analysis of the air's control volume.

$$\dot{Q} = \dot{m}(h_4 - h_3) = \dot{m}c_p(T_4 - T_3)$$

$$(3667.8 \text{ kW}) = (96.5 \text{ kg/s})(1.0047 \text{ kJ/kg-K})(338 - T_3 \text{ K})$$

$$T_3 = 300.2 \text{ K} = 27.2°\text{C}$$

$$\Delta T_A = (485.4 - 338 \text{ K}) = 147.4 \text{ K}$$

$$\Delta T_B = (485.4 - 300.2) = 185.2 \text{ K}$$

(a) $$\text{LMTD} = \frac{\Delta T_A - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{(147.4 - 185.2)}{\ln\left(\frac{147.4}{185.2}\right)} = \underline{165.6°K}$$

The effectiveness must be determined from its definition as it uses the latest heat of steam.

$$\epsilon = \frac{\text{actual heat transfer}}{\text{maximum possible heat transfer}} = \frac{h_1 - h_2}{h_1 - h_0}$$

where $h_0 = h_f$ @ $T_{\text{air in}} = h_f$ @ 27.2°C = 113.2 kJ/kg

(b) $$\epsilon = \frac{2799.6 - 909.0}{2799.6 - 113.2} = \underline{0.704}$$

For the new operating conditions, the heat transferred, as determined by a first law analysis of the air's control volume, is

$$\dot{Q} = \dot{m}(h_4 - h_3) = \dot{m}c_p(T_4 - T_3)$$

$$\dot{Q} = (50.4)(1.0047)(305 - 277 \text{ K}) = 1417.8 \text{ kW}$$

From the water's control volume

$$\dot{Q} = \dot{m}(h_2 - h_1) \qquad h_1 = h_f@280 \text{ kPa} = 551.3 \text{ kJ/kg}$$

$$(-1417.8) = (8.82)(h_2 - 551.3) \qquad T_1 = 131.2°C$$

$$h_2 = 390.5 \text{ kJ/kg} \qquad T_2 = 93.1°C$$

The temperature, T_2, is high enough so heat transfer can occur.

$$C_{air} = \dot{m}c_p = (50.4 \text{ kg/s})(1.0047 \text{ kJ/kg}\cdot\text{K}) = 50.64 \frac{\text{kW}}{\text{K}}$$

$$C_{water} = \dot{m}c_p = (8.82)(4.21) = 37.13 \frac{\text{kW}}{\text{K}}$$

From Equation 18.51

$$\epsilon C_{min}(T_{h_{in}} - T_{C_{in}}) = C_c(T_{c_{out}} - T_{c_{in}})$$

$$(0.704)\left(37.14\ \frac{kW}{K}\right)(404.2 - 277\ K) = \left(50.64\ \frac{kW}{K}\right)(T_{c_{out}} - 277\ K)$$

$$T_{c_{out}} = 342.7\ K = 69.7°C$$

(c) The heat exchanger may be used as the calculated outlet temperature can exceed that required by the operation.

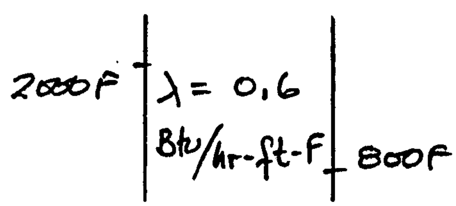
Problem *18.1

A boiler furnace wall must have a heat loss no greater than 700 Btu/hr-ft^2 and is made of a material with a thermal conductivity of 0.60 Btu/hr-ft-F. The inner wall surface temperature is 2000°F, and the outer surface temperature is 800°F. What wall thickness is required?

Given: A furnace wall of given thermal conductivity and surface temperatures must conduct no more than a specified amount of heat.

Find: The minimum wall thickness to satisfy the requirement.

Sketch and Given Data:



$q = 700 \frac{Btu}{hr\text{-}ft^2}$

Assumptions:
1) Steady-state conditions exist.
2) The material properties are uniform.

Analysis: From Fourier's law

$$q = \lambda A \frac{\Delta T}{\Delta X}$$

$$q/A = 700 \frac{Btu}{hr\text{-}ft^2} = \frac{(0.6 \text{ Btu/hr-ft-R})(2460 - 1260 \text{ R})}{(L \text{ ft})}$$

$L = \underline{1.028 \text{ ft}}$

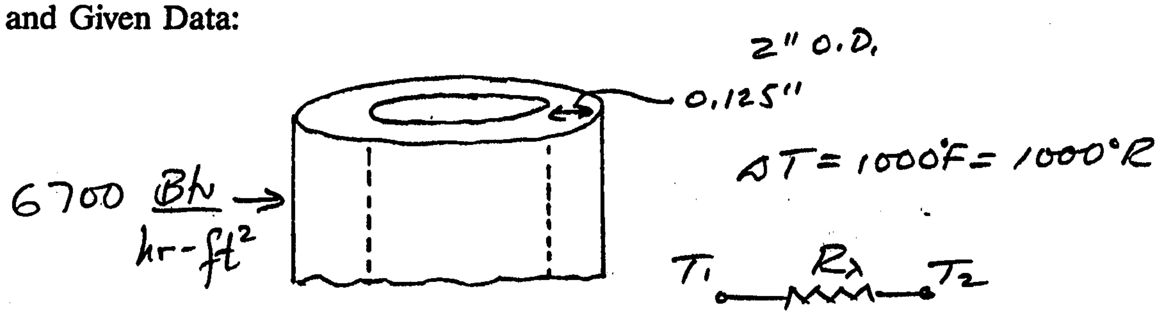
Problem *18.5

Steam-generating tubes in a boiler have a 2-in.-O.D. and a 0.125-in. thickness. The boiling water within the tube receives 6700 Btu/hr-ft² when the overall temperature drop is 1000°F. Determine the percentage of temperature decrease in the metal tube.

Given: Tubes of known dimensions receive a specified heat flux across for an imposed temperature gradient.

Find: The temperature drop across the tube expressed as a percent.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The material properties are uniform.

Analysis: The thermal conductivity of steel is $25 \frac{\text{Btu}}{\text{hr-ft-R}}$. The heat flux is expressed per ft² of surface area. Determine of tube required, noting the surface area is based on the outside diameter.

$$A = \pi d L$$

$$(1 \text{ft}^2) = (\pi)(2/12 \text{ ft})(L \text{ ft})$$

$$L = 1.91 \text{ ft}$$

$$R = \frac{\ln(d_2/d_1)}{2\pi\lambda L} = \frac{\ln\left(\frac{2.0}{1.75}\right)}{(2\pi)(25 \text{ Btu/hr-ft-R})(1.91 \text{ ft})}$$

$$R = 0.000445 \ \frac{\text{hr-R}}{\text{Btu}}$$

$$q = 6700 = \frac{\Delta T}{0.000445}$$

$$\Delta T = 2.98R$$

Of the 1000°R drop, 3°R occurs across the metal tube.

$$\% \text{ drop} = \frac{3}{1000} = \underline{0.3\%}$$

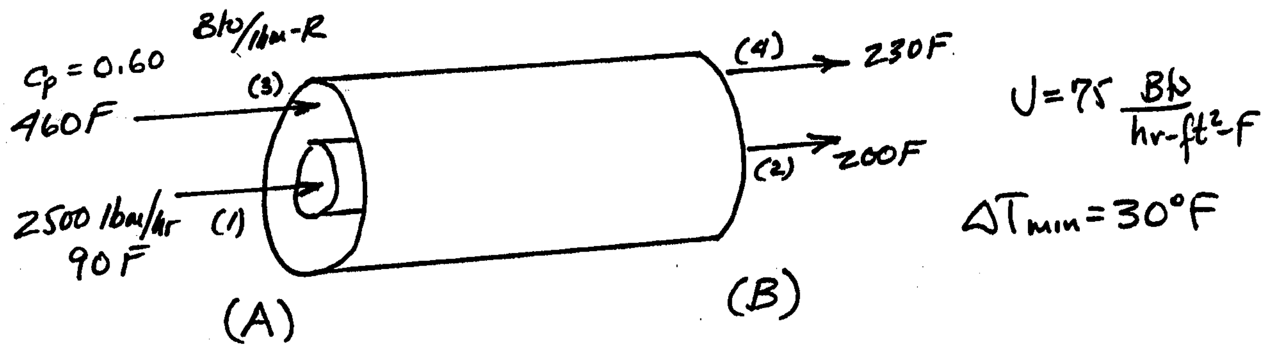
Problem *18.9

Crude oil, c_p = 0.56 Btu/lbm-R, flows at the rate of 2500 lbm/hr through the inside of a concentric, double-pipe heat exchanger and is heated from 90°F to 200°F. Another hydrocarbon, c_p = 0.60 Btu/lbm-R, enters at 460°F. The overall coefficient of heat transfer is found to be 75 Btu/hr-ft²-F. Determine for a minimum temperature difference of 30°F between the fluids (a) the LMTD for parallel flow and counterflow; (b) the surface area for parallel flow and counterflow.

Given: A double-pipe heat exchanger is used to transfer heat between two hydrocarbon fluids. The properties of each are given as is the overall coefficient of heat transfer. A minimum temperature difference is specified and the same for parallel and counterflow configurations.

Find: The LMTD and surface area for each configuration.

Sketch and Given Data:



Assumptions:
1) Steady-state conditions exist.
2) The heat exchanger is adiabatic

Analysis: Determine the oil flow rate for parallel flow. The heat transferred is

$$\dot{Q} = \dot{m}(h_2 - h_1) = \dot{m}c_p(T_2 - T_1)$$

$$\dot{Q} = \left(2500\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.56\ \frac{\text{Btu}}{\text{lbm-R}}\right)(660 - 550\ \text{R}) = 1.54\times10^5\ \frac{\text{Btu}}{\text{hr}}$$

Analysis of the hydrocarbon's control volume yields

$$\dot{Q} = \dot{m}(h_4 - h_3) = \dot{m}c_p(T_4 - T_3)$$

$$\left(-1.54\times10^5\ \frac{\text{Btu}}{\text{hr}}\right) = \left(\dot{m}\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.6\ \frac{\text{Btu}}{\text{lbm-R}}\right)(690 - 920\ \text{R})$$

$$\dot{m} = 1115.9\ \text{lbm/hr}$$

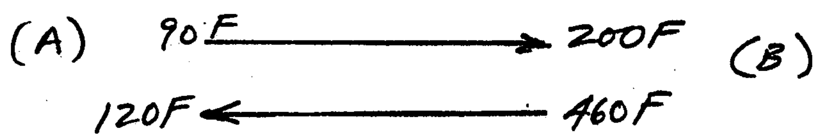
$$\Delta T_A = (920 - 550\ R) = 370\ R$$

$$\Delta T_B = (690 - 660\ R) = 30\ R$$

$$LMTD = \frac{\Delta T_a - \Delta T_B}{\ln\left(\frac{\Delta T_A}{\Delta T_B}\right)} = \frac{(370 - 30)}{\ln\left(\frac{370}{30}\right)} = \underline{135.3\ R}$$

$$A = \frac{\dot{Q}}{(U)(LMTD)} = \frac{(1.54\times10^5\ Btu/hr)}{\left(75\ \frac{Btu}{hr\text{-}ft^2\text{-}R}\right)(135.3\ R)} = \underline{15.18\ ft^2}$$

For counter flow the temperatures are



$$\Delta T_A = 30\ R$$

$$\Delta T_B = 260\ R$$

$$LMTD = \frac{(30 - 260)}{\ln\left(\frac{30}{260}\right)} = \underline{106.5\ R}$$

$$A = \frac{(1.54 \times 10^5)}{(75)(106.5)} = \underline{19.28\ ft^2}$$

Problem C18.1

Develop a TK Solver model, spreadsheet template, or computer program to calculate the heat transmitted from an insulated cylinder using equation 18.34. For three different combinations of h_0 and Γ, compute the heat transmitted for a range of radii smaller and larger than the critical radius. Plot q versus r_0.

Given: Heat transmitted from cylinder with radii smaller and larger than the critical radius.

Find: Heat transferred versus cylinder radius.

Assumptions:
1) Neglect heat transfer by radiation.
2) The inside and outside temperatures are constant.

Analysis: Using TK Solver, enter equations 18.34 and 18.35 into the Rule Sheet. Input assumed values for thermal conductivity, length, inside and outside temperatures, inside radius, and convective coefficient.

VARIABLE SHEET

St	Input	Name	Output	Unit	Comment
					Problem C18.1
L		q	43.445632	W	Heat Transfer
L	.5	lambda		W/m-K	Thermal Conductivity
	1	l		m	Length
	100	Ti		degK	Inside Temperature
	25	To		degK	Outside Temperature
L	.2	ro		m	Outside Radius
	.001	ri		m	Inside Radius
L	20	ho		W/m2-K	Outside Convective Coefficient
L		roc	.025	m	Critical Radius

RULE SHEET

```
S Rule
* q=2*PI()*lambda*l*(Ti-To)/(LN(ro/ri)+(lambda/(ho*ro)))
* roc=lambda/ho
```

List Solving for three values of convective coefficient and for a range of outside radii and plotting the results.