CHAPTER 2

The correspondence between the problem set in this fifth edition versus the problem set in the 4'th edition text. Problems that are new are marked new and those that are only slightly altered are marked as modified (mod).

New	Old	New	Old	New	Old
1	4 mod	21	13	41E	33E mod
2	new	22	14	42E	34E mod
3	new	23	15	43E	35E
4	7 mod	24	17	44E	36E
5	2 mod	25	18	45E	37E
6	new	26	new	46E	38E
7	new	27	19	47E	39E
8	new	28	20	48E	40E
9	5 mod	29	21	49E	41E
10	6	30	22		
11	8 mod	31	23		
12	new	32	24		
13	9 mod	33	new		
14	10 mod	34	25 mod		
15	11	35	26 mod		
16	new	36	27 mod		
17	new	37	28		
18	16 mod	38	29		
19	new	39E	31E mod		
20	12	40E	32E		

2.1 The "standard" acceleration (at sea level and 45° latitude) due to gravity is 9.80665 m/s^2. What is the force needed to hold a mass of 2 kg at rest in this gravitational field ? How much mass can a force of 1 N support ?

Solution:

$ma = 0 = \sum F = F - mg$

$F = mg = 2 \times 9.80665 = \mathbf{19.613\ N}$

$F = mg \quad\quad => \quad m = F/g = 1 / 9.80665 = \mathbf{0.102\ kg}$

2.2 A model car rolls down an incline with a slope so the gravitational "pull" in the direction of motion is one third of the standard gravitational force (see Problem 2.1). If the car has a mass of 0.45 kg. Find the acceleration.

Solution:

$ma = \sum F = mg / 3$

$a = mg / 3m = g/3 = 9.80665 / 3 = \mathbf{3.27\ m/s^2}$

2.3 A car drives at 60 km/h and is brought to a full stop with constant deceleration in 5 seconds. If the total car and driver mass is 1075 kg. Find the necessary force.

Solution:

Acceleration is the time rate of change of velocity.

$ma = \sum F ; \quad a = dV / dt = (60 \times 1000) / (3600 \times 5) = 3.33\ m/s^2$

$F_{net} = ma = 1075 \times 3.333 = \mathbf{3583\ N}$

2.4 A washing machine has 2 kg of clothes spinning at a rate that generates an acceleration of 24 m/s^2. What is the force needed to hold the clothes?

Solution:

$F = ma = 2\ kg \times 24\ m/s^2 = \mathbf{48\ N}$

2.5 A 1200-kg car moving at 20 km/h is accelerated at a constant rate of 4 m/s^2 up to a speed of 75 km/h. What are the force and total time required?

Solution:

$a = dV / dt \quad => \quad \Delta t = dV/a = [\ (75 - 20) / 4\ ] \times (1000 / 3600)$

$\Delta t = \mathbf{3.82\ sec}\ ; \quad F = ma = 1200 \times 4 = \mathbf{4800\ N}$

2.6 A steel plate of 950 kg accelerates from rest with 3 m/s^2 for a period of 10s. What force is needed and what is the final velocity?

Solution:

Constant acceleration can be integrated to get velocity.

$a = dV / dt \;\; => \;\; \int dV = \int a \, dt \;\; => \;\; \Delta V = a \, \Delta t = 3 \times 10 = 30 \text{ m/s}$

$V =$ **30 m/s** ; $F = ma = 950 \times 3 =$ **2850 N**

2.7 A 15 kg steel container has 1.75 kilomoles of liquid propane inside. A force of 2 kN now accelerates this system. What is the acceleration?

Solution:

$ma = \sum F \;\Rightarrow\; a = \sum F / m$

$m = m_{steel} + m_{propane} = 15 + (1.75 \times 44.094) = 92.165 \text{ kg}$

$a = 2000 / 92.165 =$ **21.7 m/s²**

2.8 A rope hangs over a pulley with the two equally long ends down. On one end you attach a mass of 5 kg and on the other end you attach 10 kg. Assuming standard gravitation and no friction in the pulley what is the acceleration of the 10 kg mass when released?

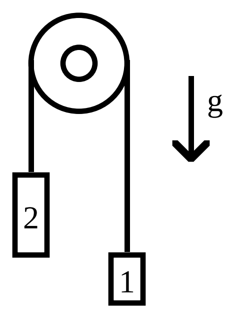
Solution:
Do the equation of motion for the mass m_2 along the downwards direction, in that case the mass m_1 moves up (i.e. has -a for the acceleration)

$$m_2 \, a = m_2 \, g - m_1 \, g - m_1 a$$

$$(m_1 + m_2) \, a = (m_2 - m_1) g$$

This is net force in motion direction

$a = (10 - 5) \, g / (10 + 5) = g / 3 =$ **3.27 m/s²**



2.9 A bucket of concrete of total mass 200 kg is raised by a crane with an acceleration of 2 m/s^2 relative to the ground at a location where the local gravitational acceleration is 9.5 m/s^2. Find the required force.

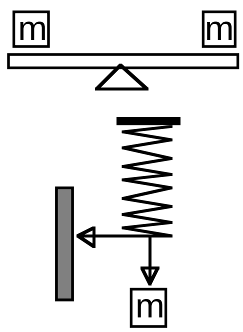
Solution:

$F = ma = F_{up} - mg$

$F_{up} = ma + mg = 200 \, (2 + 9.5) =$ **2300 N**

2.10 On the moon the gravitational acceleration is approximately one-sixth that on the surface of the earth. A 5-kg mass is “weighed” with a beam balance on the surface on the moon. What is the expected reading? If this mass is weighed with a spring scale that reads correctly for standard gravity on earth (see Problem 2.1), what is the reading?

Solution:



Moon gravitation is: $g = g_{earth}/6$

Beam Balance Reading is **5 kg**

This is mass comparison

Spring Balance Reading is in kg units

length $\propto$ F $\propto$ g

Reading will be $\mathbf{\frac{5}{6}}$ **kg**

This is force comparison

2.11 One kilogram of diatomic oxygen (O_2 molecular weight 32) is contained in a 500-L tank. Find the specific volume on both a mass and mole basis (v and $\bar{v}$).

Solution:

$$v = V/m = 0.5/1 = \mathbf{0.5\ m^3/kg}$$

$$\bar{v} = V/n = \frac{V}{m/M} = Mv = 32 \times 0.5 = \mathbf{16\ m^3/kmol}$$

2.12 A 5 m^3 container is filled with 900 kg of granite (density 2400 kg/m^3) and the rest of the volume is air with density 1.15 kg/m^3. Find the mass of air and the overall (average) specific volume.

Solution:

$$m_{air} = \rho\ V = \rho_{air}\ (\ V_{tot} - m_{granite} / \rho\ )$$

$$= 1.15\ [\ 5 - (900 / 2400)\ ] = 1.15\ \times 4.625 = \mathbf{5.32\ kg}$$

$$v = V / m = 5 / (900 + 5.32) = \mathbf{0.00552\ m^3/kg}$$

2.13 A 15-kg steel gas tank holds 300 L of liquid gasoline, having a density of 800 kg/m^3. If the system is decelerated with 6 m/s^2 what is the needed force?

Solution:

$$m = m_{tank} + m_{gasoline} = 15 + 0.3 \times 800 = 255\ kg$$

$$F = ma = 255 \times 6 = \mathbf{1530\ N}$$

2.14 A vertical hydraulic cylinder has a 125-mm diameter piston with hydraulic fluid inside the cylinder and an ambient pressure of 1 bar. Assuming standard gravity, find the piston mass that will create a pressure inside of 1500 kPa.

Solution:

Force balance: $F\uparrow = PA = F\downarrow = P_0A + m_pg$; $P_0 = 1$ bar $= 100$ kPa

$A = (\pi/4)\ D^2 = (\pi/4) \times 0.125^2 = 0.01227\ m^2$

$m_p = (P\text{-}P_0)A/g = (\ 1500 - 100\ ) \times 1000 \times 0.01227\ /\ 9.80665 =$ **1752 kg**

2.15 A barometer to measure absolute pressure shows a mercury column height of 725 mm. The temperature is such that the density of the mercury is 13550 kg/m^3. Find the ambient pressure.

Solution:

Hg : $\Delta l = 725$ mm $= 0.725$ m; $\rho = 13550\ kg/m^3$

$P = \rho\ g\Delta l = 13550 \times 9.80665 \times 0.725 \times 10^{-3} =$ **96.34 kPa**

2.16 A cannon-ball of 5 kg acts as a piston in a cylinder of 0.15 m diameter. As the gun-powder is burned a pressure of 7 MPa is created in the gas behind the ball. What is the acceleration of the ball if the cylinder (cannon) is pointing horizontally?

Solution:

The cannon ball has 101 kPa on the side facing the atmosphere.

$ma = F = P_1 \times A - P_0 \times A$

$a = (P_1 - P_0\ ) \times A\ /\ m = (\ 7000 - 101\ )\ \pi\ [\ (\ 0.15^2\ /4\ )/5\ ] =$ **24.38 m/s²**

2.17 Repeat the previous problem for a cylinder (cannon) pointing 40 degrees up relative to the horizontal direction.

Solution:

$ma = F = (\ P_1 - P_0\ )\ A - mg\ \sin\ 40^0$

$ma = (\ 7000 - 101\ ) \times \pi \times (\ 0.15^2\ /\ 4\ ) - 5 \times 9.80665 \times 0.6428$

$= 121.9 - 31.52 = 90.4$ N

$a = 90.4\ /\ 5 =$ **18.08 m/s²**

2.18 A piston/cylinder with cross sectional area of 0.01 m^2 has a piston mass of 100 kg resting on the stops, as shown in Fig. P2.18. With an outside atmospheric pressure of 100 kPa, what should the water pressure be to lift the piston?

Solution:

Force balance: $F\uparrow = F\downarrow = PA = m_p g + P_0 A$

$P = P_0 + m_p g/A = 100 \text{ kPa} + (100 \times 9.80665) / (0.01 \times 1000)$

$= 100 \text{ kPa} + 98.07 = \mathbf{198\ kPa}$

2.19 The hydraulic lift in an auto-repair shop has a cylinder diameter of 0.2 m. To what pressure should the hydraulic fluid be pumped to lift 40 kg of piston/arms and 700 kg of a car?

Solution:

$F\downarrow = ma = mg = 740 \times 9.80665 = 7256.9 \text{ N}$

Force balance: $F\uparrow = (P - P0) A = F\downarrow \quad \Rightarrow \quad P = P_0 + F\downarrow / A$

$A = \pi D^2 (1 / 4) = 0.031416 \text{ m}^2$

$P = 101 + 7256.9 / (0.031416 \times 1000) = \mathbf{332\ kPa}$

2.20 A differential pressure gauge mounted on a vessel shows 1.25 MPa and a local barometer gives atmospheric pressure as 0.96 bar. Find the absolute pressure inside the vessel.

Solution:

$P_{gauge} = 1.25 \text{ MPa} = 1250 \text{ kPa}; \quad P_0 = 0.96 \text{ bar} = 96 \text{ kPa}$

$P = P_{gauge} + P_0 = 1250 + 96 = \mathbf{1346\ kPa}$

2.21 The absolute pressure in a tank is 85 kPa and the local ambient absolute pressure is 97 kPa. If a U-tube with mercury, density 13550 kg/m^3, is attached to the tank to measure the vacuum, what column height difference would it show?

Solution:

$\Delta P = P_0 - P_{tank} = \rho g \Delta l$

$\Delta l = (P_0 - P_{tank}) / \rho g = [(97 - 85) \times 1000] / (13550 \times 9.80665)$

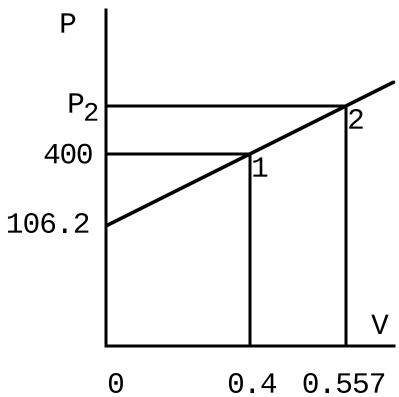
$= \mathbf{0.090\ m = 90\ mm}$

2.22 A 5-kg piston in a cylinder with diameter of 100 mm is loaded with a linear spring and the outside atmospheric pressure of 100 kPa. The spring exerts no force on the piston when it is at the bottom of the cylinder and for the state shown, the pressure is 400 kPa with volume 0.4 L. The valve is opened to let some air in, causing the piston to rise 2 cm. Find the new pressure.

Solution:

A linear spring has a force linear proportional to displacement. $F = k\ x$, so the equilibrium pressure then varies linearly with volume: $P = a + bV$, with an intersect a and a slope $b = dP/dV$. Look at the balancing pressure at zero volume ($V \to 0$) when there is no spring force $F = PA = P_oA + m_pg$ and the initial state. These two points determine the straight line shown in the P-V diagram.

Piston area $= A_p = (\pi/4) \times 0.1^2 = 0.00785\ m^2$



$$a = P_0 + \frac{m_pg}{A_p} = 100 + \frac{5 \times 9.80665}{0.00785}$$

$= 106.2$ kPa intersect for zero volume.

$$V_2 = 0.4 + 0.00785 \times 20 = 0.557\ L$$

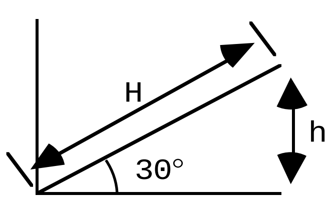
$$P_2 = P_1 + \frac{dP}{dV}\Delta V$$

$$= 400 + \frac{(400\text{-}106.2)}{0.4 - 0}(0.557 - 0.4)$$

$= \mathbf{515.3\ kPa}$

2.23 A U-tube manometer filled with water, density 1000 kg/m^3, shows a height difference of 25 cm. What is the gauge pressure? If the right branch is tilted to make an angle of 30° with the horizontal, as shown in Fig. P2.23, what should the length of the column in the tilted tube be relative to the U-tube?

Solution:



$$\Delta P = F/A = mg/A = V\rho g/A = h\rho g$$

$$= 0.25 \times 1000 \times 9.807 = 2452.5\ Pa$$

$= \mathbf{2.45\ kPa}$

$$h = H \times \sin 30°$$

$\Rightarrow H = h/\sin 30° = 2h = \mathbf{50\ cm}$

2.24 The difference in height between the columns of a manometer is 200 mm with a fluid of density 900 kg/m^3. What is the pressure difference? What is the height difference if the same pressure difference is measured using mercury, density 13600 kg/ m^3, as manometer fluid?

Solution:

$$\Delta P = \rho_1 g h_1 = 900 \times 9.807 \times 0.2 = 1765.26 \text{ Pa} = \mathbf{1.77\ kPa}$$

$$h_{hg} = \Delta P / (\rho_{hg}\ g) = (\rho_1\ gh_1) / (\rho_{hg}\ g) = \frac{900}{13600} \times 0.2 = \mathbf{0.0132\ m = 13.2\ mm}$$

2.25 Two reservoirs, A and B, open to the atmosphere, are connected with a mercury manometer. Reservoir A is moved up/down so the two top surfaces are level at h_3 as shown in Fig. P2.25. Assuming that you know ρ_A, ρ_{Hg} and measure the heights h_1, h_2 , and h_3, find the density ρ_B.

Solution:

Balance forces on each side:

$$P_0 + \rho_A g(h_3 - h_2) + \rho_{Hg} g h_2 = P_0 + \rho_B g(h_3 - h_1) + \rho_{Hg} g h_1$$

$$\Rightarrow \quad \rho_{\mathbf{B}} = \rho_{\mathbf{A}} \left(\frac{\mathbf{h_3 - h_2}}{\mathbf{h_3 - h_1}} \right) + \rho_{\mathbf{Hg}} \left(\frac{\mathbf{h_2 - h_1}}{\mathbf{h_3 - h_1}} \right)$$

2.26 Two vertical cylindrical storage tanks are full of liquid water, density 1000 kg/m^3, the top open to the atmoshere. One is 10 m tall, 2 m diameter, the other is 2.5 m tall with diameter 4m. What is the total force from the bottom of each tank to the water and what is the pressure at the bottom of each tank?

Solution:

$$V_A = H \times \pi D^2 \times (1 / 4) = 10 \times \pi \times 2^2 \times (\ 1 / 4) = 31.416 \text{ m}^3$$

$$V_B = H \times \pi D^2 \times (1 / 4) = 2.5 \times \pi \times 4^2 \times (\ 1 / 4) = 31.416 \text{ m}^3$$

Tanks have the same volume, so same mass of water

$$F = mg = \rho\ V\ g = 1000 \times 31.416 \times 9.80665 = \mathbf{308086\ N}$$

Tanks have same net force up (holds same m in gravitation field)

$$P_{bot} = P_0 + \rho\ H\ g$$

$$P_{bot,A} = 101 + (1000 \times 10 \times 9.80665 / 1000) = \mathbf{199\ kPa}$$

$$P_{bot,B} = 101 + (1000 \times 2.5 \times 9.80665 / 1000) = \mathbf{125.5\ kPa}$$

2.27 The density of mercury changes approximately linearly with temperature as

$$\rho_{Hg} = 13595 - 2.5\,T \;\; \text{kg/ m}^3 \qquad T \;\; \text{in Celsius}$$

so the same pressure difference will result in a manometer reading that is influenced by temperature. If a pressure difference of 100 kPa is measured in the summer at 35°C and in the winter at -15°C, what is the difference in column height between the two measurements?

Solution:

$$\Delta P = \rho g h \Rightarrow h = \Delta P/\rho g \; ; \qquad \rho_{su} = 13507.5 \; ; \qquad \rho_{w} = 13632.5$$

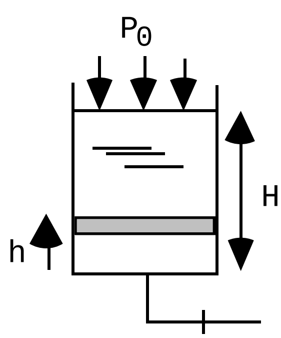
$$h_{su} = 100\times10^3/(13507.5 \times 9.807) = 0.7549 \text{ m}$$

$$h_{w} = 100\times10^3/(13632.5 \times 9.807) = 0.7480 \text{ m}$$

$$\Delta h = h_{su} - h_{w} = \mathbf{0.0069\ m = 6.9\ mm}$$

2.28 Liquid water with density ρ is filled on top of a thin piston in a cylinder with cross-sectional area *A* and total height *H*. Air is let in under the piston so it pushes up, spilling the water over the edge. Deduce the formula for the air pressure as a function of the piston elevation from the bottom, *h*.

Solution:



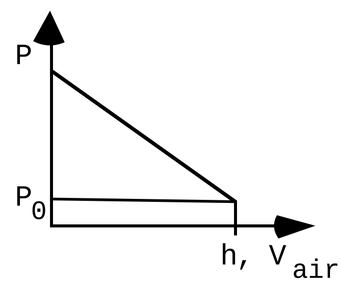
Force balance

Piston: $F\uparrow = F\downarrow$

$$PA = P_0A + m_{H_2O}g$$

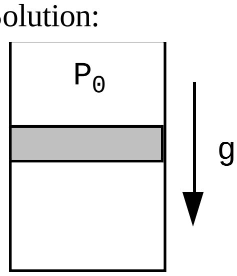
$$P = P_0 + m_{H_2O}g/A$$

$$\mathbf{P = P_0 + (H-h)\rho g}$$



2.29 A piston, m_p= 5 kg, is fitted in a cylinder, *A* = 15 cm^2, that contains a gas. The setup is in a centrifuge that creates an acceleration of 25 m/s^2 in the direction of piston motion towards the gas. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure.

Solution:



Force balance: $\quad F\uparrow = F\downarrow = P_0A + m_pg = PA$

$$P = P_0 + m_pg/A = 101.325 + 5 \times 25 / (1000 \times 0.0015)$$

$$= \mathbf{184.7\ kPa}$$

2.30 A piece of experimental apparatus is located where g = 9.5 m/s^2 and the temperature is 5°C. An air flow inside the apparatus is determined by measuring the pressure drop across an orifice with a mercury manometer (see Problem 2.27 for density) showing a height difference of 200 mm. What is the pressure drop in kPa?

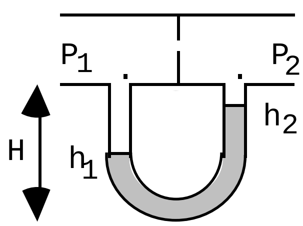
Solution:

$$\Delta P = \rho g h \; ; \qquad \rho_{Hg} = 13600$$

$$\Delta P = 13600 \times 9.5 \times 0.2 = 25840 \text{ Pa} = \mathbf{25.84\ kPa}$$

2.31 Repeat the previous problem if the flow inside the apparatus is liquid water, $\rho \cong$ 1000 kg/m^3, instead of air. Find the pressure difference between the two holes flush with the bottom of the channel. You cannot neglect the two unequal water columns.

Solution:



Balance forces in the manometer:

$$(H - h_2) - (H - h_1) = \Delta h_{Hg} = h_1 - h_2$$

$$P_1 A + \rho_{H_2O} h_1 g A + \rho_{Hg}(H - h_1) g A$$
$$= P_2 A + \rho_{H_2O} h_2 g A + \rho_{Hg}(H - h_2) g A$$

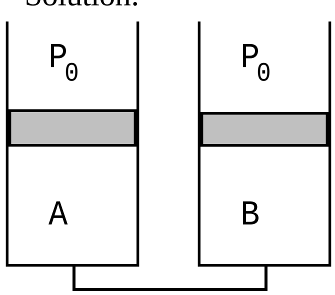
$$\Rightarrow P_1 - P_2 = \rho_{H_2O}(h_2 - h_1)g + \rho_{Hg}(h_1 - h_2)g$$

$$P_1 - P_2 = \rho_{Hg}\Delta h_{Hg} g - \rho_{H_2O}\Delta h_{Hg} g = 13600 \times 0.2 \times 9.5 - 1000 \times 0.2 \times 9.5$$

$$= 25840 - 1900 = 23940 \text{ Pa} = \mathbf{23.94\ kPa}$$

2.32 Two piston/cylinder arrangements, A and B, have their gas chambers connected by a pipe. Cross-sectional areas are A_A = 75 cm^2 and A_B = 25 cm^2 with the piston mass in A being m_A = 25 kg. Outside pressure is 100 kPa and standard gravitation. Find the mass m_B so that none of the pistons have to rest on the bottom.

Solution:



Force balance for both pistons: $F\uparrow = F\downarrow$

A: $m_{PA} g + P_0 A_A = P A_A$

B: $m_{PB} g + P_0 A_B = P A_B$

Same P in A and B gives no flow between them.

$$\frac{m_{PA} g}{A_A} + P_0 = \frac{m_{PB} g}{A_B} + P_0$$

$$\Rightarrow m_{PB} = m_{PA}\, A_A / A_B = 25 \times 25/75 = \mathbf{8.33\ kg}$$

2.33 Two hydraulic piston/cylinders are of same size and setup as in Problem 2.32, but with neglible piston masses. A single point force of 250 N presses down on piston A. Find the needed extra force on piston B so that none of the pistons have to move.

Solution:

No motion in connecting pipe: $P_A = P_B$ & Forces on pistons balance

$$A_A = 75 \text{ cm}^2 ; \qquad A_B = 25 \text{ cm}^2$$

$$P_A = P_0 + F_A / A_A = P_B = P_0 + F_B / A_B$$

$$F_B = F_A\, A_B \,/\, A_A = 250 \times 25 / 75 = \mathbf{83.33\ N}$$

2.34 At the beach, atmospheric pressure is 1025 mbar. You dive 15 m down in the ocean and you later climb a hill up to 250 m elevation. Assume the density of water is about 1000 kg/m^3 and the density of air is 1.18 kg/m^3. What pressure do you feel at each place?

Solution:

$$\Delta P = \rho g h$$

$$P_{ocean} = P_0 + \Delta P = 1025 \times 100 + 1000 \times 9.81 \times 15$$

$$= 2.4965 \times 10^5 \text{ Pa} = \mathbf{250\ kPa}$$

$$P_{hill} = P_0 - \Delta P = 1025 \times 100 - 1.18 \times 9.81 \times 250$$

$$= 0.99606 \times 10^5 \text{ Pa} = \mathbf{99.61\ kPa}$$

2.35 In the city water tower, water is pumped up to a level 25 m above ground in a pressurized tank with air at 125 kPa over the water surface. This is illustrated in Fig. P2.35. Assuming the water density is 1000 kg/m^3 and standard gravity, find the pressure required to pump more water in at ground level.

Solution:

$$P_{bottom} = P_{top} + \rho g l = 125 + 1000 \times 9.807 \times 25 \times 10^{-3}$$

$$= \mathbf{370\ kPa}$$

2.36 Two cylinders are connected by a piston as shown in Fig. P2.36. Cylinder A is used as a hydraulic lift and pumped up to 500 kPa. The piston mass is 25 kg and there is standard gravity. What is the gas pressure in cylinder B?

Solution:

Force balance for the piston: $P_BA_B + m_pg + P_0(A_A - A_B) = P_AA_A$

$A_A = (\pi/4)0.1^2 = 0.00785\ m^2$; $A_B = (\pi/4)0.025^2 = 0.000491\ m^2$

$P_BA_B = P_AA_A - m_pg - P_0(A_A - A_B) = 500\times 0.00785 - (25 \times 9.807/1000)$

$- 100\ (0.00785 - 0.000491) = 2.944\ kN$

$P_B = 2.944/0.000491 = 5996\ kPa =$ **6.0 MPa**

2.37 Two cylinders are filled with liquid water, $\rho = 1000\ kg/m^3$, and connected by a line with a closed valve. A has 100 kg and B has 500 kg of water, their cross-sectional areas are $A_A = 0.1\ m^2$ and $A_B = 0.25\ m^2$ and the height h is 1 m. Find the pressure on each side of the valve. The valve is opened and water flows to an equilibrium. Find the final pressure at the valve location.

Solution:

$V_A = v_{H_2O}m_A = m_A/\rho = 0.1 = A_Ah_A \quad => \quad h_A = 1\ m$

$V_B = v_{H_2O}m_B = m_B/\rho = 0.5 = A_Bh_B \quad => \quad h_B = 2\ m$

$P_{VB} = P_0 + \rho g(h_B+H) = 101325 + 1000 \times 9.81 \times 3 = 130\ 755\ Pa$

$P_{VA} = P_0 + \rho gh_A = 101325 + 1000 \times 9.81 \times 1 = 111\ 135\ Pa$

Equilibrium: same height over valve in both

$$V_{tot} = V_A + V_B = h_2A_A + (h_2 - H)A_B \Rightarrow h_2 = \frac{h_AA_A + (h_B+H)A_B}{A_A + A_B} = 2.43\ m$$

$P_{V2} = P_0 + \rho gh_2 = 101.325 + (1000 \times 9.81 \times 2.43)/1000 =$ **125.2 kPa**

2.38 Using the freezing and boiling point temperatures for water in both Celsius and Fahrenheit scales, develop a conversion formula between the scales. Find the conversion formula between Kelvin and Rankine temperature scales.

Solution:

$T_{Freezing} = 0\ ^oC = 32\ F$; $\quad T_{Boiling} = 100\ ^oC = 212\ F$

$\Delta T = 100\ ^oC = 180\ F \ \Rightarrow\ To_C = (T_F - 32)/1.8$ or $T_F = 1.8\ To_C + 32$

For the absolute K & R scales both are zero at absolute zero.

$T_R = 1.8 \times T_K$

English Unit Problems

2.39E A 2500-lbm car moving at 15 mi/h is accelerated at a constant rate of 15 ft/s^2 up to a speed of 50 mi/h. What are the force and total time required?

Solution:

$$a = \frac{dV}{dt} = \Delta V / \Delta t \quad \Rightarrow \; \Delta t = \Delta V / a$$

$$\Delta t = (50 - 15) \times 1609.34 \times 3.28084/(3600 \times 15) = \mathbf{3.42\ sec}$$

$$F = ma = 2500 \times 15 / 32.174 \text{ lbf} = \mathbf{1165\ lbf}$$

2.40E Two pound moles of diatomic oxygen gas are enclosed in a 20-lbm steel container. A force of 2000 lbf now accelerates this system. What is the acceleration?

Solution:

$$m_{O_2} = n_{O_2} M_{O_2} = 2 \times 32 = 64 \text{ lbm}$$

$$m_{tot} = m_{O_2} + m_{steel} = 64 + 20 = 84 \text{ lbm}$$

$$a = \frac{Fg_c}{m_{tot}} = (2000 \times 32.174) / 84 = \mathbf{766\ ft/s^2}$$

2.41E A bucket of concrete of total mass 400 lbm is raised by a crane with an acceleration of 6 ft/s^2 relative to the ground at a location where the local gravitational acceleration is 31 ft/s^2. Find the required force.

Solution:

$$F = ma = F_{up} - mg$$

$$F_{up} = ma + mg = 400 \times (6 + 31) / 32.174 = \mathbf{460\ lbf}$$

2.42E One pound-mass of diatomic oxygen (O_2 molecular weight 32) is contained in a 100-gal tank. Find the specific volume on both a mass and mole basis (v and $\bar{v}$).

Solution:

$$v = V/m = 15/1 = \mathbf{15\ ft^3/lbm}$$

$$\bar{v} = V/n = \frac{V}{m/M} = Mv = 32 \times 15 = \mathbf{480\ ft^3/lbmol}$$

2.43E A 30-lbm steel gas tank holds 10 ft^3 of liquid gasoline, having a density of 50 lbm/ft^3. What force is needed to accelerate this combined system at a rate of 15 ft/s^2?

Solution:

$$m = m_{tank} + m_{gasoline} = 30 + 10 \times 50 = 530 \text{ lbm}$$

$$F = \frac{ma}{g_C} = (530 \times 15) / 32.174 = \mathbf{247.1\ lbf}$$

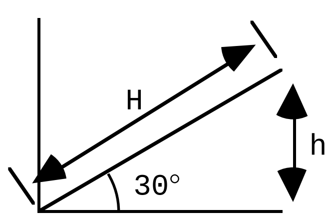
2.44E A differential pressure gauge mounted on a vessel shows 185 lbf/in.^{2} and a local barometer gives atmospheric pressure as 0.96 atm. Find the absolute pressure inside the vessel.

Solution:

$$P = P_{gauge} + P_0 = 185 + 0.96 \times 14.696 = \mathbf{199.1\ lbf/in^2}$$

2.45E A U-tube manometer filled with water, density 62.3 lbm/ft^3, shows a height difference of 10 in. What is the gauge pressure? If the right branch is tilted to make an angle of 30° with the horizontal, as shown in Fig. P2.23, what should the length of the column in the tilted tube be relative to the U-tube?

Solution:



$$\Delta P = F/A = mg/Ag_C = h\rho g/g_C$$
$$= [(10/12) \times 62.3 \times 32.174] / 32.174 \times 144$$
$$= P_{gauge} = \mathbf{0.36\ lbf/in^2}$$

$$h = H \times \sin 30°$$
$$\Rightarrow H = h/\sin 30° = 2h = 20 \text{ in} = \mathbf{0.833\ ft}$$

2.46E A piston/cylinder with cross-sectional area of 0.1 ft^2 has a piston mass of 200 lbm resting on the stops, as shown in Fig. P2.18. With an outside atmospheric pressure of 1 atm, what should the water pressure be to lift the piston?

Solution:

$$P = P_0 + m_p g/Ag_c = 14.696 + (200 \times 32.174) / (0.1 \times 144 \times 32.174)$$
$$= 14.696 + 13.88 = \mathbf{28.58\ lbf/in^2}$$

2.47E The density of mercury changes approximately linearly with temperature as

$$\rho_{Hg} = 851.5 - 0.086\, T \;\; \text{lbm/ft}^3 \qquad T \;\text{ in degrees Fahrenheit}$$

so the same pressure difference will result in a manometer reading that is influenced by temperature. If a pressure difference of 14.7 lbf/in.^{2} is measured in the summer at 95 F and in the winter at 5 F, what is the difference in column height between the two measurements?

Solution:

$$\Delta P = \rho g h / g_c \;\; \Rightarrow \;\; h = \Delta P g_c / \rho g$$

$$\rho_{su} = 843.33 \text{ lbm/ft}^3; \qquad \rho_w = 851.07 \text{ lbm/ft}^3$$

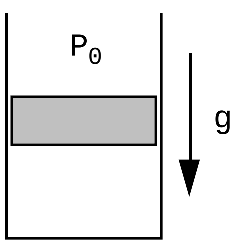
$$h_{su} = \frac{14.7 \times 144 \times 32.174}{843.33 \times 32.174} = 2.51 \text{ ft} = 30.12 \text{ in}$$

$$h_w = \frac{14.7 \times 144 \times 32.174}{851.07 \times 32.174} = 2.487 \text{ ft} = 29.84 \text{ in}$$

$$\Delta h = h_{su} - h_w = 0.023 \text{ ft} = \mathbf{0.28 \text{ in}}$$

2.48E A piston, m_p = 10 lbm, is fitted in a cylinder, A = 2.5 in.^{2}, that contains a gas. The setup is in a centrifuge that creates an acceleration of 75 ft/s^2. Assuming standard atmospheric pressure outside the cylinder, find the gas pressure.

Solution:



$$F\!\downarrow\; = F\!\uparrow\; = P_0 A + m_p g = PA$$

$$P = P_0 + m_p g / A g_c = 14.696 + \frac{10 \times 75}{2.5 \times 32.174}$$

$$= 14.696 + 9.324 = 24.02 \text{ lbf/in}^2$$

2.49E At the beach, atmospheric pressure is 1025 mbar. You dive 30 ft down in the ocean and you later climb a hill up to 300 ft elevation. Assume the density of water is about 62.3 lbm/ft^3 and the density of air is 0.0735 lbm/ft^3. What pressure do you feel at each place?

Solution:

$$\Delta P = \rho g h; \; P_0 = (1.025/1.01325) \times 14.696 = 14.866 \text{ lbf/in}^2$$

$$P_{ocean} = P_0 + \Delta P = 14.866 + \frac{62.3 \times 30 \times g}{g_c \times 144} = 27.84 \text{ lbf/in}^2$$

$$P_{hill} = P_0 - \Delta P = 14.866 - \frac{0.0735 \times 300 \times g}{g_c \times 144} = 14.71 \text{ lbf/in}^2$$

CHAPTER 3

The SI set of problems are revised from the 4th edition as:

New	Old	New	Old	New	Old
1	new	21	new	41	33
2	new	22	13 mod	42	34
3	new	23	16 mod	43	35
4	new	24	17	44	36 mod
5	new	25	new	45	37 mod
6	new	26	18 mod	46	38 mod
7	7 mod	27	19 d.mod	47	39
8	3	28	20 e.mod	48	40
9	2	29	21 a.b.mod	49	41
10	4	30	22 b.mod	50	42 mod
11	5	31	23	51	43
12	new	32	24	52	44
13	6	33	26	53	45
14	8 mod	34	27 mod	54	46
15	10	35	14	55	47
16	11	36	28	56	48
17	12	37	29 mod	57	49
18	new	38	30 mod	58	50
19	15 mod	39	31	59	51
20	new	40	32 mod	60	52

The english unit problem set is revised from the 4th edition as:

New	Old	New	Old	New	Old
61	new	69	61	77	69
62	53	70	62 mod	78	70
63	55	71	63	79	71
64	56	72	64	80	72
65	new	73	65	81	new
66	new	74	66	82	74
67	59 mod	75	67	83	75 mod
68	60	76	68		

mod indicates a modification from the previous problem that changes the solution but otherwise is the same type problem.

3.1 Water at 27°C can exist in different phases dependent upon the pressure. Give the approximate pressure range in kPa for water being in each one of the three phases vapor, liquid or solid.

Solution:

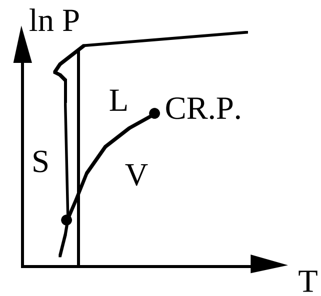
The phases can be seen in Fig. 3.6, a sketch of which is shown to the right.

T =27 °C = 300 K

From Fig. 3.6:

$P_{VL} \approx 4 \times 10^{-3}$ MPa = 4 kPa,

$P_{LS} = 10^3$ MPa



P < 4 kPa VAPOR **P > 1000 MPa SOLID(ICE)**

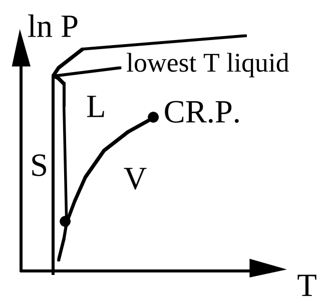
0.004 MPa < P < 1000 MPa LIQUID

3.2 Find the lowest temperature at which it is possible to have water in the liquid phase. At what pressure must the liquid exist?

Solution:

There is no liquid at lower temperatures than on the fusion line, see Fig. 3.6, saturated ice III to liquid phase boundary is at

T ≈ 263K ≈ - 10°C and P ≈ 2100 MPa



3.3 If density of ice is 920 kg/m^3, find the pressure at the bottom of a 1000 m thick ice cap on the north pole. What is the melting temperature at that pressure?

Solution: $\rho_{ICE} = 920$ kg/m^3

$\Delta P = \rho g H = 920 \times 9.80665 \times 1000 = 9022118$ Pa

$P = P_o + \Delta P = 101.325 + 9022 = 9123$ kPa

See figure 3.6 liquid solid interphase => $\mathbf{T_{LS} = -1°C}$

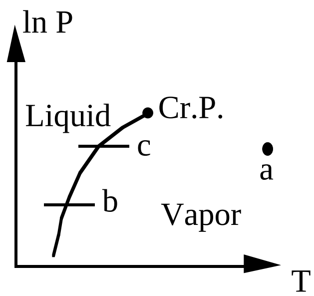
3.4 A substance is at 2 MPa, 17°C in a rigid tank. Using only the critical properties can the phase of the mass be determined if the substance is nitrogen, water or propane ?

Solution: Find state relative to critical point properties which are:

a) Nitrogen N_2 : 3.39 MPa 126.2 K
b) Water H_2O : 22.12 MPa 647.3 K
c) Propane C_3H_8 : 4.25 MPa 369.8 K

State is at 17 °C = 290 K and 2 MPa < Pc for all cases:

N_2 : T >> Tc Superheated vapor P < Pc
H_2O : T << Tc ; P << Pc
you cannot say.
C_3H_8 : T < Tc ; P < Pc you cannot say



3.5 A cylinder fitted with a frictionless piston contains butane at 25°C, 500 kPa. Can the butane reasonably be assumed to behave as an ideal gas at this state ?

Solution Butane 25°C, 500 kPa, Table A.2: T_c = 425 K; P_c = 3.8 MPa

T_r = (25 + 273) / 425 = 0.701; P_r = 0.5/3.8 = 0.13

Look at generalized chart in Figure D.1

Actual $P_r > P_{r,\,sat}$ => **liquid!! not a gas**

3.6 A 1-m^3 tank is filled with a gas at room temperature 20°C and pressure 100 kPa. How much mass is there if the gas is a) air, b) neon or c) propane ?

Solution: Table A.2 T= 20 °C = 293.15 K ; P = 100 kPa << P_c for all

Air : T >> $T_{C,N2}$; $T_{C,O2}$ = 154.6 K so ideal gas; R= 0.287

Neon : T >> T_c = 44.4 K so ideal gas; R = 0.41195

Propane: T < T_c = 370 K, but P << P_c = 4.25 MPa so gas R = 0.18855

a) m = PV/RT = 100 ×1 / 0.287 × 293.15 = **1.189 kg**

b) m = 100 × 1/ 0.41195 × 293.15 = **0.828 kg**

c) m = 100 × 1 / 0.18855 × 293.15 = **1.809 kg**

3.7 A cylinder has a thick piston initially held by a pin as shown in Fig. P3.7. The cylinder contains carbon dioxide at 200 kPa and ambient temperature of 290 K. The metal piston has a density of 8000 kg/m^3 and the atmospheric pressure is 101 kPa. The pin is now removed, allowing the piston to move and after a while the gas returns to ambient temperature. Is the piston against the stops?

Solution:

Force balance on piston determines equlibrium float pressure.

Piston $m_p = A_p \times l \times \rho$ $\qquad\qquad$ $\rho_{piston} = 8000$ kg/m^3

$$P_{ext\ on\ CO_2} = P_0 + \frac{m_p g}{A_p} = 101 + \frac{A_p \times 0.1 \times 9.807 \times 8000}{A_p \times 1000} = 108.8 \text{ kPa}$$

Pin released, as $P_1 > P_{float}$ piston moves up, $T_2 = T_o$ & if piston at stops,

then $V_2 = V_1 \times 150 / 100$

$$\Rightarrow \quad P_2 = P_1 \times V_1 / V_2 = 200 \times \frac{100}{150} = 133 \text{ kPa} \; > \; P_{ext}$$

$\Rightarrow$ **piston is at stops, and P_2 = 133 kPa**

3.8 A cylindrical gas tank 1 m long, inside diameter of 20 cm, is evacuated and then filled with carbon dioxide gas at 25°C. To what pressure should it be charged if there should be 1.2 kg of carbon dioxide?

Solution:

Assume CO_2 is an ideal gas table A.5: $\qquad$ $P = mRT/V$

$$V_{cyl} = A \times L = \frac{\pi}{4}(0.2)^2 \times 1 = 0.031416 \text{ m}^3$$

$\Rightarrow P = 1.2 \times 0.18892\ (273.15 + 25)/0.031416 =$ **2152 kPa**

3.9 A 1-m^3 rigid tank with air at 1 MPa, 400 K is connected to an air line as shown in Fig. P3.9. The valve is opened and air flows into the tank until the pressure reaches 5 MPa, at which point the valve is closed and the temperature inside is 450K.

a. What is the mass of air in the tank before and after the process?

b. The tank eventually cools to room temperature, 300 K. What is the pressure inside the tank then?

Solution:

P, T known at both states and assume the air behaves as an ideal gas.

$$m_{air1} = \frac{P_1V}{RT_1} = \frac{1000 \times 1}{0.287 \times 400} = \mathbf{8.711\ kg}$$

$$m_{air2} = \frac{P_2V}{RT_2} = \frac{5000 \times 1}{0.287 \times 450} = \mathbf{38.715\ kg}$$

Process 2 $\rightarrow$ 3 is constant V, constant mass cooling to T_3

$$P_3 = P_2 \times (T_3/T_2) = 5000 \times (300/450) = \mathbf{3.33\ MPa}$$

3.10 A hollow metal sphere of 150-mm inside diameter is weighed on a precision beam balance when evacuated and again after being filled to 875 kPa with an unknown gas. The difference in mass is 0.0025 kg, and the temperature is 25°C. What is the gas, assuming it is a pure substance listed in Table A.5 ?

Solution:

Assume an ideal gas with total volume: $V = \frac{\pi}{6}(0.15)^3 = 0.001767\ m^3$

$$M = \frac{m\bar{R}T}{PV} = \frac{0.0025 \times 8.3145 \times 298.2}{875 \times 0.001767} = \mathbf{4.009} \approx M_{He}$$

=> **Helium Gas**

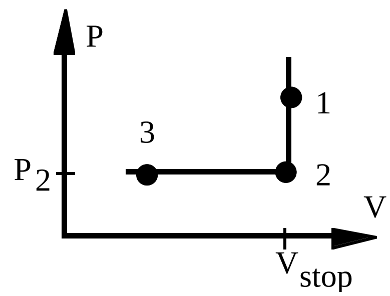
3.11 A piston/cylinder arrangement, shown in Fig. P3.11, contains air at 250 kPa, 300°C. The 50-kg piston has a diameter of 0.1 m and initially pushes against the stops. The atmosphere is at 100 kPa and 20°C. The cylinder now cools as heat is transferred to the ambient.

a. At what temperature does the piston begin to move down?

b. How far has the piston dropped when the temperature reaches ambient?

Solution:

Piston $A_p = \frac{\pi}{4} \times 0.1^2 = 0.00785\ m^2$



Balance forces when piston floats:

$$P_{float} = P_o + \frac{m_p g}{A_p} = 100 + \frac{50 \times 9.807}{0.00785 \times 1000}$$

$$= 162.5\ kPa = P_2 = P_3$$

To find temperature at 2 assume ideal gas:

$$T_2 = T_1 \times \frac{P_2}{P_1} = 573.15 \times \frac{162.5}{250} = \mathbf{372.5\ K}$$

b) Process 2 -> 3 is constant pressure as piston floats to $T_3 = T_o = 293.15$ K

$$V_2 = V_1 = A_p \times H = 0.00785 \times 0.25 = 0.00196\ m^3 = 1.96\ L$$

Ideal gas and $P_2 = P_3$ => $V_3 = V_2 \times \frac{T_3}{T_2} = 1.96 \times \frac{293.15}{372.5} = \mathbf{1.54\ L}$

$$\Delta H = (V_2 - V_3)/A = (1.96-1.54) \times 0.001/0.00785 = \mathbf{0.053\ m = 5.3\ cm}$$

3.12 Air in a tank is at 1 MPa and room temperature of 20°C. It is used to fill an initially empty balloon to a pressure of 200 kPa, at which point the diameter is 2 m and the temperature is 20°C. Assume the pressure in the balloon is linearly proportional to its diameter and that the air in the tank also remains at 20°C throughout the process. Find the mass of air in the balloon and the minimum required volume of the tank.

Solution: Assume air is an ideal gas.

Balloon final state: $V_2 = (4/3)\ \pi\ r^3 = (4/3)\ \pi\ 2^3 = 33.51\ m^3$

$$m_{2bal} = P_2 V_2 / RT_2 = 200 \times 33.51 / 0.287 \times 293.15 = \mathbf{79.66\ kg}$$

Tank must have $P_2 \geq 200$ kPa => $m_{2\ tank} \geq P_2 V_{TANK} / RT_2$

Initial mass must be enough: $m_1 = m_{2bal} + m_{2\ tank} = P_1 V_1 / R\ T_1$

$$P_1 V_{TANK} / R\ T_1 = m_{2bal} + P_2 V_{TANK} / RT_2 \quad =>$$

$$V_{TANK} = RTm_{2bal} / (P_1 - P_2) = 0.287 \times 293.15 \times 79.66 / (1000 - 200)$$

$$= \mathbf{8.377\ m^3}$$

3.13 A vacuum pump is used to evacuate a chamber where some specimens are dried at 50°C. The pump rate of volume displacement is 0.5 m^3/s with an inlet pressure of 0.1 kPa and temperature 50°C. How much water vapor has been removed over a 30-min period?

Solution:

Use ideal gas P << lowest P in steam tables. R is from table A.5

$m = \dot{m}\,\Delta t$ with mass flow rate as: $\dot{m} = \dot{V}/v = P\dot{V}/RT$ (ideal gas)

$$\Rightarrow \quad m = P\dot{V}\Delta t/RT = \frac{0.1 \times 0.5 \times 30 \times 60}{(0.46152 \times 323.15)} = \mathbf{0.603\ kg}$$

3.14 An initially deflated and flat balloon is connected by a valve to a 12 m^3 storage tank containing helium gas at 2 MPa and ambient temperature, 20°C. The valve is opened and the balloon is inflated at constant pressure, P_o = 100 kPa, equal to ambient pressure, until it becomes spherical at D_1 = 1 m. If the balloon is larger than this, the balloon material is stretched giving a pressure inside as

$$P = P_0 + C\left(1 - \frac{D_1}{D}\right)\frac{D_1}{D}$$

The balloon is inflated to a final diameter of 4 m, at which point the pressure inside is 400 kPa. The temperature remains constant at 20°C. What is the maximum pressure inside the balloon at any time during this inflation process? What is the pressure inside the helium storage tank at this time?

Solution:

At the end of the process we have D = 4 m so we can get the constant C as

$$P = 400 = P_0 + C\,(1 - \frac{1}{4})\,\frac{1}{4} = 100 + C \times 3/16 \quad \Rightarrow \quad C = 1600$$

The pressure is: $P = 100 + 1600\,(1 - X^{-1})\,X^{-1}$; $\quad X = D / D_1$

Differentiate to find max: $\quad \frac{dP}{dD} = C\,(-X^{-2} + 2X^{-3})\,/\,D_1 = 0$

$$\Rightarrow \quad -X^{-2} + 2X^{-3} = 0 \quad \Rightarrow \quad X = 2$$

at max P => $D = 2D_1 = 2$ m; $\quad V = \frac{\pi}{6}D^3 = 4.18\ m^3$

$$P_{max} = 100 + 1600\,(1 - \frac{1}{2})\,\frac{1}{2} = \mathbf{500\ kPa}$$

Helium is ideal gas A.5: $\quad m = PV/RT = \frac{500 \times 4.189}{2.0771 \times 293.15} = 3.44$ kg

$m_{TANK,1} = PV/RT = 2000 \times 12/(2.0771 \times 293.15) = 39.416$ kg

$m_{TANK,2} = 39.416 - 3.44 = 35.976$ kg

$P_{T2} = m_{TANK,2}\,RT/V = (m_{TANK,1} / m_{TANK,2}) \times P_1 = \mathbf{1825.5\ kPa}$

3.15 The helium balloon described in Problem 3.14 is released into the atmosphere and rises to an elevation of 5000 m, with a local ambient pressure of P_O = 50 kPa and temperature of –20°C. What is then the diameter of the balloon?

Solution:

Balloon of Problem 3.14, where now after filling D = 4 m, we have :

$m_1 = P_1V_1/RT_1 = 400\ (\pi/6)\ 4^3 /2.077 \times 293.15 = 22.015$ kg

$P_1 = 400 = 100 + C(1 - 0.25)0.25 \quad \Rightarrow \quad C = 1600$

For final state we have : $P_0 = 50$ kPa, $T_2 = T_0 = -20°C = 253.15$ K

State 2: T_2 and on process line for balloon, i.e. the P-V relation:

$P = 50 + 1600\ (D^{*\ -1} - D^{*\ -2}), \quad D^* = D/D_1\ ; \quad V = (\pi/6)\ D^3$

$P_2V_2 = m\ R\ T_2 = 22.015 \times 2.077 \times 253.15 = 11575$

or $PD^{+3} = 11575 \times 6/\ \pi = 22107$ substitute P into the P-V relation

$22107\ D^{*\ -3} = 50 + 1600\ (D^{*\ -1} - D^{*\ -2})$ Divide by 1600

$13.8169\ D^{*\ -3} - 0.03125 - D^{*\ -1} + D^{*\ -2} = 0$ Multiply by D^{*3}

$13.8169 - 0.03125\ D^{*\ 3} - D^{*\ 2} + D^{*\ 1} = 0$ Qubic equation.

By trial and error $D^* = 3.98$ so $D = D^*D_1 =$ **3.98 m**

3.16 A cylinder is fitted with a 10-cm-diameter piston that is restrained by a linear spring (force proportional to distance) as shown in Fig. P3.16. The spring force constant is 80 kN/m and the piston initially rests on the stops, with a cylinder volume of 1 L. The valve to the air line is opened and the piston begins to rise when the cylinder pressure is 150 kPa. When the valve is closed, the cylinder volume is 1.5 L and the temperature is 80°C. What mass of air is inside the cylinder?

Solution:

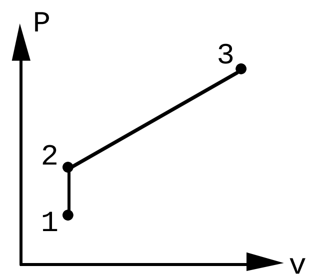
$F_s = k_s\Delta x = k_s\ \Delta V/A_p\ ; \quad V_1 = 1\ L = 0.001\ m^3, \quad A_p = \frac{\pi}{4} 0.1^2 = 0.007854\ m^2$

State 2: $V_3 = 1.5\ L = 0.0015\ m^3; \quad T_3 = 80°C = 353.15$ K

The pressure varies linearly with volume seen from a force balance as:

$$PA_p = P_0\ A_p + m_p\ g + k_s(V - V_0)/A_p$$

Between the states 1 and 2 only volume varies so:



$$P_3 = P_2 + \frac{k_s(V_3-V_2)}{A_p^2} = 150 + \frac{80\times10^3(0.0015 - 0.001)}{0.007854^2 \times 1000}$$

$= 798.5$ kPa

$$m = \frac{P_3V_3}{RT_3} = \frac{798.5 \times 0.0015}{0.287 \times 353.15} = \mathbf{0.012\ kg}$$

3.17 Air in a tire is initially at –10°C, 190 kPa. After driving awhile, the temperature goes up to 10°C. Find the new pressure. You must make one assumption on your own.

Solution:

Assume constant volume and that air is an ideal gas

$P_2 = P_1 \times T_2/T_1 = 190 \times 283.15/263.15 =$ **204.4 kPa**

3.18 A substance is at 2 MPa, 17°C in a 0.25-m^3 rigid tank. Estimate the mass from the compressibility factor if the substance is a) air, b) butane or c) propane.

Solution: Figure D.1 for compressibility Z and table A.2 for critical properties.

Nitrogen $P_r = 2/3.39 = 0.59$; $T_r = 290/126.2 = 2.3$; $Z \approx 0.98$

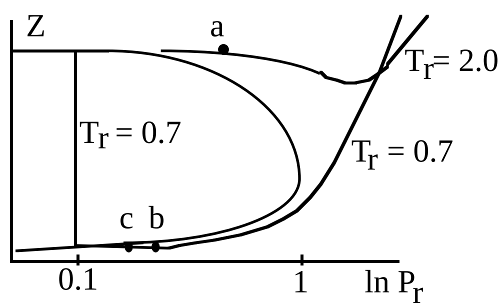
$m = PV/ZRT = 2000 \times 0.25/(0.98 \times 0.2968 \times 290) =$ **5.928 kg**

Butane $P_r = 2/3.80 = 0.526$; $T_r = 290/425.2 = 0.682$; $Z \approx 0.085$

$m = PV/ZRT = 2000 \times 0.25/(0.085 \times 0.14304 \times 290) =$ **141.8 kg**

Propane $P_r = 2/4.25 = 0.47$; $T_r = 290/369.8 = 0.784$; $Z \approx 0.08$

$m = PV/ZRT = 2000 \times 0.25/(0.08 \times 0.18855 \times 290) =$ **114.3 kg**



3.19 Argon is kept in a rigid 5 m^3 tank at –30°C, 3 MPa. Determine the mass using the compressibility factor. What is the error (%) if the ideal gas model is used?

Solution: No Argon table so we use generalized chart Fig. D.1

$T_r = 243.15/150.8 = 1.612$, $P_r = 3000/4870 = 0.616$ => $Z \cong 0.96$

$$m = \frac{PV}{ZRT} = \frac{3000 \times 5}{0.96 \times 0.2081 \times 243.2} = \mathbf{308.75\ kg}$$

Ideal gas Z = 1

$m = PV/RT = 296.4$ kg **4% error**

3.20 A bottle with a volume of 0.1 m^3 contains butane with a quality of 75% and a temperature of 300 K. Estimate the total butane mass in the bottle using the generalized compressibility chart.

Solution:

$m = V/v$ so find v given T_1 and x as : $v = v_f + x\, v_{fg}$

$T_r = 300/425.2 = 0.705$ => Fig. D.1 $Z_f \approx 0.02$; $Z_g \approx 0.9$

$P = P_{sat} = P_{rsat} \times P_c = 0.1 \times 3.80 \times 1000 = 380$ kPa

$v_f = Z_f RT/P = 0.02 \times 0.14304 \times 300/380 = 0.00226\ m^3/kg$

$v_g = Z_g RT/P = 0.9 \times 0.14304 \times 300/380 = 0.1016\ m^3/kg$

$v = 0.00226 + 0.75 \times (0.1016 - 0.00226) = 0.076765\ m^3/kg$

$m = 0.1/0.076765 =$ **1.303 kg**

3.21 A mass of 2 kg of acetylene is in a 0.045 m^3 rigid container at a pressure of 4.3 MPa. Use the generalized charts to estimate the temperature. (This becomes trial and error).

Solution:

Table A.2, A.5: $P_r = 4.3/6.14 = 0.70$; $T_c = 308.3$; $R = 0.3193$

$v = V/m = 0.045/2 = 0.0225\ m^3/kg$

State given by (P, v) $v = ZRT/P$

Since Z is a function of the state Fig. D.1 and thus T, we have trial and error.

Try sat. vapor at $P_r = 0.7$ => Fig. D.1: $Z_g = 0.59$; $T_r = 0.94$

$v_g = 0.59 \times 0.3193 \times 0.94 \times 308.3/4300 = 0.0127$ too small

$T_r = 1$ => $Z = 0.7$ => $v = 0.7 \times 0.3193 \times 1 \times 308.3/4300 = 0.016$

$T_r = 1.2$ => $Z = 0.86$ => $v = 0.86 \times 0.3193 \times 1.2 \times 308.3/4300 = 0.0236$

Interpolate to get: $T_r \approx 1.17$ **$T \approx 361$ K**

3.22 Is it reasonable to assume that at the given states the substance behaves as an ideal gas?

Solution:

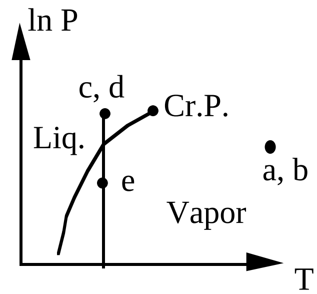
a) Oxygen, O_2 at 30°C, 3 MPa **Ideal Gas** ($T \gg T_c = 155$ K from A.2)

b) Methane, CH_4 at 30°C, 3 MPa **Ideal Gas** ($T \gg T_c = 190$ K from A.2)

c) Water, H_2O at 30°C, 3 MPa **NO** compressed liquid $P > P_{sat}$ (B.1.1)

d) R-134a at 30°C, 3 MPa **NO** compressed liquid $P > P_{sat}$ (B.5.1)

e) R-134a at 30°C, 100 kPa **Ideal Gas** P is low < P_{sat} (B.5.1)



3.23 Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

Solution: All states start in table B.1.1 (if T given) or B.1.2 (if P given)

a. 10 MPa, 0.003 m^3/kg

v_f = 0.001452; v_g = 0.01803 m^3/kg, so mixture of liquid and vapor.

b. 1 MPa, 190°C : T > Tsat = 179.91^{o}C so it is superheated vapor

c. 200°C, 0.1 m^3/kg: $v < v_g$ = 0.12736 m^3/kg, so it is two-phase

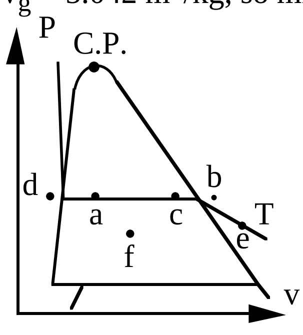
d. 10 kPa, 10°C : $P > P_g$ = 1.2276 kPa so compressed liquid

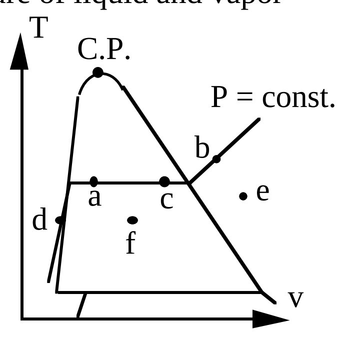
e. 130°C, 200 kPa: $P < P_g$ = 270.1 kPa so superheated vapor

f. 70°C, 1 m^3/kg

v_f = 0.001023; v_g = 5.042 m^3/kg, so mixture of liquid and vapor

States shown are placed relative to the two-phase region, not to each other.





3.24 Determine whether refrigerant R-22 in each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

Solution:

All cases are seen in Table B.4.1

a. 50°C, 0.05 m^3/kg superheated vapor, $v > v_g$ =0.01167 at 50°C

b. 1.0 MPa, 20°C compressed liquid, $P > P_g$ = 909.9 kPa at 20°C

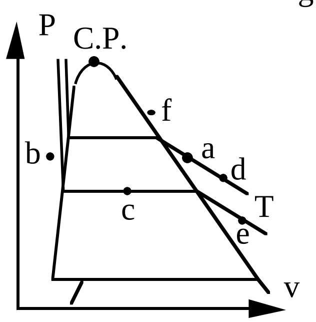
c. 0.1 MPa, 0.1 m^3/kg mixture liq. & vapor, $v_f < v < v_g$ at 0.1 MPa

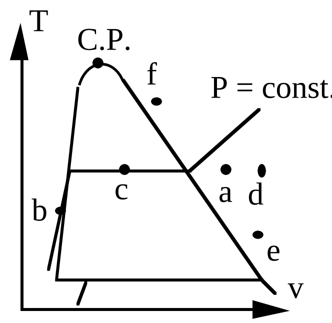
d. 50°C, 0.3 m^3/kg superheated vapor, $v > v_g$ = 0.01167 at 50°C

e −20°C, 200 kPa superheated vapor, $P < P_g$ = 244.8 kPa at -20°C

f. 2 MPa, 0.012 m^3/kg superheated vapor, $v > v_g$ = 0.01132 at 2 MPa

States shown are placed relative to the two-phase region, not to each other.





3.25 Verify the accuracy of the ideal gas model when it is used to calculate specific volume for saturated water vapor as shown in Fig. 3.9. Do the calculation for 10 kPa and 1 MPa.

Solution:

Look at the two states assuming ideal gas and then the steam tables.

Ideal gas:

$v = RT/P$ => $v_1 = 0.46152 \times (45.81 + 273.15)/10 = 14.72$ m^3/kg

$v_2 = 0.46152 \times (179.91 + 273.15)/1000 = 0.209$ m^3/kg

Real gas:

Table B.1.2: v_1 = **14.647** m^3/kg so error = 0.3 %

v_2 = **0.19444** m^3/kg so error = 7.49 %

3.26 Determine the quality (if saturated) or temperature (if superheated) of the following substances at the given two states:
Solution:

a) Water, H_2O, use Table B.1.1 or B.1.2

1) 120°C, 1 m^3/kg => $v > v_g$ superheated vapor, T = 120 °C

2) 10 MPa, 0.01 m^3/kg => two-phase $v < v_g$

$x = (0.01 – 0.001452) / 0.01657 = 0.516$

b) Nitrogen, N_2, table B.6

1) 1 MPa, 0.03 m^3/kg => superheated vapor since $v > v_g$

Interpolate between sat. vapor and superheated vapor B.6.2:

$T \cong 103.73 + (0.03\text{-}0.02416)\times(120\text{-}103.73)/(0.03117\text{-}0.02416) =$ **117 K**

2) 100 K, 0.03 m^3/kg => sat. liquid + vapor as two-phase $v < v_g$

$v = 0.03 = 0.001452 + x \times 0.029764 \;\Rightarrow\;$ **x = 0.959**

c) Ammonia, NH_3, table B.2

1) 400 kPa, 0.327 m^3/kg => $v > v_g = 0.3094$ m^3/kg at 400 kPa

Table B.2.2 superheated vapor $T \cong 10$ °C

2) 1 MPa, 0.1 m^3/kg => $v < v_g$ 2-phase roughly at 25 °C

$x = (0.1 – 0.001658) / 0.012647 = 0.7776$

d) R-22, table B.4

1) 130 kPa, 0.1 m^3/kg => sat. liquid + vapor as $v < v_g$

$v_f \cong 0.000716$ m^3/kg, $v_g \cong 0.1684$ m^3/kg

$v = 0.1 = 0.000716 + x \times 0.16768 \;\Rightarrow\; x = 0.592$

2) 150 kPa, 0.17 m^3/kg => $v > v_g$ superheated vapor, $T \cong 0$°C

3.27 Calculate the following specific volumes
Solution:

a. R-134a: 50°C, 80% quality in Table B.5.1

$v = 0.000908 + x \times 0.014217 = 0.01228$ m^3/kg

b. Water 4 MPa, 90% quality in Table B.1.2

$v = 0.001252(1\text{-}x) + x \times 0.04978 = 0.04493$ m^3/kg

c. Methane 140 K, 60% quality in Table B.7.1

$v = 0.00265 + x \times 0.09574 = 0.06009$ m^3/kg

d. Ammonia 60°C, 25% quality in Table B.2.1

$v = 0.001834 + x \times 0.04697 = 0.01358$ m^3/kg

3.28 Give the phase and the specific volume.

Solution:

a. H_2O $T = 275°C$ $P = 5$ MPa Table B.1.1 or B.1.2

$P_{sat} = 5.94$ MPa => **superheated vapor** $v =$ **0.04141 m³/kg**

b. H_2O $T = -2°C$ $P = 100$ kPa Table B.1.5

$P_{sat} = 0.518$ kPa =>**compressed solid** $v \cong v_i =$ **0.0010904 m³/kg**

c. CO_2 $T = 267°C$ $P = 0.5$ MPa Table A.5

sup. vap. assume ideal gas $v = \frac{RT}{P} = \frac{0.18892 \times 540}{500} =$ **0.204 m³/kg**

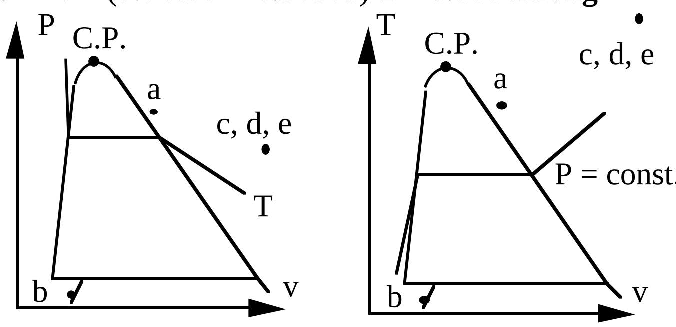
d. Air $T = 20°C$ $P = 200$ kPa Table A.5

sup. vap. assume ideal gas $v = \frac{RT}{P} = \frac{0.287 \times 293}{200} =$ **0.420 m³/kg**

e. NH_3 $T = 170°C$ $P = 600$ kPa Table B.2.2

$T > T_c$ => **sup. vap.** $v = (0.34699 + 0.36389)/2 =$ **0.3554m³/kg**

States shown are placed relative to the two-phase region, not to each other.



3.29 Give the phase and the specific volume.

Solution:

a. R-22 $T = -25°C$ $P = 100$ kPa => Table B.4.1 $P_{sat} = 201$ kPa

sup. vap. B.4.2 $v \cong (0.22675 + 0.23706)/2 =$ **0.2319 m³/kg**

b. R-22 $T = -25°C$ $P = 300$ kPa => Table B.4.1 $P_{sat} = 201$ kPa

compr. liq. as $P > P_{sat}$ $v \cong v_f =$ **0.000733 m³/kg**

c. R-12 $T = 5°C$ $P = 300$ kPa => Table B.3.1 $P_{sat} = 362.6$ kPa

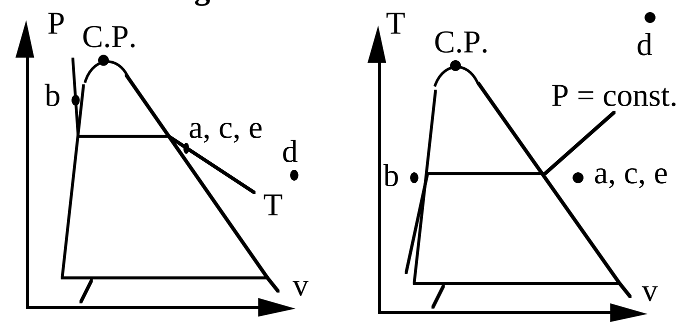
sup. vap. B.3.2 $v \cong (0.0569 + 0.05715)/2 =$ **0.05703 m³/kg**

d. Ar $T = 200°C$ $P = 200$ kPa Table A.5

ideal gas $v = \frac{RT}{P} = \frac{0.20813 \times 473}{200} =$ **0.4922 m³/kg**

e. NH_3 $T = 20°C$ $P = 100$ kPa => Table B.2.1 $P_{sat} = 847.5$ kPa
sup. vap. B.2.2 v = **1.4153 m^3/kg**

States shown are placed relative to the two-phase region, not to each other.



3.30 Find the phase, quality x if applicable and the missing property P or T.

Solution:

a. H_2O $T = 120°C$ $v = 0.5\ m^3/kg$ < v_g Table B.1.1
sat. liq. + vap. P = **198.5 kPa,** x = (0.5 - 0.00106)/0.8908 = 0.56

b. H_2O $P = 100$ kPa $v = 1.8\ m^3/kg$ Table B.1.2 $v > v_g$
sup. vap., interpolate in Table B.1.3

$$T = \frac{1.8 - 1.694}{1.93636 - 1.694}(150 - 99.62) + 99.62 = \mathbf{121.65\ °C}$$

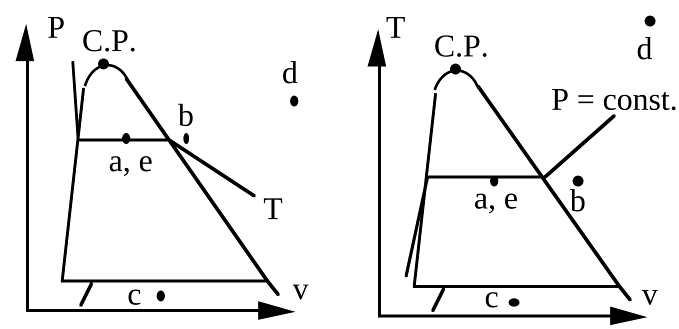
c. H_2O $T = 263$ K $v = 200\ m^3/kg$ Table B.1.5
sat. solid + vap., P = **0.26 kPa**, x = (200-0.001)/466.756 = 0.4285

d. Ne $P = 750$ kPa $v = 0.2\ m^3/kg$; Table A.5

ideal gas, $T = \frac{Pv}{R} = \frac{750 \times 0.2}{0.41195} = \mathbf{364.1\ K}$

e. NH_3 $T = 20°C$ $v = 0.1\ m^3/kg$ Table B.2.1
sat. liq. + vap. , P = **857.5 kPa,** x = (0.1-0.00164)/0.14758 = 0.666

States shown are placed relative to the two-phase region, not to each other.



3.31 Give the phase and the missing properties of P, T, v and x.

Solution:

a. R-22 $T = 10°C$ $v = 0.01\ m^3/kg$ Table B.4.1

sat. liq. + vap. P = 680.7 kPa, x = (0.01-0.0008)/0.03391 = 0.2713

b. H_2O $T = 350°C$ $v = 0.2\ m^3/kg$ Table B.1.1 $v > v_g$

sup. vap. P ≅ 1.40 MPa, x = undefined

c. CO_2 $T = 800\ K$ $P = 200\ kPa$ Table A.5

ideal gas $$v = \frac{RT}{P} = \frac{0.18892 \times 800}{200} = 0.756\ m^3/kg$$

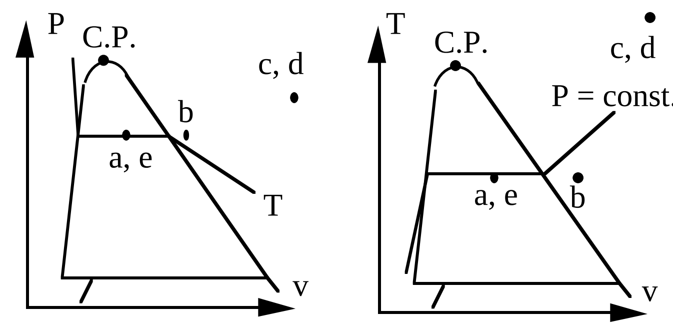
d. N_2 $T = 200\ K$ $P = 100\ kPa$ Table B.6.2 T > Tc

sup. vap. $v = 0.592\ m^3/kg$

e. CH_4 $T = 190\ K$ $x = 0.75$ Table B.7.1 P = 4520 kPa

sat. liq + vap. $v = 0.00497 + x \times 0.003 = 0.00722\ m^3/kg$

States shown are placed relative to the two-phase region, not to each other.



3.32 Give the phase and the missing properties of P, T, v and x. These may be a little more difficult if the appendix tables are used instead of the software.

Solution:

a) R-22 at $T = 10°C$, $v = 0.036\ m^3/kg$: Table B.4.1 $v > v_g$ at 10°C

=> **sup. vap.** Table B.4.2 interpolate between sat. and sup. both at 10°C

P = 680.7 + (0.036-0.03471)(600-680.7)/(0.04018-0.03471) = **661.7 kPa**

b) H_2O $v = 0.2\ m^3/kg$, $x = 0.5$: Table B.1.1

sat. liq. + vap. $v = (1-x)\ v_f + x\ v_g$ => $v_f + v_g = 0.4\ m^3/kg$

since v_f is so small we find it approximately where $v_g = 0.4\ m^3/kg$.

$v_f + v_g = 0.39387$ at 150°C, $v_f + v_g = 0.4474$ at 145°C.

An iterpolation gives T ≅ **149.4°C,** P ≅ **468.2 kPa**

c) H_2O $\quad T = 60°C,\ v = 0.001016\ m^3/kg$: Table B.1.1 $\quad v < v_f = 0.001017$

=> **compr. liq.** see Table B.1.4

$v = 0.001015$ at 5 MPa so $\quad P \cong 0.5(5000 + 19.9) =$ **2.51 MPa**

d) NH_3 $\quad T = 30°C,\ P = 60$ kPa : Table B.2.1 $\quad P < Psat$

=> **sup. vapor** interpolate in Table B.2.2

$v = 2.94578 + (60\text{-}50)(1.95906\text{-}2.94578)/(75\text{-}50) =$ **2.551 m^3/kg**

v is not linearly proportional to P (more like 1/P) so the computer table gives a more accurate value of 2.45

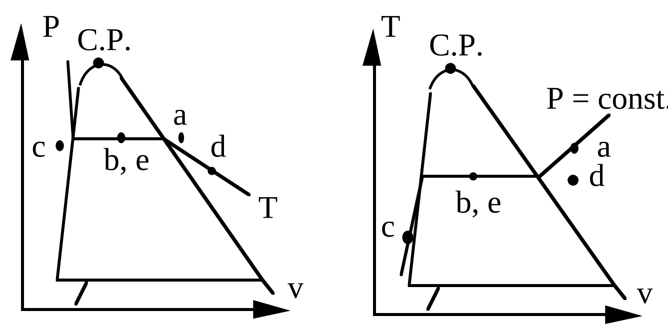
e) R-134a $\ v = 0.005 m^3/kg$, $x = 0.5$: **sat. liq. + vap.** Table B.5.1

$v = (1\text{-}x)\ v_f + x\ v_g \quad => \quad v_f + v_g = 0.01\ m^3/kg$

$v_f + v_g = 0.010946$ at 65°C, $\quad v_f + v_g = 0.009665$ at 70°C.

An iterpolation gives: $\quad T \cong$ **68.7°C**, P = **2.06 MPa**

States shown are placed relative to the two-phase region, not to each other.



3.33 What is the percent error in specific volume if the ideal gas model is used to represent the behavior of superheated ammonia at 40°C, 500 kPa? What if the generalized compressibility chart, Fig. D.1, is used instead?

Solution:

NH_3 $\quad T = 40°C = 313.15$ K, Tc = 405.5 K, Pc = 11.35 MPa from Table A.1

Table B.2.2: $\quad v =$ **0.2923 m^3/kg**

Ideal gas: $v = \frac{RT}{P} = \frac{0.48819 \times 313}{500} =$ **0.3056 m^3/kg** $\quad \Rightarrow$ **4.5% error**

Figure D.1: $T_r = 313.15/405.5 = 0.772,\ P_r = 0.5/11.35 = 0.044 \ \Rightarrow\ Z =$ **0.97**

$v = ZRT/P =$ **0.2964 m^3/kg** $\Rightarrow$ **1.4% error**

3.34 What is the percent error in pressure if the ideal gas model is used to represent the behavior of superheated vapor R-22 at 50°C, 0.03082 m^3/kg? What if the generalized compressibility chart, Fig. D.1, is used instead (iterations needed)?

Solution: Real gas behavior: $P = 900$ kPa from Table B.4.2

Ideal gas constant: $R = \bar{R}/M = 8.31451/86.47 = 0.096155$

$$P = RT/v = 0.096155 \times (273.15 + 50) / 0.03082$$

$$= \mathbf{1008\ kPa\ \ which\ is\ 12\%\ too\ high}$$

Generalized chart Fig D.1 and critical properties from A.2:

$$T_r = 323.2/363.3 = 0.875; \quad P_c = 4970 \text{ kPa}$$

Assume $P = 900$ kPa => $P_r = 0.181$ => $Z \cong 0.905$

$$v = ZRT/P = 0.905 \times 0.096155 \times 323.15 / 900 = 0.03125 \text{ too high}$$

Assume $P = 950$ kPa => $P_r = 0.191$ => $Z \cong 0.9$

$$v = ZRT/P = 0.9 \times 0.096155 \times 323.15 / 950 = 0.029473 \text{ too low}$$

$$P \cong 900 + (950 - 900) \times \frac{0.03082 - 0.029437}{0.03125 - 0.029437} = \mathbf{938\ kPa} \qquad \mathbf{4.2\ \%\ high}$$

3.35 Determine the mass of methane gas stored in a 2 m^3 tank at –30°C, 3 MPa. Estimate the percent error in the mass determination if the ideal gas model is used.

Solution:

The methane Table B.7.2 linear interpolation between 225 and 250 K.

$$\Rightarrow \quad v \cong 0.03333 + \frac{243.15\text{-}225}{250\text{-}225} \times (0.03896\text{-}0.03333) = 0.03742 \text{ m}^3\text{/kg}$$

$$m = V/v = 2/0.03742 = \mathbf{53.45\ kg}$$

Ideal gas assumption

$$v = RT/P = 0.51835 \times 243.15/3000 = 0.042$$

$$m = V/v = 2/0.042 = 47.62 \text{ kg}$$

Error: 5.83 kg **10.9% too small**

3.36 A water storage tank contains liquid and vapor in equilibrium at 110°C. The distance from the bottom of the tank to the liquid level is 8 m. What is the absolute pressure at the bottom of the tank?

Solution:

Saturated conditions from Table B.1.1: Psat = 143.3 kPa

$$v_f = 0.001052 \text{ m}^3\text{/kg}; \quad \Delta P = \frac{gh}{v_f} = \frac{9.807 \times 8}{0.001052} = 74578 \text{ Pa} = 74.578 \text{ kPa}$$

$$P_{bottom} = P_{top} + \Delta P = 143.3 + 74.578 = \mathbf{217.88\ kPa}$$

3.37 A sealed rigid vessel has volume of 1 m^3 and contains 2 kg of water at 100°C. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 200°C?

Solution:

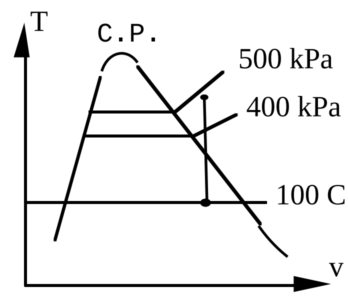
Process: v = V/m = constant

$v_1 = 1/2 = 0.5\ m^3/kg$ 2-phase

200°C, 0.5 m^3/kg seen in Table B.1.3 to be between 400 and 500 kPa so interpolate

$$P \cong 400 + \frac{0.5\text{-}0.53422}{0.42492\text{-}0.53422} \times (500\text{-}400)$$

= 431.3 kPa



3.38 A 500-L tank stores 100 kg of nitrogen gas at 150 K. To design the tank the pressure must be estimated and three different methods are suggested. Which is the most accurate, and how different in percent are the other two?

a. Nitrogen tables, Table B.6
b. Ideal gas
c. Generalized compressibility chart, Fig. D.1

Solution:

State 1: 150 K, v = V/m = 0.5/100 = 0.005 m^3/kg

a) Table B.6, interpolate between 3 & 6 MPa with both at 150 K:

3 MPa : v = 0.01194   6 MPa : v = 0.0042485

P= 3 + (0.005-0.01194)×(6-3)/(0.0042485-0.01194) = 5.707 MPa

b) Ideal gas table A.5: $P = \frac{RT}{v} = \frac{0.2968 \times 150}{0.005} = 8.904$ MPa

c) Table A.2 Tc = 126.2 K, Pc = 3.39 MPa so $T_r = 150/126.2 = 1.189$

Z is a function of P so it becomes trial and error. Start with P = 5.7 MPa

$P_r \cong 1.68 \;\Rightarrow\; Z = 0.60 \;\Rightarrow\; P = \frac{ZRT}{v} = 5342$ kPa

$\Rightarrow\; P_r = 1.58 \;\Rightarrow\; Z = 0.62 \;\Rightarrow\; P = 5520$ kPa OK

ANSWER: **a) is the most accurate** with others off by b) **60%** c) **1%**

3.39 A 400-m^3 storage tank is being constructed to hold LNG, liquified natural gas, which may be assumed to be essentially pure methane. If the tank is to contain 90% liquid and 10% vapor, by volume, at 100 kPa, what mass of LNG (kg) will the tank hold? What is the quality in the tank?

Solution:

CH_4 at P = 100 kPa from Table B.7.1 by interpolation.

$$m_{liq} = \frac{V_{liq}}{v_f} = \frac{0.9 \times 400}{0.00236} = 152542 \text{ kg}; \qquad m_{vap} = \frac{V_{vap}}{v_g} = \frac{0.1 \times 400}{0.5726} = 69.9 \text{ kg}$$

m_{tot} = **152 612 kg,** $\quad x = m_{vap} / m_{tot}$ = $\mathbf{4.58 \times 10^{-4}}$

(If you use computer table, $v_f \cong 0.002366$, $\quad v_g \cong 0.5567$)

3.40 A storage tank holds methane at 120 K, with a quality of 25 %, and it warms up by 5°C per hour due to a failure in the refrigeration system. How long time will it take before the methane becomes single phase and what is the pressure then?

Solution: Use Table B.7.1

Assume rigid tank $v = \text{const} = v_1 = 0.002439 + 0.25 \times 0.30367 = 0.078366$

All single phase when $\quad v = v_g \;\Rightarrow\; T \cong 145$ K

$\Delta t = \Delta T/5°C \cong (145 - 120) / 5$ = **5 hours** $\qquad P = P_{sat}$ = **824 kPa**

3.41 Saturated liquid water at 60°C is put under pressure to decrease the volume by 1% keeping the temperature constant. To what pressure should it be compressed?

Solution: H_2O T = 60°C , x = 0.0; Table B.1.1

$v = 0.99 \times v_{f\ (60°C)} = 0.99 \times 0.001017 = 0.0010068\ m^3/kg$

Between 20 & 30 MPa in Table B.1.4, P ≅ **23.8 MPa**

3.42 Saturated water vapor at 60°C has its pressure decreased to increase the volume by 10% keeping the temperature constant. To what pressure should it be expanded?

Solution:

From initial state: $\quad v = 1.10 \times v_g = 1.1 \times 7.6707 = 8.4378\ m^3/kg$

Interpolate at 60°C between saturated (P = 19.94 kPa) and superheated vapor P = 10 kPa in Tables B.1.1 and B.1.3

$P \cong 19.941 + (8.4378 - 7.6707)(10-19.941)/(15.3345-7.6707)$ = **18.9 kPa**

Comment: T,v $\Rightarrow$ P = 18 kPa (software) v is not linear in P, more like 1/P, so the linear interpolation in P is not very accurate.

3.43 A boiler feed pump delivers 0.05 m^3/s of water at 240°C, 20 MPa. What is the mass flowrate (kg/s)? What would be the percent error if the properties of saturated liquid at 240°C were used in the calculation? What if the properties of saturated liquid at 20 MPa were used?

Solution:

At 240°C, 20 MPa: $v = 0.001205\ m^3/kg$ (from B.1.4)

$\dot{m} = \dot{V}/v = 0.05/0.001205 =$ **41.5 kg/s**

$v_{f\ (240°C)} = 0.001229 \Rightarrow \dot{m} = 40.68$ kg/s **error 2%**

$v_{f\ (20\ MPa)} = 0.002036 \Rightarrow \dot{m} = 24.56$ kg/s **error 41%**

3.44 A glass jar is filled with saturated water at 500 kPa, quality 25%, and a tight lid is put on. Now it is cooled to −10°C. What is the mass fraction of solid at this temperature?

Solution:

Constant volume and mass $\Rightarrow v_1 = v_2$ From Table B.1.2 and B.1.5:

$v_1 = 0.001093 + 0.25 \times 0.3738 = 0.094543 = v_2 = 0.0010891 + x_2 \times 446.756$

$\Rightarrow x_2 = 0.0002$ mass fraction vapor

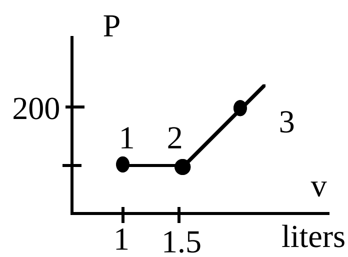
$x_{solid} = 1 - x_2 = 0.9998$ or **99.98 %**

3.45 A cylinder/piston arrangement contains water at 105°C, 85% quality with a volume of 1 L. The system is heated, causing the piston to rise and encounter a linear spring as shown in Fig. P3.45. At this point the volume is 1.5 L, piston diameter is 150 mm, and the spring constant is 100 N/mm. The heating continues, so the piston compresses the spring. What is the cylinder temperature when the pressure reaches 200 kPa?

Solution:

$P_1 = 120.8$ kPa, $v_1 = v_f + x\, v_{fg} = 0.001047 + 0.85*1.41831 = 1.20661$

$m = V_1 / v_1 = \frac{0.001}{1.20661} = 8.288\times10^{-4}$ kg



$v_2 = v_1 (V_2 / V_1) = 1.20661\times 1.5 = 1.8099$

& $P = P_1 = 120.8$ kPa ($T_2 = 203.5°C$)

$P_3 = P_2 + (k_s/A_p^2)\, m(v_3 - v_2)$ linear spring

$A_p = (\pi/4) \times 0.15^2 = 0.01767\ m^2$; $k_s = 100$ kN/m (matches P in kPa)

$200 = 120.8 + (100/0.01767^2) \times 8.288\times10^{-4}(v_3 - 1.8099)$

$200 = 120.8 + 265.446\ (v_3 - 1.8099) \Rightarrow \quad v_3 = 2.1083\ m^3/kg$

$T_3 \cong 600 + 100 \times (2.1083 - 2.01297)/(2.2443 - 2.01297) \cong$ **641°C**

3.46 Saturated (liquid + vapor) ammonia at 60°C is contained in a rigid steel tank. It is used in an experiment, where it should pass through the critical point when the system is heated. What should the initial mass fraction of liquid be?

Solution:

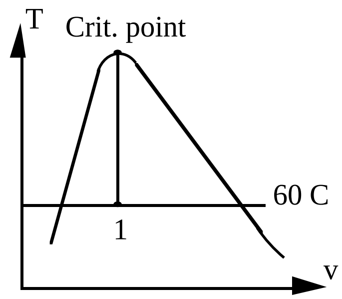
Process: Constant mass and volume, $v = C$

From table B.2.1:

$v_1 = v_2 = 0.004255 = 0.001834 + x_1 \times 0.04697$

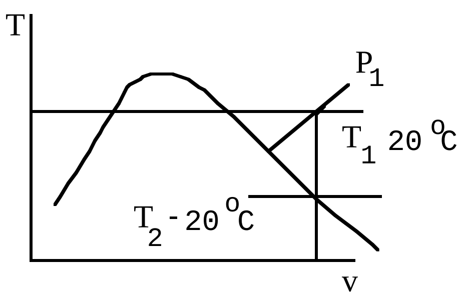
=> $x_1 = 0.01515$

liquid = $1 - x_1$ = **0.948**



3.47 For a certain experiment, R-22 vapor is contained in a sealed glass tube at 20°C. It is desired to know the pressure at this condition, but there is no means of measuring it, since the tube is sealed. However, if the tube is cooled to −20°C small droplets of liquid are observed on the glass walls. What is the initial pressure?

Solution: R-22 fixed volume (V) & mass (m) at 20°C cool to -20°C ~ sat. vapor



$v = \text{const} = v_{g \text{ at } -20°C} = 0.092843 \text{ m}^3\text{/kg}$

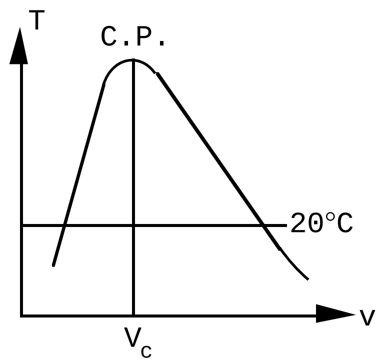
State 1: 20°C, $0.092843 \text{ m}^3\text{/kg}$

interpolate between 250 and 300 kPa in Table B.4.2

=> **P = 291 kPa**

3.48 A steel tank contains 6 kg of propane (liquid + vapor) at 20°C with a volume of 0.015 m^3. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 1 kg instead of 6 kg?

Solution: Constant volume and mass $v_2 = v_1 = V/m = 0.0025\ m^3/kg$



$v_c = 0.203/44.094 = 0.004604 > v_1$

eventually reaches sat. liq.

$\Rightarrow$ **level rises to top**

If m = 1 kg $\Rightarrow$ $v_1 = 0.015 > v_c$

then it will reach sat. vap.

$\Rightarrow$ **level falls**

3.49 A cylinder containing ammonia is fitted with a piston restrained by an external force that is proportional to cylinder volume squared. Initial conditions are 10°C, 90% quality and a volume of 5 L. A valve on the cylinder is opened and additional ammonia flows into the cylinder until the mass inside has doubled. If at this point the pressure is 1.2 MPa, what is the final temperature?

Solution:

State 1 Table B.2.1: $v_1 = 0.0016 + 0.9(0.205525 - 0.0016) = 0.18513\ m^3/kg$

$P_1 = 615$ kPa; $V_1 = 5\ L = 0.005\ m^3$

$m_1 = V/v = 0.005/0.18513 = 0.027$ kg

State 2: $P_2 = 1.2$ MPa, Flow in so: $m_2 = 2\ m_1 = 0.054$ kg

Process: Piston $F_{ext} = KV^2 = PA$ => $P = CV^2$ => $P_2 = P_1\ (V_2/V_1)^2$

From the process equation we then get:

$$V_2 = V_1\ (P_2/P_1)^{1/2} = 0.005\ \left(\frac{1200}{615}\right)^{1/2} = 0.006984\ m^3$$

$$v_2 = V/m = \frac{0.006984}{0.054} = 0.12934\ m^3/kg$$

At P_2, v_2: $T_2 =$ **70.9°C**

3.50 A container with liquid nitrogen at 100 K has a cross sectional area of 0.5 m^2. Due to heat transfer, some of the liquid evaporates and in one hour the liquid level drops 30 mm. The vapor leaving the container passes through a valve and a heater and exits at 500 kPa, 260 K. Calculate the volume rate of flow of nitrogen gas exiting the heater.

Solution:

Properties from table B.6.1 for volume change, exit flow from table B.6.2:

$$\Delta V = A \times \Delta h = 0.5 \times 0.03 = 0.015 \text{ m}^3$$

$$\Delta m_{liq} = -\Delta V/v_f \qquad = -0.015/0.001452 = -10.3306 \text{ kg}$$

$$\Delta m_{vap} = \Delta V/v_g \qquad = 0.015/0.0312 = 0.4808 \text{ kg}$$

$$m_{out} = 10.3306 - 0.4808 = 9.85 \text{ kg}$$

$$v_{exit} = 0.15385 \text{ m}^3/\text{kg}$$

$$\dot{V} = \dot{m}v_{exit} = (9.85 / 1h) \times 0.15385 = 1.5015 \text{ m}^3/\text{h} = \mathbf{0.02526\ m^3/min}$$

3.51 A pressure cooker (closed tank) contains water at 100°C with the liquid volume being 1/10 of the vapor volume. It is heated until the pressure reaches 2.0 MPa. Find the final temperature. Has the final state more or less vapor than the initial state?

Solution:

$$V_f = m_f v_f = V_g/10 = m_g v_g/10 \ ; \ v_f = 0.001044, \ v_g = 1.6729$$

$$x_1 = \frac{m_g}{m_g + m_f} = \frac{10\ m_f v_f / v_g}{m_f + 10\ m_f v_f / v_g} = \frac{10\ v_f}{10\ v_f + v_g} = \frac{0.01044}{0.01044 + 1.6729} = 0.0062$$

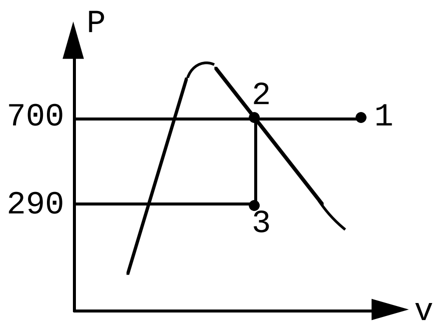
$$v_1 = 0.001044 + 0.0062 \times 1.67185 = 0.01141 = v_2 < v_g(2\text{MPa}) \text{ so two-phase}$$

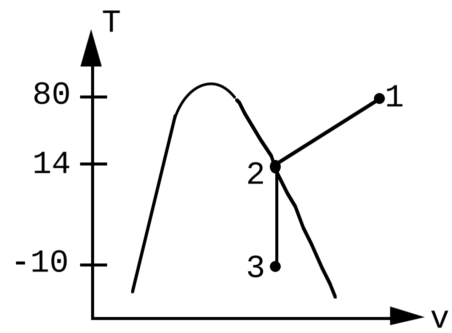
$$0.01141 = 0.001177 + x_2 \times 0.09845 \quad \Rightarrow \quad x_2 = 0.104 \quad \textbf{More vapor}$$

$$T_2 = T_{sat}(2\text{MPa}) = \mathbf{212.4°C}$$

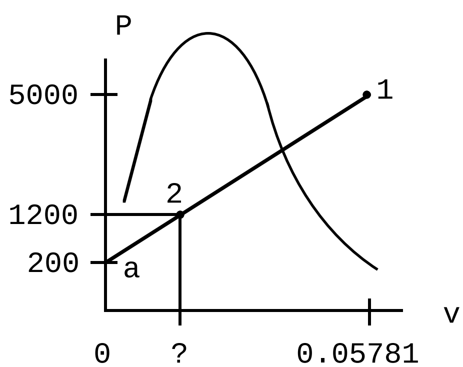
3.52 Ammonia in a piston/cylinder arrangement is at 700 kPa, 80°C. It is now cooled at constant pressure to saturated vapor (state 2) at which point the piston is locked with a pin. The cooling continues to −10°C (state 3). Show the processes 1 to 2 and 2 to 3 on both a *P–v* and *T–v* diagram.

Solution:





3.53 A piston/cylinder arrangement is loaded with a linear spring and the outside atmosphere. It contains water at 5 MPa, 400°C with the volume being 0.1 m^3. If the piston is at the bottom, the spring exerts a force such that P_{lift} = 200 kPa. The system now cools until the pressure reaches 1200 kPa. Find the mass of water, the final state (T_2, v_2) and plot the *P–v* diagram for the process.



1: Table B.1.3 $\Rightarrow$ v_1= 0.05781

$m = V/v_1 = 0.1/0.05781 = 1.73$ kg

Straight line: $P = P_a + Cv$

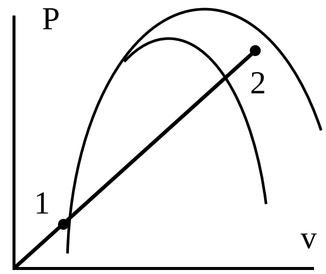
$$v_2 = v_1 \frac{P_2 - P_a}{P_1 - P_a} = \mathbf{0.01204\ m^3/kg}$$

$v_2 < v_g$(1200 kPa) so two-phase T_2 = **188°C**

$\Rightarrow$ $x_2 = (v_2 - 0.001139)/0.1622 = 0.0672$

3.54 Water in a piston/cylinder is at 90°C, 100 kPa, and the piston loading is such that pressure is proportional to volume, $P = CV$. Heat is now added until the temperature reaches 200°C. Find the final pressure and also the quality if in the two-phase region.

Solution:



Final state: 200°C , on process line $P = CV$

State 1: Table B.1.1: $v_1 = 0.001036 \text{ m}^3/\text{kg}$

$P_2 = P_1 v_2/v_1$ from process equation

Check state 2 in Table B.1.1

$v_g(T_2) = 0.12736$; $P_g(T_2) = 1.5538$ MPa

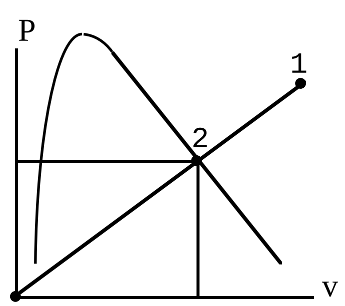
If $v_2 = v_g(T_2) \Rightarrow P_2 = 12.3 \text{ MPa} > P_g$ not OK

If sat. $P_2 = P_g(T_2) = 1553.8 \text{ kPa} \Rightarrow v_2 = 0.0161 \text{ m}^3\text{kg} < v_g$ sat. OK,

$\mathbf{P_2 = 1553.8\ kPa}$, $x_2 = (0.0161 - 0.001156) / 0.1262 = \mathbf{0.118}$

3.55 A spring-loaded piston/cylinder contains water at 500°C, 3 MPa. The setup is such that pressure is proportional to volume, $P = CV$. It is now cooled until the water becomes saturated vapor. Sketch the P-v diagram and find the final pressure.

Solution:



$P = Cv \Rightarrow C = P_1/v_1 = 3000/0.11619 = 25820$

State 2: $x_2 = 1$ & $P_2 = Cv_2$ (on process line)

Trial & error on T_{2sat} or P_{2sat}:

at 2 MPa $v_g = 0.09963 \Rightarrow C = 20074$

2.5 MPa $v_g = 0.07998 \Rightarrow C = 31258$

2.25 MPa $v_g = 0.08875 \Rightarrow C = 25352$

Interpolate to get right C $\Rightarrow$ $\mathbf{P_2 = 2270\ kPa}$

3.56 Refrigerant-12 in a piston/cylinder arrangement is initially at 50°C, $x = 1$. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 100 kPa. Find the final temperature and specific volume.

Solution:

State 1: 50°C, x=1 $\Rightarrow$ $P_1 = 1219.3$ kPa, $v_1 = 0.01417 \text{ m}^3/\text{kg}$

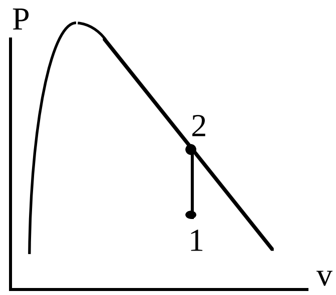
Process: $Pv = C = P_1 v_1$; => $P_2 = C/v_2 = P_1 v_1/v_2$

State 2: 100 kPa and $v_2 = v_1 P_1/P_2 = \mathbf{0.1728\ m^3/kg}$

$T_2 \cong \mathbf{-13.2°C}$ from Table B.3.2

3.57 A sealed rigid vessel of 2 m^3 contains a saturated mixture of liquid and vapor R-134a at 10°C. If it is heated to 50°C, the liquid phase disappears. Find the pressure at 50°C and the initial mass of the liquid.

Solution:



Process: constant volume and constant mass.

State 2 is saturated vapor, from table B.5.1

$P_2 = P_{sat}(50°C) = \mathbf{1.318\ MPa}$

State 1: same specific volume as state 2

$v_1 = v_2 = 0.015124\ m^3/kg$

$v_1 = 0.000794 + x_1 \times 0.048658$

$\Rightarrow\ x_1 = 0.2945$

$m = V/v_1 = 2/0.015124 = 132.24$ kg; $m_{liq} = (1 - x_1)m = \mathbf{93.295\ kg}$

3.58 Two tanks are connected as shown in Fig. P3.58, both containing water. Tank A is at 200 kPa, $v = 0.5\ m^3/kg$, $V_A = 1\ m^3$ and tank B contains 3.5 kg at 0.5 MPa, 400°C. The valve is now opened and the two come to a uniform state. Find the final specific volume.

Solution:

Control volume: both tanks. Constant total volume and mass process.

$m_A = V_A/v_A = 1/0.5 = 2$ kg

$v_B = 0.6173\ \Rightarrow\ V_B = m_B v_B = 3.5 \times 0.6173 = 2.1606\ m^3$

Final state: $m_{tot} = m_A + m_B = 5.5$ kg

$V_{tot} = V_A + V_B = 3.1606\ m^3$

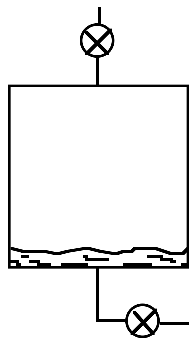
$v_2 = V_{tot}/m_{tot} = \mathbf{0.5746\ m^3/kg}$

3.59 A tank contains 2 kg of nitrogen at 100 K with a quality of 50%. Through a volume flowmeter and valve, 0.5 kg is now removed while the temperature remains constant. Find the final state inside the tank and the volume of nitrogen removed if the valve/meter is located at

a. The top of the tank

b. The bottom of the tank

Solution



$m_2 = m_1 - 0.5 = 1.5$ kg

$v_1 = 0.001452 + x_1 \times 0.029764 = 0.016334$

$V_{tank} = m_1 v_1 = 0.0327 \text{ m}^3$

$v_2 = V_{tank}/m_2 = 0.0218 < v_g(T)$

$$x_2 = \frac{0.0218\text{-}0.001452}{0.031216\text{-}0.001452} = \mathbf{0.6836}$$

Top: flow out is sat. vap. $v_g = 0.031216$

$$V_{out} = m_{out} v_g = \mathbf{0.0156\ m^3}$$

Bottom: flow out is sat. liq. $v_f = 0.001452$

$$V_{out} = m_{out} v_f = \mathbf{0.000726\ m^3}$$

3.60 Consider two tanks, A and B, connected by a valve, as shown in Fig. P3.60. Each has a volume of 200 L and tank A has R-12 at 25°C, 10% liquid and 90% vapor by volume, while tank B is evacuated. The valve is now opened and saturated vapor flows from A to B until the pressure in B has reached that in A, at which point the valve is closed. This process occurs slowly such that all temperatures stay at 25°C throughout the process. How much has the quality changed in tank A during the process?

$$m_{A1} = \frac{V_{liq1}}{v_{f\ 25°C}} + \frac{V_{vap1}}{v_{g\ 25°C}} = \frac{0.1 \times 0.2}{0.000763} + \frac{0.9 \times 0.2}{0.026854} = 26.212 + 6.703 = 32.915 \text{ kg}$$

$$x_{A1} = \frac{6.703}{32.915} = 0.2036 \ ; \quad m_{B2} = \frac{V_B}{v_{g\ 25°C}} = \frac{0.2}{0.26854} = 7.448 \text{ kg}$$

$$\Rightarrow m_{A2} = 32.915 - 7.448 = 25.467 \text{ kg}$$

$$v_{A2} = \frac{0.2}{25.467} = 0.007853 = 0.000763 + x_{A2} \times 0.026091$$

$x_{A2} = 0.2718 \quad \Delta x = \mathbf{6.82\%}$

English Unit Problems

3.61E A substance is at 300 lbf/in.^{2}, 65 F in a rigid tank. Using only the critical properties can the phase of the mass be determined if the substance is nitrogen, water or propane?

Solution: Find state relative to the critical point properties, table C.1

Nitrogen	492 lbf/in.^{2}	227.2 R
Water	3208 lbf/in.^{2}	1165.1 R
Propane	616 lbf/in.^{2}	665.6 R

$P < P_c$ for all and $T = 65\text{ F} = 65 + 459.67 = 525\text{ R}$

N_2	$T >> T_c$	Yes gas and $P < P_c$
H_2O	$T << T_c$	$P << P_c$ so you cannot say
C_3H_8	$T < T_c$	$P < P_c$ you cannot say

3.62E A cylindrical gas tank 3 ft long, inside diameter of 8 in., is evacuated and then filled with carbon dioxide gas at 77 F. To what pressure should it be charged if there should be 2.6 lbm of carbon dioxide?

Solution:

Assume CO_2 is an ideal gas table C.4: $P = mRT/V$

$$V_{cyl} = A \times L = \frac{\pi}{4}(8)^2 \times 3 \times 12 = 1809.6\text{ in}^3$$

$$P = \frac{2.6 \times 35.1 \times (77 + 459.67) \times 12}{1809.6} = \mathbf{324.8\ lbf/in^2}$$

3.63E A vacuum pump is used to evacuate a chamber where some specimens are dried at 120 F. The pump rate of volume displacement is 900 ft^3/min with an inlet pressure of 1 mm Hg and temperature 120 F. How much water vapor has been removed over a 30-min period?

Solution:

Use ideal gas as $P <<$ lowest P in steam tables. R is from table C.4

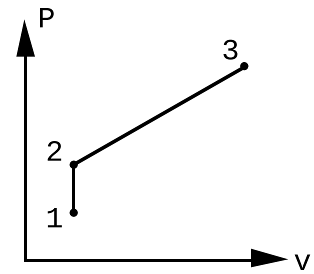
$P = 1\text{ mmHg} = 0.01934\text{ lbf/in}^2$

$$\dot{m} = \frac{P\dot{V}}{RT} \Rightarrow m = \frac{P\dot{V}\Delta t}{RT} = \frac{0.01934 \times 900 \times 30 \times 144}{85.76 \times (120 + 459.67)} = \mathbf{1.513\ lbm}$$

3.64E A cylinder is fitted with a 4-in.-diameter piston that is restrained by a linear spring (force proportional to distance) as shown in Fig. P3.16. The spring force constant is 400 lbf/in. and the piston initially rests on the stops, with a cylinder volume of 60 in.^{3}. The valve to the air line is opened and the piston begins to rise when the cylinder pressure is 22 lbf/in.^{2}. When the valve is closed, the cylinder volume is 90 in.^{3} and the temperature is 180 F. What mass of air is inside the cylinder?

Solution: $V_1 = V_2 = 60\ in^3$; $A_p = \frac{\pi}{4} \times 4^2 = 12.566\ in^2$

$P_2 = 22\ lbf/in^2$; $V_3 = 90\ in^3$, $T_3 = 180°F = 639.7\ R$



Linear spring: $P_3 = P_2 + \frac{k_s(V_3\text{-}V_2)}{A_p^2}$

$= 22 + \frac{400}{12.566^2}(90\text{-}60) = 98\ lbf/in^2$

$$m = \frac{P_3V_3}{RT_3} = \frac{98 \times 90}{12 \times 53.34 \times 639.7} = \mathbf{0.02154\ lbm}$$

3.65E A substance is at 70 F, 300 lbf/in.^{2} in a 10 ft^3 tank. Estimate the mass from the compressibility chart if the substance is a) air, b) butane or c) propane.
Solution:

Use Fig. D.1 for compressibility Z and table C.1 for critical properties

m =PV/ZRT = 300 ×144 ×10 / 530 Z R = 815.09 / Z R = 815.09 / Z R

Air use nitrogen 492 lbf/in.^{2}**;** 227.2 R $P_r = 0.61$; $T_r = 2.33$; Z = 0.98

m =PV/ZRT = 815.09 / Z R = 815.09/(0.98× 55.15) = **15.08 lbm**

Butane 551 lbf/in.^{2}**;** 765.4 R $P_r = 0.544$; $T_r = 0.692$; Z = 0.09

m =PV/ZRT = 815.09 / Z R = 815.09 /(0.09× 26.58) = **340.7 lbm**

Propane 616 lbf/in.^{2}; 665.6 R $P_r = 0.487$; $T_r = 0.796$; Z = 0.08

m =PV/ZRT = 815.09 / Z R = 815.09 / (0.08× 35.04) = **290.8 lbm**

3.66E Determine the mass of an ethane gas stored in a 25 ft^3 tank at 250 F, 440 lbf/in.^{2} using the compressibility chart. Estimate the error (%) if the ideal gas model is used.

Solution

Table C.1: T_r = (250 + 460) / 549.7 = 1.29 and P_r = 440/708 = 0.621

Figure D.1 ⇒ Z = 0.9

m = PV/ZRT = 440 × 144 × 25 / (51.38 × 710 × 0.9) = **48.25 lbm**

Ideal gas Z = 1 ⇒ m = 43.21 lbm **10% error**

3.67E Argon is kept in a rigid 100 ft^3 tank at –30 F, 450 lbf/in.^{2}. Determine the mass using the compressibility factor. What is the error (%) if the ideal gas model is used?

Solution: Use the generalized chart in Fig. D.1 and critical values from C.1.

T_r = (460 – 30) / 271.4 = 1.58, P_r = 450/706 = 0.64 $\Rightarrow$ Z = 0.95

$m = PV/ZRT = 450 \times 144 \times 100 / (0.95 \times 38.68 \times 430) =$ **410 lbm**

Ideal gas Z = 1 $\Rightarrow$ m = PV/RT = 390 lbm **5% error**

3.68E Determine whether water at each of the following states is a compressed liquid, a superheated vapor, or a mixture of saturated liquid and vapor.

Solution: All cases can be seen from Table C.8.1

a. 1800 lbf/in.^{2}, 0.03 ft^3/lbm

v_g **= 0.2183,** v_f **= 0.02472** ft^3/lbm, so **liq + vap. mixture**

b. 150 lbf/in.^{2}, 320 F: **compr. liquid** P > P_{sat}(T) **= 89.6 lbf/in^2**

c. 380 F, 3 ft^3/lbm: **sup. vapor** v > v_g(T) **= 2.339** ft^3/lbm

d. 2 lbf/in.^{2}, 50 F: **compr. liquid** P > P_{sat}(T) = **0.178**

e. 270 F, 30 lbf/in.^{2}: **sup. vapor** P < P_{sat}(T) = **41.85 lbf/in^2**

f. 160 F, 10 ft^3/lbm

v_g = **77.22,** v_f = **0.0164** ft^3/lbm, so **liq. + vap. mixture**

3.69E Give the phase and the specific volume.

Solution:

a. H_2O *T* = 520F *P* = 700 lbf/in.^{2} Table C.8.1
Psat = 811.5 => **sup. vapor** v = **0.6832 ft^3/lbm**

b. H_2O *T* = 30 F *P* = 15 lbf/in.^{2} Table C.8.4
Psat = 0.0886 => compr. solid **v = v_i = 0.01747 ft^3/lbm**

c. CO_2 *T* = 510 F *P* = 75 lbf/in.^{2} Table C.4

sup. vap. ideal gas $v = RT/P = \dfrac{35.1 \times (510 + 459.7)}{75 \times 144} =$ **3.152 ft^3/lbm**

d. Air *T* = 68 F *P* = 2 atm Table C.4

sup. vap. ideal gas $v = RT/P = \dfrac{53.34 \times (68 + 459.7)}{2 \times 14.6 \times 144} =$ **6.6504 ft^3/lbm**

e. NH_3 *T* = 290 F *P* = 90 lbf/in.^{2} Table C.9.2
sup. vap. v = **4.0965 ft^3/lbm**

3.70E Give the phase and the specific volume.

Solution:

a. R-22 $T = -10$ F, $P = 30$ lbf/in.^{2} Table C.10.1 $P < P_{sat} = 31.2$ psia

$\Rightarrow$ sup.vap. $v \cong 1.7439 + \frac{-10+11.71}{11.71}(1.7997 - 1.7439) = \mathbf{1.752\ ft^3/lbm}$

b. R-22 $T = -10$ F, $P = 40$ lbf/in.^{2} Table C.10.1 $P_{sat} = 31.2$ psia

$P > P_{sat} \Rightarrow$ compresssed Liquid $v \cong v_f = \mathbf{0.01178\ ft^3/lbm}$

c. H_2O $T = 280$ F, $P = 35$ lbf/in.^{2} Table C.8.1 $P < P_{sat} = 49.2$ psia

$\Rightarrow$ sup.vap $v \cong 21.734 + (10.711 - 21.734) \times (15/20) = \mathbf{1.0669\ ft^3/lbm}$

d. Ar $T = 300$ F, $P = 30$ lbf/in.^{2} Table C.4

Ideal gas: $v = RT/P = 38.68\ (300 + 459.7) / (30 \times 144) = \mathbf{6.802\ ft^3/lbm}$

e. NH_3 $T = 60$ F, $P = 15$ lbf/in.^{2} Table C.9.1 $P_{sat} = 107.6$ psia

$P < P_{sat} \Rightarrow$ sup.vap $v \cong \mathbf{21.564\ ft^3/lbm}$

3.71E Give the phase and the missing properties of *P*, *T*, *v* and *x*. These may be a little more difficult if the appendix tables are used instead of the software.

Solution:

a. R-22 at $T = 50$ F, $v = 0.6$ ft^3/lbm: Table C.10.1 $v > v_g$

sup. vap. C.10.2 interpolate between sat. and sup. vap at 50F.

$P \cong 98.73 + (0.6 - 0.5561)(80 - 98.73)/(0.708 - 0.5561) = \mathbf{93.3\ lbf/in^2}$

b. H_2O $v = 2$ ft^3/lbm, $x = 0.5$: Table C.8.1

since v_f is so small we find it approximately where $v_g = 4$ ft^3/lbm.

$v_f + v_g = 4.3293$ at 330 F, $v_f + v_g = 3.80997$ at 340 F.

linear interpolation $T \cong$ **336 F,** $P \cong \mathbf{113\ lbf/in^2}$

c. H_2O $T = 150$ F, $v = 0.01632$ ft^3/lbm: Table C.8.1, $v < v_f$

compr. liquid $P \cong \mathbf{500\ lbf/in^2}$

d. NH_3 $T = 80$ F, $P = 13$ lbf/in.^{2} Table C.9.1 P < Psat

sup. vap. interpolate between 10 and 15 psia: $v = \mathbf{26.97\ ft^3/lbm}$

v is not linear in P (more like 1/P) so computer table is more accurate.

e. R-134a $v = 0.08$ ft^3/lbm, $x = 0.5$: Table C.11.1

since v_f is so small we find it approximately where $v_g = 0.16$ ft^3/lbm.

$v_f + v_g = 0.1729$ at 150 F, $v_f + v_g = 0.1505$ at 160 F.

linear interpolation $T \cong$ **156 F,** $P \cong \mathbf{300\ lbf/in^2}$

3.72E What is the percent error in specific volume if the ideal gas model is used to represent the behavior of superheated ammonia at 100 F, 80 lbf/in.^{2}? What if the generalized compressibility chart, Fig. D.1, is used instead?

Solution:

Ammonia Table C.9.2: $v = 4.186\ \mathrm{ft^3/lbm}$

Ideal gas $v = \dfrac{RT}{P} = \dfrac{90.72 \times 559.7}{80 \times 144} = 4.4076\ \mathrm{ft^3/lbm}$ **5.3% error**

Generalized compressibility chart and Table C.1

$T_r = 559.7/729.9 = 0.767,\ \ P_r = 80/1646 = 0.0486 \ \ \Rightarrow \ \ Z \cong 0.96$

$v = ZRT/P = 0.96 \times 4.4076 = 4.231\ \mathrm{ft^3/lbm}$ **1.0% error**

3.73E A water storage tank contains liquid and vapor in equilibrium at 220 F. The distance from the bottom of the tank to the liquid level is 25 ft. What is the absolute pressure at the bottom of the tank?

Solution:

Table C.8.1: $v_f = 0.01677\ \mathrm{ft^3/lbm}$

$$\Delta P = \frac{g\,l}{g_c v_f} = \frac{32.174 \times 25}{32.174 \times 0.01677 \times 144} = \mathbf{10.35\ lbf/in^2}$$

3.74E A sealed rigid vessel has volume of 35 ft^3 and contains 2 lbm of water at 200 F. The vessel is now heated. If a safety pressure valve is installed, at what pressure should the valve be set to have a maximum temperature of 400 F?

Solution:

Process: $v = V/m = \text{constant} = v_1 = 17.5\ \mathrm{ft^3/lbm}$

Table C.8.2: 400 F, 17.5 ft^3/lbm $\Rightarrow$ between 20 & 40 lbf/in^2

$P \cong$ **32.4 lbf/in^2** (28.97 by software)

3.75E Saturated liquid water at 200 F is put under pressure to decrease the volume by 1%, keeping the temperature constant. To what pressure should it be compressed?

Solution:

$v = 0.99 \times v_f = 0.99 \times 0.016634 = 0.016468\ \mathrm{ft^3/lbm}$

Table C.8.4 $P \sim$ **3200 lbf/in^2**

3.76E Saturated water vapor at 200 F has its pressure decreased to increase the volume by 10%, keeping the temperature constant. To what pressure should it be expanded?

Solution:

$v = 1.1 \times v_g = 1.1 \times 33.63 = 36.993\ ft^3/lbm$

Interpolate between sat. at 200 F and sup. vapor in Table C.8.2 at 200 F, 10 lbf/in^2 $\qquad$ $P \cong$ **10.54 lbf/in^2**

3.77E A boiler feed pump delivers 100 ft^3/min of water at 400 F, 3000 lbf/in.^{2}. What is the mass flowrate (lbm/s)? What would be the percent error if the properties of saturated liquid at 400 F were used in the calculation? What if the properties of saturated liquid at 3000 lbf/in.^{2} were used?

Solution: Table C.8.4: $v = 0.0183\ ft^3/lbm$

$$\dot{m} = \frac{\dot{V}}{v} = \frac{100}{60 \times 0.018334} = 91.07\ lbm/s$$

$v_{f\ (400\ F)} = 0.01864 \Rightarrow \dot{m} = 89.41$ **error 1.8%**

$v_{f\ (3000\ lbf/in^2)} = 0.03475 \Rightarrow \dot{m} = 47.96$ **error 47%**

3.78E Saturated (liquid + vapor) ammonia at 140 F is contained in a rigid steel tank. It is used in an experiment, where it should pass through the critical point when the system is heated. What should the initial mass fraction of liquid be?

Solution:

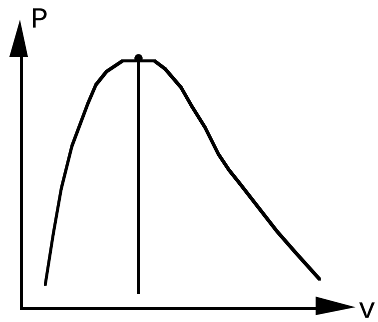
P process constant volume & mass. From Table C.9.1:

$v_1 = v_c = 0.031532\ ft^3/lbm = 0.01235 + x_1 \times 1.1398 \quad => \quad x_1 = 0.01683$

Liquid fraction = $1 - x_1$ = **0.983**

3.79E A steel tank contains 14 lbm of propane (liquid + vapor) at 70 F with a volume of 0.25 ft^3. The tank is now slowly heated. Will the liquid level inside eventually rise to the top or drop to the bottom of the tank? What if the initial mass is 2 lbm instead of 14 lbm?

Solution:



Constant volume and mass

$v_2 = v_1 = V/m = 0.25/14 = 0.01786$

$v_c = 3.2/44.097 = 0.07256$ ft^3/lbm

$v_2 < v_c$ so eventually sat. liquid

$\Rightarrow$ **level rises**

If $\quad v_2 = v_1 = 0.25/2 = 0.125 > v_c$

Now sat. vap. is reached so **level drops**

3.80E A pressure cooker (closed tank) contains water at 200 F with the liquid volume being 1/10 of the vapor volume. It is heated until the pressure reaches 300 lbf/in.^{2}. Find the final temperature. Has the final state more or less vapor than the initial state?

Solution:

Process: Constant volume and mass.

$V_f = m_f v_f = V_g/10 = m_g v_g/10;$ Table C.8.1: $v_f = 0.01663,\quad v_g = 33.631$

$$x_1 = \frac{m_g}{m_g + m_f} = \frac{10\ m_f v_f / v_g}{m_f + 10\ m_f v_f / v_g} = \frac{10\ v_f}{10\ v_f + v_g} = \frac{0.1663}{0.1663 + 33.631} = 0.00492$$

$v_2 = v_1 = 0.01663 + x_1 \times 33.615 = 0.1820$ ft^3/lbm

$P_2, v_2 \Rightarrow T_2 = T_{sat} = \mathbf{417.43\ F}$

$0.1820 = 0.01890 + x_2 \times 1.5286$

$x_2 = \mathbf{0.107}$ more vapor than state 1.

3.81E Two tanks are connected together as shown in Fig. P3.58, both containing water. Tank A is at 30 lbf/in.^{2}, v = 8 ft^3/lbm, V = 40 ft^3 and tank B contains 8 lbm at 80 lbf/in.^{2}, 750 F. The valve is now opened and the two come to a uniform state. Find the final specific volume.

Solution:

Control volume both tanks. Constant total volume and mass.

$m_A = V_A/v_A = 40/8 = 5$ lbm

Table C.8.2: $v_B = (8.561 + 9.322)/2 = 8.9415$

$\Rightarrow\ V_B = m_B v_B = 8 \times 8.9415 = 71.532\ \text{ft}^3$

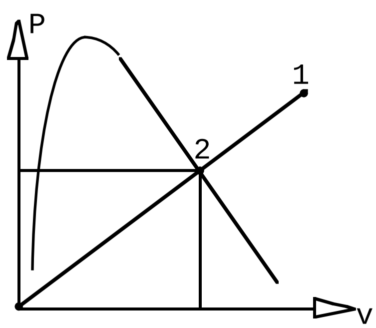
Final state: $m_{tot} = m_A + m_B = 5 + 8 = 13$ lbm

$V_{tot} = V_A + V_B = 111.532\ \text{ft}^3$

$v_2 = V_{tot}/m_{tot} = 111.532/13 =$ **$8.579\ \text{ft}^3/\text{lbm}$**

3.82E A spring-loaded piston/cylinder contains water at 900 F, 450 lbf/in.^{2}. The setup is such that pressure is proportional to volume, $P = CV$. It is now cooled until the water becomes saturated vapor. Find the final pressure.

Solution:



State 1: $v_1 = 1.7524\ \text{ft}^3/\text{lbm}$

$P = Cv \ \Rightarrow\ C = P_1/v_1 = 256.79$

State 2: sat. vap. $x_2 = 1$

Trial & error on T_2 or P_2

At 350 lbf/in^2: $P_g/v_g = 263.8\ > C$

At 300 lbf/in^2: $P_g/v_g = 194.275\ < C$

Interpolation: $P_2 \cong$ **345 lbf/in^2**

3.83E Refrigerant-22 in a piston/cylinder arrangement is initially at 120 F, $x = 1$. It is then expanded in a process so that $P = Cv^{-1}$ to a pressure of 30 lbf/in.^{2}. Find the final temperature and specific volume.

Solution:

State 1: $P_1 = 274.6$ lbf/in^2 $\quad v_1 = 0.1924$ ft^3/lbm

Process: $Pv = C = P_1v_1 = P_2v_2$

State 2: $P_2 = 30$ lbf/in^2 and on process line (equation).

$$v_2 = \frac{v_1P_1}{P_2} = 0.1924 \times 274.6/30 = \mathbf{1.761\ ft^3/lbm}$$

Table C.10.2 between saturated at -11.71 F and 0 F: $\quad T_2 \cong$ **-8.1 F**

CHAPTER 4

The new problem set relative to the problems in the fourth edition.

New	Old	New	Old	New	Old
1	new	21	21	41	41
2	new	22	22	42	42
3	4	23	23	43	43 mod
4	5	24	24 mod	44	32
5	1	25	25	45	16
6	2	26	new	46	33
7	7	27	27	47	new HT
8	new	28	26 mod	48	new HT
9	new	29	28	49	new HT
10	new	30	29	50	new HT
11	8	31	30	51	new HT
12	9	32	new	52	new HT
13	new	33	14	53	new HT
14	11	34	34	54	new HT
15	new	35	35	55	new HT
16	13	36	37	56	new HT
17	15	37	38	57	new HT
18	31	38	20	58	44
19	18	39	39	59	45
20	new	40	40	60	46
				61	47 mod

English unit problems

62	48	68	57	74	59
63	new	69	new	75	60 mod
64	49	70	54	76	61
65	50	71	55 mod	77	new
66	new	72	56	78	new
67	52	73	new	79	new

4.1 A piston of mass 2 kg is lowered 0.5 m in the standard gravitational field. Find the required force and work involved in the process.

Solution:

$$F = ma = 2 \times 9.80665 = \mathbf{19.61\ N}$$

$$W = \int F\,dx = F \int dx = F\,\Delta x = 19.61 \times 0.5 = \mathbf{9.805\ J}$$

4.2 An escalator raises a 100 kg bucket of sand 10 m in 1 minute. Determine the total amount of work done and the instantaneous rate of work during the process.

Solution:

$$W = \int F\,dx = F \int dx = F\,\Delta x = 100 \times 9.80665 \times 10 = \mathbf{9807\ J}$$

$$\dot{W} = W / \Delta t = 9807 / 60 = \mathbf{163\ W}$$

4.3 A linear spring, $F = k_s(x - x_o)$, with spring constant $k_s = 500$ N/m, is stretched until it is 100 mm longer. Find the required force and work input.

Solution:

$$F = k_s(x - x_0) = 500 \times 0.1 = \mathbf{50\ N}$$

$$W = \int F\,dx = \int k_s(x - x_0)d(x - x_0) = k_s(x - x_0)^2/2$$

$$= 500 \times 0.1^2/2 = \mathbf{2.5\ J}$$

4.4 A nonlinear spring has the force versus displacement relation of $F = k_{ns}(x - x_o)^n$. If the spring end is moved to x_1 from the relaxed state, determine the formula for the required work.

Solution:

$$W = \int F dx = \int k_{ns}(x - x_0)^n\, d(x - x_0) = \frac{k_{ns}}{n + 1}(x_1 - x_0)^{n+1}$$

4.5 A cylinder fitted with a frictionless piston contains 5 kg of superheated refrigerant R-134a vapor at 1000 kPa, 140°C. The setup is cooled at constant pressure until the R-134a reaches a quality of 25%. Calculate the work done in the process.

Solution:

Constant pressure process boundary work. State properties from Table B.5.2

State 1: $v = 0.03150\ m^3/kg$,

State 2: $v = 0.000871 + 0.25 \times 0.01956 = 0.00576\ m^3/kg$

Interpolated to be at 1000 kPa, numbers at 1017 kPa could have been used in which case: $v = 0.00566$

$$W_{12} = \int P\,dV = P\,(V_2 - V_1) = mP\,(v_2 - v_1)$$

$$= 5 \times 1000(0.00576 - 0.03150) = \mathbf{-128.7\ kJ}$$

4.6 A piston/cylinder arrangement shown in Fig. P4.6 initially contains air at 150 kPa, 400°C. The setup is allowed to cool to the ambient temperature of 20°C.

a. Is the piston resting on the stops in the final state? What is the final pressure in the cylinder?

b. What is the specific work done by the air during this process?

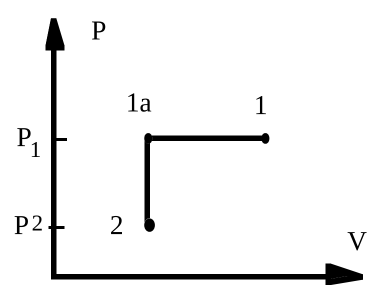
Solution:

$P_1 = 150$ kPa, $T_1 = 400°C = 673.2$ K

$T_2 = T_0 = 20°C = 293.2$ K

For all states air behave as an ideal gas.

a) If piston at stops at 2, $V_2 = V_1/2$ and pressure less than $P_{lift} = P_1$



$$\Rightarrow P_2 = P_1 \times \frac{V_1}{V_2} \times \frac{T_2}{T_1} = 150 \times 2 \times \frac{293.2}{673.2} = 130.7\ \text{kPa} < P_1$$

$\Rightarrow$ Piston is resting on stops.

b) Work done while piston is moving at const $P_{ext} = P_1$.

$$W_{12} = \int P_{ext}\,dV = P_1\,(V_2 - V_1)\ ; \quad V_2 = \frac{1}{2}V_1 = \frac{1}{2}m\ RT_1/P_1$$

$$w_{12} = W_{12}/m = RT_1\,(\frac{1}{2} - 1\,) = -\frac{1}{2} \times 0.287 \times 673.2 = \mathbf{-96.6\ kJ/kg}$$

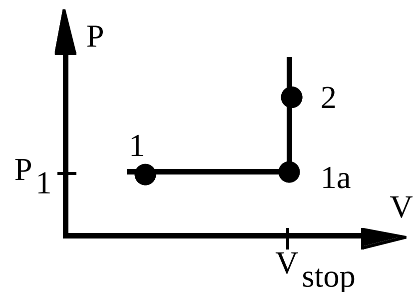
4.7 The refrigerant R-22 is contained in a piston/cylinder as shown in Fig. P4.7, where the volume is 11 L when the piston hits the stops. The initial state is –30°C, 150 kPa with a volume of 10 L. This system is brought indoors and warms up to 15°C.

a. Is the piston at the stops in the final state?

b. Find the work done by the R-22 during this process.

Solution:

Initially piston floats, $V < V_{stop}$ so the piston moves at constant $P_{ext} = P_1$ until it reaches the stops or 15°C, whichever is first.



a) From Table B.4.2: $v_1 = 0.1487$,

$$m = V/v = \frac{0.010}{0.1487} = 0.06725 \text{ kg}$$

Check the temperature at state 1a: $P_{1a} = 150$ kPa, $v = V_{stop}/m$.

$$v_2 = V/m = \frac{0.011}{0.06725} = 0.16357 \text{ m}^3\text{/kg} \quad => \quad T_{1a} = -9\ °C \ \ \& \ T_2 = 15°C$$

Since $T_2 > T_{1a}$ then it follows that $P_2 > P_1$ and the piston is againts stop.

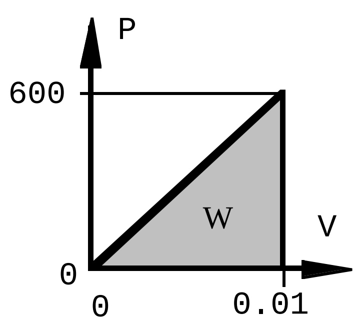
b) Work done at const $P_{ext} = P_1$.

$$W_{12} = \int P_{ext}\, dV = P_{ext}(V_2 - V_1) = 150(0.011 - 0.010) = \mathbf{0.15\ kJ}$$

4.8 Consider a mass going through a polytropic process where pressure is directly proportional to volume (n = – 1). The process start with $P = 0$, $V = 0$ and ends with $P = 600$ kPa, $V = 0.01$ m^3.The physical setup could be as in Problem 2.22. Find the boundary work done by the mass.

Solution:

The setup has a pressure that varies linear with volume going through the initial and the final state points. The work is the area below the process curve.



$$W = \int P dV = \text{AREA}$$

$$= \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(P_2 + 0)(V_2 - 0)$$

$$= \frac{1}{2} P_2 V_2 = \frac{1}{2} \times 600 \times 0.01 = \mathbf{3\ kJ}$$

4.9 A piston/cylinder contains 50 kg of water at 200 kPa with a volume of 0.1 m^3. Stops in the cylinder restricts the enclosed volume to 0.5 m^3, similar to the setup in Problem 4.7. The water is now heated to 200°C. Find the final pressure, volume and the work done by the water.

Solution:

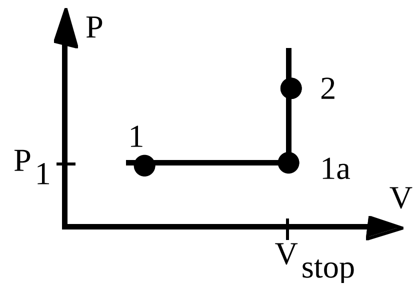
Initially the piston floats so the equilibrium lift pressure is 200 kPa

1: 200 kPa, $v_1 = 0.1/50 = 0.002\ m^3/kg$,

2: 200 °C, ON LINE

Check state 1a: $v_{stop} = 0.5/50 = 0.01$ =>

Table B.1.2: 200 kPa , $v_f < v_{stop} < v_g$



State 1a is two phase at 200 kPa and $T_{stop} \approx 120.2$ °C so as $T_2 > T_{stop}$ the state is higher up in the P-V diagram with $v_2 = v_{stop} < v_g = 0.127$ (at 200°C)

State 2 two phase => $P_2 = P_{sat}(T_2) =$ **1.554 MPa**, $V_2 = V_{stop} =$ **0.5 m³**

$${}_1W_2 = {}_1W_{stop} = 200\ (0.5 - 0.1) = \mathbf{80\ kJ}$$

4.10 A piston/cylinder contains 1 kg of liquid water at 20°C and 300 kPa. Initially the piston floats, similar to the setup in Problem 4.7, with a maximum enclosed volume of 0.002 m^3 if the piston touches the stops. Now heat is added so a final pressure of 600 kPa is reached. Find the final volume and the work in the process.

Solution:

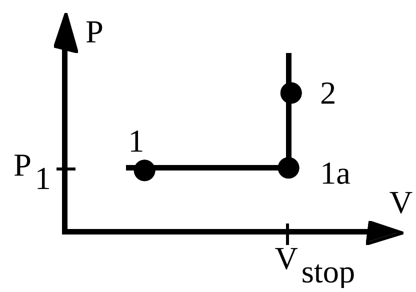
Take CV as the water which is a control mass: $m_2 = m_1 = m$;

Table B.1.1: 20°C => $P_{sat} = 2.34$ kPa

State 1: Compressed liquid

$v = v_f(20) = 0.001002\ m^3/kg$

State 1a: $v_{stop} = 0.002\ m^3/kg$, 300 kPa



State 2: Since $P = 600 > P_{lift}$ then $v = v_{stop} = 0.002$ and $V = 0.002\ m^3$

For the given P : $v_f < v < v_g$ so 2-phase $T = T_{sat} = 158.85$ °C

Work is done while piston moves at P_{lift} = constant = 300 kPa so we get

$${}_1W_2 = \int P\,dV = m\,P_{lift}(v_2 - v_1) = 1 \times 300(0.002 - 0.001002) = \mathbf{0.30\ kJ}$$

4.11 A piston/cylinder contains butane, C_4H_{10}, at 300°C, 100 kPa with a volume of 0.02 m^3. The gas is now compressed slowly in an isothermal process to 300 kPa.

a. Show that it is reasonable to assume that butane behaves as an ideal gas during this process.

b. Determine the work done by the butane during the process.

Solution:

a) $T_{r1} = \dfrac{T}{T_c} = \dfrac{573.15}{425.2} = 1.35;\qquad P_{r1} = \dfrac{P}{P_c} = \dfrac{100}{3800} = 0.026$

From the generalized chart in figure D.1 $\quad Z_1 = 0.99$

$T_{r2} = \dfrac{T}{T_c} = \dfrac{573.15}{425.2} = 1.35;\qquad P_{r2} = \dfrac{P}{P_c} = \dfrac{300}{3800} = 0.079$

From the generalized chart in figure D.1 $\quad Z_2 = 0.98$

Ideal gas model is adequate for both states.

b) Ideal gas $\quad T = \text{constant} \;\Rightarrow\; PV = mRT = \text{constant}$

$$W = \int PdV = P_1V_1 \ln\frac{P_1}{P_2} = 100 \times 0.02 \times \ln\frac{100}{300} = \mathbf{-2.2\ kJ}$$

4.12 The piston/cylinder shown in Fig. P4.12 contains carbon dioxide at 300 kPa, 100°C with a volume of 0.2 m^3. Mass is added at such a rate that the gas compresses according to the relation $PV^{1.2}$ = constant to a final temperature of 200°C. Determine the work done during the process.

Solution:

From Eq. 4.4 for $PV^n = \text{const}\ (n \neq 1)$

$$W_{12} = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1 - n}$$

Assuming ideal gas, PV = mRT

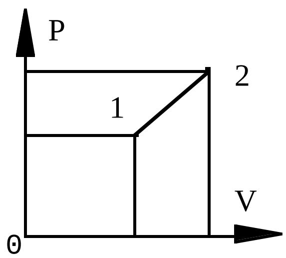
$$W_{12} = \frac{mR(T_2 - T_1)}{1 - n}, \quad \text{But} \quad mR = \frac{P_1V_1}{T_1} = \frac{300 \times 0.2}{373.15} = 0.1608$$

$$W_{12} = \frac{0.1608(473.2 - 373.2)}{1 - 1.2} = \mathbf{-80.4\ kJ}$$

4.13 Air in a spring loaded piston/cylinder has a pressure that is linear with volume, $P = A + BV$. With an initial state of P = 150 kPa, V = 1 L and a final state of 800 kPa and volume 1.5 L it is similar to the setup in Problem 3.16. Find the work done by the air.

Solution:

Knowing the process equation: P = A + BV giving a linear variation of pressure versus volume the straight line in the P-V diagram is fixed by the two points as state 1 and state 2. The work as the integral of PdV equals the area under the process curve in the P-V diagram.



State 1: $P_1 = 150$ kPa $V_1 = 1$ L $= 0.001$ m^3

State 2: $P_2 = 800$ kPa $V_2 = 1.5$ L $= 0.0015$ m^3

Process: P = A + BV linear in V

$$\Rightarrow {}_1W_2 = \int_1^2 PdV = \left(\frac{P_1 + P_2}{2}\right)(V_2 - V_1)$$

$$= \frac{1}{2}(150 + 800)(1.5 - 1)\times 0.001 = \mathbf{0.2375\ kJ}$$

4.14 A gas initially at 1 MPa, 500°C is contained in a piston and cylinder arrangement with an initial volume of 0.1 m^3. The gas is then slowly expanded according to the relation $PV =$ constant until a final pressure of 100 kPa is reached. Determine the work for this process.

Solution:

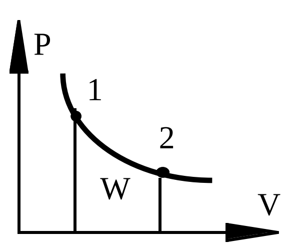
By knowing the process and the states 1 and 2 we can find the relation between the pressure and the volume so the work integral can be performed.

Process: PV = C $\Rightarrow$ $V_2 = P_1V_1/P_2 = 1000 \times 0.1/100 = 1$ m^3

$$W_{12} = \int P\, dV = \int CV^{-1}dV = C \ln(V_2/V_1)$$

$$W_{12} = P_1V_1 \ln\frac{V_2}{V_1} = 1000 \times 0.1 \ln(1/0.1)$$

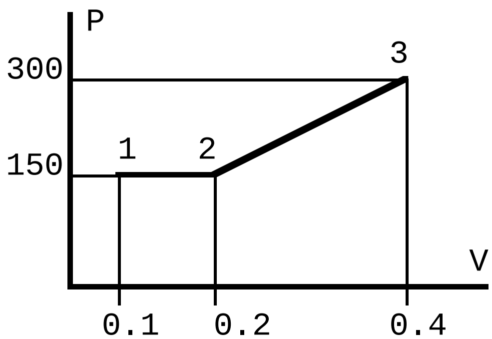
$$= \mathbf{230.3\ kJ}$$



4.15 Consider a two-part process with an expansion from 0.1 to 0.2 m^3 at a constant pressure of 150 kPa followed by an expansion from 0.2 to 0.4 m^3 with a linearly rising pressure from 150 kPa ending at 300 kPa. Show the process in a P-V diagram and find the boundary work.

Solution:

By knowing the pressure versus volume variation the work is found.



$$ {}_1W_3 = {}_1W_2 + {}_2W_3 $$

$$ = \int_1^2 PdV + \int_2^3 PdV $$

$$ = P_1 (V_2 - V_1) $$

$$ + \frac{1}{2} (P_2 + P_3)(V_3\text{-}V_2) $$

$$ W = 150\ (0.2\text{-}1.0) + \frac{1}{2}\ (150 + 300)\ (0.4 - 0.2) = 15 + 45 = \mathbf{60\ kJ} $$

4.16 A cylinder fitted with a piston contains propane gas at 100 kPa, 300 K with a volume of 0.2 m^3. The gas is now slowly compressed according to the relation $PV^{1.1}$ = constant to a final temperature of 340 K. Justify the use of the ideal gas model. Find the final pressure and the work done during the process.

Solution:

The process equation and T determines state 2. Use ideal gas law to say

$$ P_2 = P_1 \left(\frac{T_2}{T_1}\right)^{\frac{n}{n-1}} = 100 \left(\frac{340}{300}\right)^{\frac{1.1}{0.1}} = \mathbf{396\ kPa} $$

$$ V_2 = V_1 \left(\frac{P_1}{P_2}\right)^{1/n} = 0.2 \left(\frac{100}{396}\right)^{1/1.1} = 0.0572\ m^3 $$

For propane Table A.2: T_C = 370 K, P_C = 4260 kPa, Figure D.1 gives Z.

T_{r1} = 0.81, P_{r1} = 0.023 => Z_1 = 0.98

T_{r2} = 0.92, P_{r2} = 0.093 => Z_2 = 0.95

Ideal gas model **OK** for both states, minor corrections could be used.

$$ W_{12} = \int_1^2 PdV = \frac{P_2V_2\text{-}P_1V_1}{1\text{-}n} = \frac{(396 \times 0.0572) - (100 \times 0.2)}{1 - 1.1} = \mathbf{-26.7\ kJ} $$

4.17 The gas space above the water in a closed storage tank contains nitrogen at 25°C, 100 kPa. Total tank volume is 4 m^3, and there is 500 kg of water at 25°C. An additional 500 kg water is now forced into the tank. Assuming constant temperature throughout, find the final pressure of the nitrogen and the work done on the nitrogen in this process.

Solution:

The water is compressed liquid and in the process the pressure goes up so the water stays as liquid. Incompressible so the specific volume does not change. The nitrogen is an ideal gas and thus highly compressible.

State 1: $V_{H_2O\,1} = 500 \times 0.001003 = 0.5015 \text{ m}^3$

$V_{N_2\,1} = 4.0 - 0.5015 = 3.4985 \text{ m}^3$

State 2: $V_{N_2\,2} = 4.0 - 2 \times 0.5015 = 2.997 \text{ m}^3$

$$\left.\begin{array}{l}\text{Ideal Gas}\\ T = \text{const}\end{array}\right\} \quad P_{N_2\,2} = 100 \times \frac{3.4985}{2.997} = \mathbf{116.7\ kPa}$$

Constant temperature gives $P = mRT/V$ i.e. pressure inverse in V

$$W_{12\text{ by }N_2} = \int_1^2 P_{N_2} dV_{N_2} = P_1V_1 \ln(V_2/V_1)$$

$$= 100 \times 3.4985 \times \ln\frac{2.997}{3.4985} = \mathbf{-54.1\ kJ}$$

4.18 A steam radiator in a room at 25°C has saturated water vapor at 110 kPa flowing through it, when the inlet and exit valves are closed. What is the pressure and the quality of the water, when it has cooled to 25^{o}C? How much work is done?

Solution: Control volume radiator.

After the valve is closed no more flow, constant volume and mass.

1: $x_1 = 1$, $P_1 = 110$ kPa $\Rightarrow$ $v_1 = 1.566 \text{ m}^3/\text{kg}$ from Table B.1.2

2: $T_2 = 25°C$, $v_2 = v_1 = 1.566 = 0.001003 + x_2 \times 43.359$

$\mathbf{x_2 = 0.0361}$, $\mathbf{P_2 = Psat = 3.169\ kPa}$ and $\mathbf{W_{12}} = \int PdV = \mathbf{0}$

4.19 A balloon behaves such that the pressure inside is proportional to the diameter squared. It contains 2 kg of ammonia at 0°C, 60% quality. The balloon and ammonia are now heated so that a final pressure of 600 kPa is reached. Considering the ammonia as a control mass, find the amount of work done in the process.

Solution:

Process : $P \propto D^2$, with $V \propto D^3$ this implies $P \propto D^2 \propto V^{2/3}$ so

$PV^{-2/3}$ = constant, which is a polytropic process, $n = -2/3$

From table B.2.1: $V_1 = mv_1 = 2(0.001566 + 0.6 \times 0.28783) = 0.3485\ m^3$

$$V_2 = V_1\left(\frac{P_2}{P_1}\right)^{3/2} = 0.3485\left(\frac{600}{429.3}\right)^{3/2} = 0.5758\ m^3$$

$$W_{12} = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1 - n} \qquad \text{(Equation 4.4)}$$

$$= \frac{600 \times 0.5758 - 429.3 \times 0.3485}{1 - (-2/3)} = \mathbf{117.5\ kJ}$$

4.20 Consider a piston cylinder with 0.5 kg of R-134a as saturated vapor at -10°C. It is now compressed to a pressure of 500 kPa in a polytropic process with n = 1.5. Find the final volume and temperature, and determine the work done during the process.

Solution:

Take CV as the R-134a which is a control mass. $m_2 = m_1 = m$

Process: $Pv^{1.5}$ = constant until P = 500 kPa

1: (T, x) $v_1 = 0.09921\ m^3/kg$, $P = Psat = 201.7$ kPa from Table B.5.1

2: (P, process) $v_2 = v_1 (P_1/P_2)^{(1/1.5)} = 0.09921\times (201.7/500)^{0.66666} = \mathbf{0.05416}$

Given (P,v) at state 2 it is superheated vapor at $\mathbf{T_2 = 79\ °C}$

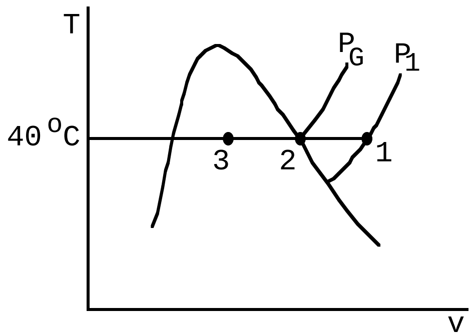
Process gives $P = C\ v^{(-1.5)}$, which is integrated for the work term, Eq.(4.4)

$_1W_2 = \int P\ dV = m(P_2v_2 - P_1v_1)/(1 - 1.5)$

$= -2\times0.5\times (500\times0.05416 - 201.7\times0.09921) = \mathbf{-7.07\ kJ}$

4.21 A cylinder having an initial volume of 3 m^3 contains 0.1 kg of water at 40°C. The water is then compressed in an isothermal quasi-equilibrium process until it has a quality of 50%. Calculate the work done in the process. Assume the water vapor is an ideal gas.

Solution: C.V. Water



$$v_1 = V_1/m = \frac{3}{0.1} = 30\ m^3/kg\ (> v_G\ )$$

Tbl B.1.1 => P_G = 7.384 kPa very low

so H_2O ~ ideal gas from 1-2

$$P_1 = P_G \frac{v_G}{v_1} = 7.384 \times \frac{19.52}{30} = 4.8\ kPa$$

$$V_2 = mv_2 = 0.1 \times 19.52 = 1.952\ m^3$$

$$T = C: \quad W_{12} = \int_1^2 PdV = P_1V_1 \ln \frac{V_2}{V_1} = 4.8 \times 3.0 \times \ln \frac{1.952}{3} = -6.19\ kJ$$

$$v_3 = 0.001008 + 0.5 \times 19.519 = 9.7605 \quad => \quad V_3 = mv_3 = 0.976\ m^3$$

$$P = C = P_g: \quad W_{23} = \int_2^3 PdV = P_g\ (V_3\text{-}V_2) = 7.384(0.976 - 1.952) = -7.21\ kJ$$

Total work: $W_{13} = -6.19 - 7.21 =$ **-13.4 kJ**

4.22 Consider the nonequilibrium process described in Problem 3.7. Determine the work done by the carbon dioxide in the cylinder during the process.

Solution:

Knowing the process (P vs. V) and the states 1 and 2 we can find W.

If piston floats or moves:

$$P = P_{lift} = P_o + \rho hg = 101.3 + 8000*0.1*9.807 / 1000 = 108.8\ kPa$$

$$V_2 = V_1 \times 150 / 100 = (\pi/4)\ 0.1^2 \times 0.1 \times 1.5 = 0.000785 \times 1.5 = 0.0011775\ m^3$$

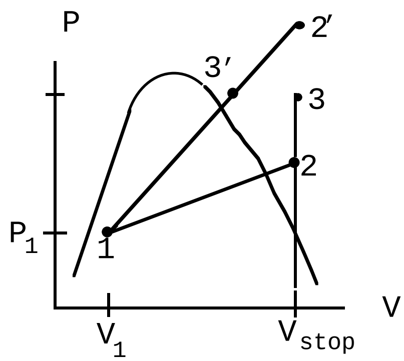
For max volume we must have $P > P_{lift}$ so check using ideal gas and constant T process: $P_2 = P_1\ V_1/\ V_2 =$ 200/1.5 = 133 kPa and piston is at stops.

$$W_{12} = \int P_{lift}\ dV = P_{lift}\ (V_2 - V_1) = 108.8\ (0.0011775 - 0.000785)$$

= **0.0427 kJ**

4.23 Two kilograms of water is contained in a piston/cylinder (Fig. P4.23) with a massless piston loaded with a linear spring and the outside atmosphere. Initially the spring force is zero and $P_1 = P_o = 100$ kPa with a volume of 0.2 m^3. If the piston just hits the upper stops the volume is 0.8 m^3 and $T = 600°C$. Heat is now added until the pressure reaches 1.2 MPa. Find the final temperature, show the *P–V* diagram and find the work done during the process.

Solution:



State 1: $v_1 = V/m = 0.2 / 2 = 0.1\ m^3/kg$

Process: $1 \rightarrow 2 \rightarrow 3$ or $1 \rightarrow 3'$

State at stops: 2 or 2'

$v_2 = V_{stop}/m = 0.4\ m^3/kg$ & $T_2 = 600°C$

Table B.1.3 $\Rightarrow$ $P_{stop} = 1\ MPa < P_3$

since $P_{stop} < P_3$ the process is as $1 \rightarrow 2 \rightarrow 3$

State 3: $P_3 = 1.2$ MPa, $v_3 = v_2 = 0.4\ m^3/kg$ $\Rightarrow$ $T_3 \cong$ **770°C**

$$W_{13} = W_{12} + W_{23} = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) + 0 = \frac{1}{2}(100 + 1000)(0.8 - 0.2)$$

$$= \mathbf{330\ kJ}$$

4.24 A piston/cylinder (Fig. P4.24) contains 1 kg of water at 20°C with a volume of 0.1 m^3. Initially the piston rests on some stops with the top surface open to the atmosphere, P_o and a mass so a water pressure of 400 kPa will lift it. To what temperature should the water be heated to lift the piston? If it is heated to saturated vapor find the final temperature, volume and the work, ${}_1W_2$.

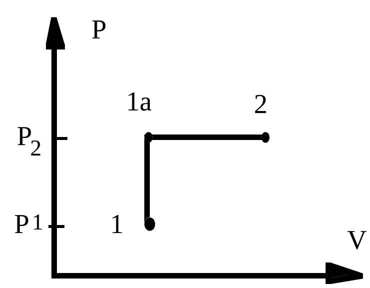
Solution:

(a) State to reach lift pressure of

$P = 400$ kPa, $v = V/m = 0.1\ m^3/kg$

Table B.1.2: $v_f < v < v_g = 0.4625$

=> $T = T_{sat}$ = **143.63°C**



(b) State 2 is saturated vapor at 400 kPa

since state a is two-phase.

$v_2 = v_g = 0.4625\ m^3/kg$, $V_2 = m\ v_2 = 0.4625\ m^3$,

Pressure is constant as volume increase beyond initial volume.

$${}_1W_2 = \int P\ dV = P\ (V_2 - V_1) = mP\ (v_2 - v_1) = 400\ (0.4625 - 0.1) = \mathbf{145\ kJ}$$

4.25 Assume the same system as in the previous problem, but let the piston be locked with a pin. If the water is heated to saturated vapor find the final temperature, volume and the work, ${}_1W_2$.

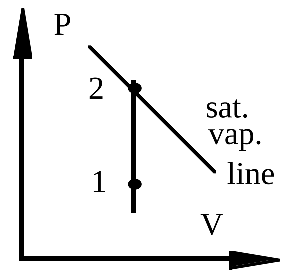
Solution:

Constant mass and constant volume process

State 2: $x_2 = 1$, $v_2 = v_1 = V_1/m = 0.1\ m^3/kg$

$v_g(T) = 0.1$ Table B.1.1 => $T_2 \cong$ **212.5°C**

$V_2 = V_1 =$ **0.1 m³**, ${}_1W_2 = \int PdV =$ **0**



4.26 A piston cylinder setup similar to Problem 4.24 contains 0.1 kg saturated liquid and vapor water at 100 kPa with quality 25%. The mass of the piston is such that a pressure of 500 kPa will float it. The water is heated to 300°C. Find the final pressure, volume and the work, ${}_1W_2$.

Solution:

Take CV as the water: $m_2 = m_1 = m$

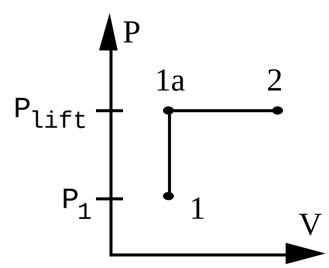
Process: v = constant until $P = P_{lift}$

To locate state 1: Table B.1.2

$v_1 = 0.001043 + 0.25\times1.69296 = 0.42428$

1a: $v_{1a} = v_1 = 0.42428 > v_g$ at 500 kPa

so state 1a is Sup.Vapor $T_{1a} = 200°C$



State 2 is 300°C so heating continues after state 1a to 2 at constant P =>

2: T_2, $\mathbf{P_2=P_{lift}}$ => Tbl B.1.3 v_2 =0.52256 ; $\mathbf{V_2 = mv_2 = 0.05226\ m^3}$

${}_1W_2 = P_{lift}(V_2-V_1) = 500(0.05226-0.04243) =$ **4.91 kJ**

4.27 A 400-L tank, A (see Fig. P4.27) contains argon gas at 250 kPa, 30°C. Cylinder B, having a frictionless piston of such mass that a pressure of 150 kPa will float it, is initially empty. The valve is opened and argon flows into B and eventually reaches a uniform state of 150 kPa, 30°C throughout. What is the work done by the argon?

Solution:

Take C.V. as all the argon in both A and B. Boundary movement work done in cylinder B against constant external pressure of 150 kPa. Argon is an ideal gas, so write out that the mass and temperature at state 1 and 2 are the same

$$P_{A1}V_A = m_A R T_{A1} = m_A R T_2 = P_2(\, V_A + V_{B2})$$

$$\Rightarrow \quad V_{B2} = \frac{250 \times 0.4}{150} - 0.4 = 0.2667 \text{ m}^3$$

$$W_{12} = \int_1^2 P_{ext} dV = P_{ext}(V_{B2} - V_{B1}) = 150\ (0.2667 - 0) = \mathbf{40\ kJ}$$

4.28 Air at 200 kPa, 30°C is contained in a cylinder/piston arrangement with initial volume 0.1 m^3 . The inside pressure balances ambient pressure of 100 kPa plus an externally imposed force that is proportional to $V^{0.5}$. Now heat is transferred to the system to a final pressure of 225 kPa. Find the final temperature and the work done in the process.

Solution:

C.V. Air. This is a control mass. Use initial state and process to find T_2

$$P_1 \ = P_0 + CV^{1/2}; \qquad 200 = 100 + C(0.1)^{1/2}, \qquad C = 316.23 \Rightarrow$$

$$225 = 100 + CV_2^{1/2} \quad \Rightarrow \quad V_2 = 0.156 \text{ m}^3$$

$$P_2V_2 = mRT_2 = \frac{P_1V_1}{T_1} T_2 \Rightarrow$$

$$T_2 = (P_2V_2 / P_1V_1)\, T_1 = 225 \times 0.156 \times 303.15 / (200 \times 0.1) = 532 \text{ K} = 258.9°\text{C}$$

$$W_{12} = \int P\, dV \ = \int \left(P_0 + CV^{1/2}\right) dV$$

$$= P_0\, (V_2 - V_1) + C \times \frac{2}{3} \times (V_2^{3/2} - V_1^{3/2})$$

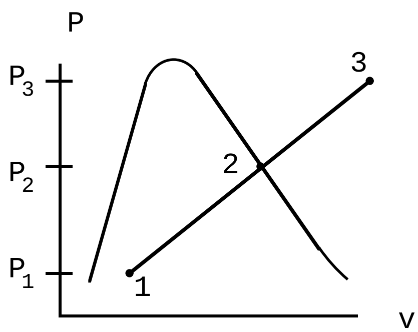
$$= 100\ (0.156 - 0.1) + 316.23 \times \frac{2}{3} \times (0.156^{3/2} - 0.1^{3/2})$$

$$= 5.6 + 6.32 = \mathbf{11.9\ kJ}$$

4.29 A spring-loaded piston/cylinder arrangement contains R-134a at 20°C, 24% quality with a volume 50 L. The setup is heated and thus expands, moving the piston. It is noted that when the last drop of liquid disappears the temperature is 40°C. The heating is stopped when T = 130°C. Verify the final pressure is about 1200 kPa by iteration and find the work done in the process.

Solution:

C.V. R-134a. This is a control mass.



State 1: Table B.5.1 =>

$v_1 = 0.000817 + 0.24*0.03524 = 0.009274$

$P_1 = 572.8$ kPa,

$m = V/ v_1 = 0.050 / 0.009274 = 5.391$ kg

Process: Linear Spring

$P = A + Bv$

State 2: $x_2 = 1, T_2 \quad \Rightarrow \quad P_2 = 1.017$ MPa, $\quad v_2 = 0.02002\ m^3/kg$

Now we have fixed two points on the process line so for final state 3:

$$P_3 = P_1 + \frac{P_2 - P_1}{v_2 - v_1}(v_3 - v_1) = RHS \qquad \text{Relation between } P_3 \text{ and } v_3$$

State 3: T_3 and on process line $\Rightarrow$ iterate on P_3 given T_3

at $P_3 = 1.2$ MPa => $v_3 = 0.02504$ => P_3 - RHS = -0.0247

at $P_3 = 1.4$ MPa => $v_3 = 0.02112$ => P_3 - RHS = 0.3376

Linear interpolation gives :

$$P_3 \cong 1200 + \frac{0.0247}{0.3376 + 0.0247}(1400\text{-}1200) = 1214 \text{ kPa}$$

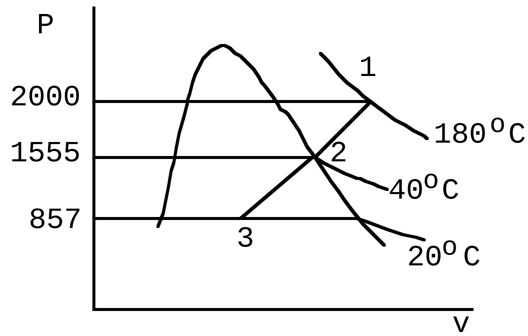
$$v_3 = 0.02504 + \frac{0.0247}{0.3376 + 0.0247}(0.02112\text{-}0.02504) = 0.02478\ m^3/kg$$

$$W_{13} = \int P\, dV = \frac{1}{2}(P_1 + P_3)(V_3 - V_1) = \frac{1}{2}(P_1 + P_3)\, m\, (v_3 - v_1)$$

$$= \frac{1}{2}\ 5.391(572.8 + 1214)(0.02478 - 0.009274) = \mathbf{74.7\ kJ}$$

4.30 A cylinder containing 1 kg of ammonia has an externally loaded piston. Initially the ammonia is at 2 MPa, 180°C and is now cooled to saturated vapor at 40°C, and then further cooled to 20°C, at which point the quality is 50%. Find the total work for the process, assuming a piecewise linear variation of *P* versus *V*.

Solution:



State 1: (T, P) Table B.2.2

$v_1 = 0.10571$

State 2: (T, x) Table B.2.1 sat. vap.

$P_2 = 1555$ kPa, $v_2 = 0.08313$

State 3: (T, x) $P_3 = 857$ kPa,

$v_3 = (0.001638+0.14922)/2 = 0.07543$

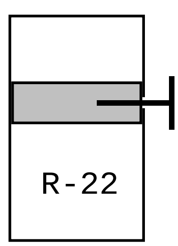
$$W_{13} = \int_1^3 PdV \approx (\frac{P_1 + P_2}{2})m(v_2 - v_1) + (\frac{P_2 + P_3}{2})m(v_3 - v_2)$$

$$= \frac{2000 + 1555}{2} 1(0.08313 - 0.10571) + \frac{1555 + 857}{2} 1(0.07543 - 0.08313)$$

$= \mathbf{-49.4\ kJ}$

4.31 A vertical cylinder (Fig. P4.31) has a 90-kg piston locked with a pin trapping 10 L of R-22 at 10°C, 90% quality inside. Atmospheric pressure is 100 kPa, and the cylinder cross-sectional area is 0.006 m^2. The pin is removed, allowing the piston to move and come to rest with a final temperature of 10°C for the R-22. Find the final pressure, final volume and the work done by the R-22.

Solution:



State 1: (T,x) from table B.4.1

$v_1 = 0.0008 + 0.9 \times 0.03391 = 0.03132$

$m = V_1/v_1 = 0.010/0.03132 = 0.319$ kg

Force balance on piston gives the equilibrium pressure

$$P_2 = P_0 + m_P g/ A_P = 100 + \frac{90 \times 9.807}{0.006 \times 1000} = \mathbf{247\ kPa}$$

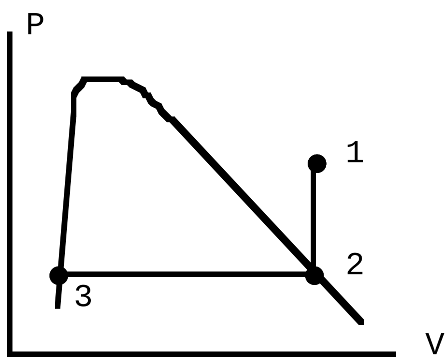
State 2: (T,P) interpolate $V_2 = mv_2 = 0.319 \times 0.10565 = 0.0337\ m^3 = \mathbf{33.7\ L}$

$$W_{12} = \int P_{equil}\, dV = P_2(V_2\text{-}V_1) = 247(0.0337\text{-} 0.010) = \mathbf{5.85\ kJ}$$

4.32 A piston/cylinder has 1 kg of R-134a at state 1 with 110°C, 600 kPa, and is then brought to saturated vapor, state 2, by cooling while the piston is locked with a pin. Now the piston is balanced with an additional constant force and the pin is removed. The cooling continues to a state 3 where the R-134a is saturated liquid. Show the processes in a P-V diagram and find the work in each of the two steps, 1 to 2 and 2 to 3.

Solution :

CV R-134a This is a control mass.



Properties from table B.5.1 and 5.2

State 1: (T,P) => $v = 0.04943$

State 2 given by fixed volume and $x_2 = 1.0$

State 2: $v_2 = v_1 = v_g$ => $T = 10$ C

State 3 reached at constant P (F = constant)

Final state 3: $v_3 = v_f = 0.000794$

Since no volume change from 1 to 2 => $\mathbf{{}_1W_2 = 0}$

${}_2W_3 = \int P\,dV = P(V_3 - V_2) = mP(v_3 - v_2)$ Constant pressure

$= 415.8(0.000794-0.04943)\ 1 =$ **-20.22 kJ**

4.33 Consider the process described in Problem 3.49. With the ammonia as a control mass, determine the boundary work during the process.

Solution :

This is a polytropic process with n = -2. From Table B.2.1 we have:

1: $P_1 = P_{sat} = 615$ kPa

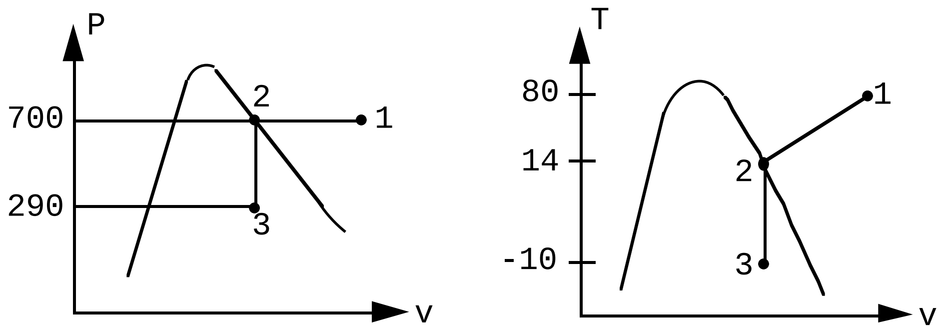
2: $V_2 = V_1 \left(\frac{P_2}{P_1}\right)^{1/2} = 0.005 \left(\frac{1200}{615}\right)^{1/2} = 0.006984 \text{ m}^3$

$$P = KV^2 \quad \text{or} \quad PV^{-2} = \text{const} \;\Rightarrow\; W_{12} = \int_1^2 P dV = \frac{P_2V_2 - P_1V_1}{1 - (-2)}$$

$$W_{12} = \frac{1200(0.006984) - 615(0.005)}{3} = \mathbf{1.769\ kJ}$$

4.34 Find the work for Problem 3.52.

Solution :



$${}_1W_3 = {}_1W_2 + {}_2W_3 = \int_1^2 PdV = P_1(V_2 - V_1) = mP_1(v_2 - v_1)$$

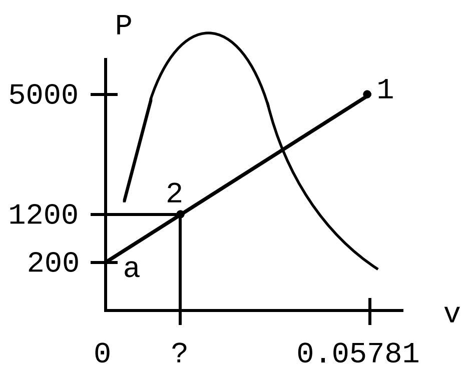
Since constant volume from 2 to 3, see P-v diagram. From table B.2

$v_1 = 0.2367$, $P_1 = 700$ kPa, $v_2 = v_g = 0.1815\ m^3/kg$

${}_1w_3 = P_1(v_2 - v_1) = 700 \times (0.1815 - 0.2367) = \mathbf{-38.64\ kJ/kg}$

4.35 Find the work for Problem 3.53.

Solution :



1: 5 MPa, 400°C $\Rightarrow v_1 = 0.05781$

$m = V/v_1 = 0.1/0.05781 = 1.73$ kg

Straight line: $P = P_a + Cv$

$$v_2 = v_1 \frac{P_2 - P_a}{P_1 - P_a} = \mathbf{0.01204\ m^3/kg}$$

$v_2 < v_g$(1200 kPa) so two-phase $T_2 = \mathbf{188°C}$

$\Rightarrow x_2 = (v_2 - 0.001139)/0.1622 = 0.0672$

The P-V coordinates for the two states are then:

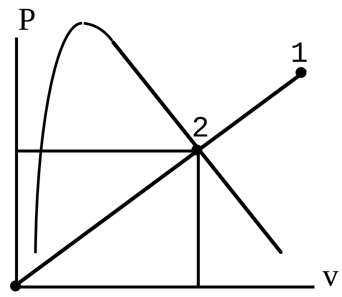
$P_1 = 5$ MPa, $V_1 = 0.1\ m^3$, $P_2 = 1200$ kPa, $V_2 = mv_2 = 0.02083\ m^3$

P vs. V is linear so $\quad {}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$

$$= \frac{1}{2}(5000 + 1200)(0.02083 - 0.1) = \mathbf{-245.4\ kJ}$$

4.36 Find the work for Problem 3.55.

Solution :



Process equation: $P = Cv \Rightarrow$

Tabel B.1.3: $C = P_1/v_1 = 3000/0.11619 = 25820$

State 2: $x_2 = 1$ & $P_2 = Cv_2$ (on process line)

Trial & error on T_{2sat} or P_{2sat}:

at 2 MPa $v_g = 0.09963 \Rightarrow C = P/v_g = 20074$

2.5 MPa $v_g = 0.07998 \Rightarrow C = P/v_g = 31258$

2.25 MPa $v_g = 0.08875 \Rightarrow C = P/v_g = 25352$

Now interpolate to match the right slope C:

$P_2 = 2270$ kPa, $v_2 = P_2/C = 2270/25820 = 0.0879$ m^3/kg

P is linear in V so the work becomes (area in P-v diagram)

$${}_1w_2 = \int P\, dv = \frac{1}{2}(P_1 + P_2)(v_2 - v_1)$$

$$= \frac{1}{2}(3000+2270)(0.0879 - 0.11619) = \mathbf{-\ 74.5\ kJ/kg}$$

4.37 Find the work for Problem 3.56.

Solution:

Knowing the process (P versus V) and states 1 and 2 allows calculation of W.

State 1: 50°C, x=1 Table B.3.1: $P_1 = 1219.3$ kPa, $v_1 = 0.01417$ m^3/kg

Process: $P = Cv^{-1} \Rightarrow {}_1w_2 = \int P\, dv = C \ln \frac{v_2}{v_1}$

State 2: 100 kPa and $v_2 = v_1P_1/P_2 = 0.1728$ m^3/kg

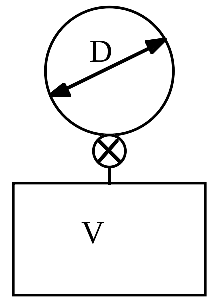
$${}_1w_2 = P_1v_1 \ln \frac{v_2}{v_1} = 1219.3 \times 0.01417 \times \ln \frac{0.1728}{0.01417} = \mathbf{43.2\ kJ/kg}$$

4.38 A spherical elastic balloon initially containing 5 kg ammonia as saturated vapor at 20°C is connected by a valve to a 3-m^3 evacuated tank. The balloon is made such that the pressure inside is proportional to the diameter. The valve is now opened, allowing ammonia to flow into the tank until the pressure in the balloon has dropped to 600 kPa, at which point the valve is closed. The final temperature in both the balloon and the tank is 20°C. Determine

a. The final pressure in the tank b. The work done by the ammonia

Solution :

C.V. Balloon and the tank. Control mass.



Balloon State 1: (T, x) and size $m_1 = 5$ kg

Table B.2.1: $v_1 = 0.14922\ m^3/kg$, $P_1 = 857$ kPa

$V_1 = m_1 v_1 = 0.7461\ m^3 = \frac{\pi}{6} D_1^3 \Rightarrow D_1 = 1.125$ m

Tank state 1: $V = 3\ m^3$; $m_1 = 0$

Process in the balloon: $P = K_1 D = K_2 V^{1/3} \quad \Rightarrow \quad PV^{-1/3} = \text{constant}$

This is a polytropic process with $n = - 1/3$.

Final state 2: Balloon has $P_2 = 600$ kPa and $T_2 = 20°C$

Table B.2.2: $v_2 = 0.22154\ m^3$

From process equation: $\frac{D_2}{D_1} = \frac{P_2}{P_1} = \frac{600}{857} \Rightarrow D_2 = 0.7876$ m

$V_2 = \frac{\pi}{6} D_2^3 = 0.2558\ m^3$ => $m_2 = V_2/v_2 = 1.155$ kg in balloon

Final state 2 in tank: $T_2 = 20°C$ and it receives a certain amount of mass.

m_2 = mass out of balloon = 5 - 1.155 = 3.845 kg

$v_2 = \frac{V_{tank}}{m_2} = 0.7802 \quad \Rightarrow \quad P_2 = \mathbf{180\ kPa}$

b) Work done at balloon boundary is in polytropic process

$$W_{12\ Balloon} = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - (-1/3)}$$

$$= \frac{600 \times 0.2558 - 857 \times 0.7461}{4/3} = \mathbf{-364.4\ kJ}$$

4.39 A 0.5-m-long steel rod with a 1-cm diameter is stretched in a tensile test. What is the required work to obtain a relative strain of 0.1%? The modulus of elasticity of steel is 2×10^8 kPa.

Solution :

$$-W_{12} = \frac{AEL_0}{2}(e)^2, \quad A = \frac{\pi}{4}(0.01)^2 = 78.54\times10^{-6}\ m^2$$

$$-W_{12} = \frac{78.54\times10^{-6} \times 2\times10^8 \times 0.5}{2}(10^{-3})^2 = \mathbf{3.93\ J}$$

4.40 A film of ethanol at 20°C has a surface tension of 22.3 mN/m and is maintained on a wire frame as shown in Fig. P4.40. Consider the film with two surfaces as a control mass and find the work done when the wire is moved 10 mm to make the film 20 × 40 mm.

Solution :

Assume a free surface on both sides of the frame, i.e., there are two surfaces 20 × 30 mm

$$W = -\int S\ dA = -22.3\times10^{-3} \times 2(800 - 600)\times10^{-6}$$

$$= -8.92\times10^{-6}\ J = \mathbf{-8.92\ \mu J}$$

4.41 A simple magnetic substance is one involving only magnetic work, that is, a change in magnetization of a substance in the presence of a magnetic field. For such a substance undergoing a quasiequilibrium process at constant volume, the work is

$$\delta W = -\ C_o\ \mathcal{H}\ d\ \mathfrak{M}$$

where $\mathcal{H}$ = magnetic field intensity, $\mathfrak{M}$ = magnetization, and C_o = a proportionality constant. For a first approximation, assume that magnetization is proportional to the magnetic field intensity divided by the temperature of the magnetic substance. Determine the work done in an isothermal process during a change of magnetization from $\mathfrak{M}_1$ to $\mathfrak{M}_2$.

Solution : Assume $M = cH/T$

For T = constant (and neglecting volume change)

$$\delta W = \mu_o H\ d(VM) = \frac{\mu_o Vc}{T}(H\ dH)$$

$$\text{or} \quad W_{12} = \frac{\mu_o Vc}{2T}(H_2^2 - H_1^2), \quad \text{or} \quad = \frac{\mu_o VT}{2c}(M_2^2 - M_1^2)$$

4.42 For the magnetic substance described in Problem 4.41, determine the work done in a process at constant magnetic field intensity (temperature varies), instead of one at constant temperature.

Solution :

Assume $M = cH / T$

For H = constant (and neglecting volume change)

$$\delta W = \mu_o H \, d(VM) = \mu_o H^2 Vc \, d\left(\frac{1}{T}\right)$$

or $$W_{12} = \mu_o H^2 \, Vc \left[\frac{1}{T_2} - \frac{1}{T_1}\right]$$

4.43 A battery is well insulated while being charged by 12.3 V at a current of 6 A. Take the battery as a control mass and find the instantaneous rate of work and the total work done over 4 hours..

Solution :

Battery thermally insulated $\Rightarrow$ Q = 0

For constant voltage E and current i,

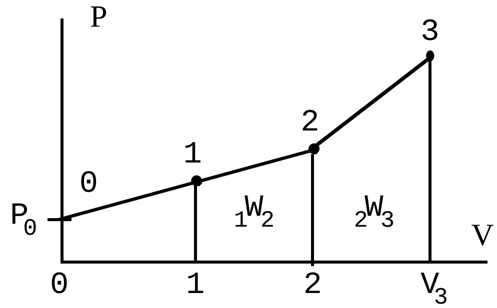
Power = E i = 12.3 $\times$ 6 = 73.8 W [Units V*A = W]

$$W = \int \text{power } dt = \text{power } \Delta t$$

$$= 73.8 \times 4 \times 60 \times 60 = 1062720 \text{ J} = 1062.7 \text{ kJ}$$

4.44 Two springs with same spring constant are installed in a massless piston/cylinder with the outside air at 100 kPa. If the piston is at the bottom, both springs are relaxed and the second spring comes in contact with the piston at $V = 2\ m^3$. The cylinder (Fig. P4.44) contains ammonia initially at −2°C, $x = 0.13$, $V = 1\ m^3$, which is then heated until the pressure finally reaches 1200 kPa. At what pressure will the piston touch the second spring? Find the final temperature and the total work done by the ammonia.

Solution :



State 1: P = 399.7 kPa Table B.2.1

$v = 0.00156 + 0.13\times0.3106 = 0.0419$

At bottom state 0: $0\ m^3$, 100 kPa

State 2: $V = 2\ m^3$ and on line 0-1-2

Final state 3: 1200 kPa, on line segment 2.

Slope of line 0-1-2: $\Delta P/ \Delta V = (P_1 - P_0)/\Delta V = (399.7\text{-}100)/1 = 299.7\ \text{kPa}/ m^3$

$$P_2 = P_1 + (V_2 - V_1)\Delta P/\Delta V = 399.7 + (2\text{-}1)\times 299.7 = \mathbf{699.4\ kPa}$$

State 3: Last line segment has twice the slope.

$$P_3 = P_2 + (V_3 - V_2)2\Delta P/\Delta V \quad \Rightarrow \quad V_3 = V_2 + (P_3 - P_2)/(2\Delta P/\Delta V)$$

$$V_3 = 2 + (1200\text{-}699.4)/599.4 = 2.835\ m^3$$

$$v_3 = v_1V_3/V_1 = 0.0419\times2.835/1 = 0.1188 \quad \Rightarrow \quad T = \mathbf{51°C}$$

$${}_1W_3 = {}_1W_2 + {}_2W_3 = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) + \frac{1}{2}(P_3 + P_2)(V_3 - V_2)$$

$$= 549.6 + 793.0 = \mathbf{1342.6\ kJ}$$

4.45 Consider the process of inflating a helium balloon, as described in Problem 3.14. For a control volume that consists of the space inside the balloon, determine the work done during the overall process.

Solution :

Inflation at constant $P = P_0 = 100$ kPa to $D_1 = 1$ m, then

$$P = P_0 + C\,(D^{*\,-1} - D^{*\,-2}), \qquad D^* = D / D_1,$$

to $D_2 = 4$ m, $P_2 = 400$ kPa, from which we find the constant C as:

$$400 = 100 + C[\,(1/4) - (1/4)^2\,] \quad => \quad C = 1600$$

The volumes are: $V = \frac{\pi}{6} D^3 \quad => \quad V_1 = 0.5236\ m^3; \quad V_2 = 33.51\ m^3$

$$W_{CV} = P_0(V_1 - 0) + \int_1^2 PdV$$

$$= P_0(V_1 - 0) + P_0(V_2 - V_1) + \int_1^2 C(D^{*\,-1} - D^{*\,-2})dV$$

$$V = \frac{\pi}{6} D^3, \qquad dV = \frac{\pi}{2} D^2\, dD = \frac{\pi}{2} D_1^3\, D^{*\,2}\, dD^*$$

$$\Rightarrow W_{CV} = P_0V_2 + 3CV_1 \int_{D_1^*=1}^{D_2^*=4} (D^*-1)dD^*$$

$$= P_0V_2 + 3CV_1\left[\frac{D_2^{*\,2} - D_1^{*\,2}}{2} - (D_2^* - D_1^*)\right]_1^4$$

$$= 100 \times 33.51 + 3 \times 1600 \times 0.5236\left[\frac{16-1}{2} - (4-1)\right]$$

= **14661 kJ**

4.46 A cylinder (Fig. P4.46), A_{cyl} = 7.012 cm^2, has two pistons mounted, the upper one, m_{p1} = 100 kg, initially resting on the stops. The lower piston, m_{p2} = 0 kg, has 2 kg water below it, with a spring in vacuum connecting the two pistons. The spring force is zero when the lower piston stands at the bottom, and when the lower piston hits the stops the volume is 0.3 m^3. The water, initially at 50 kPa, V = 0.00206 m^3, is then heated to saturated vapor.

a. Find the initial temperature and the pressure that will lift the upper piston.

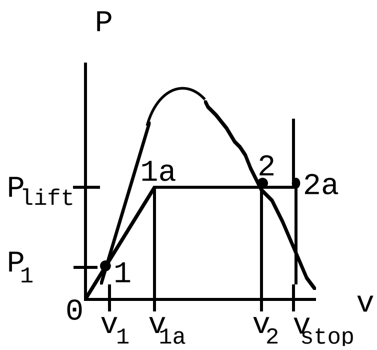
b. Find the final T, P, v and the work done by the water.

Solution :

State 1: P_1, $v_1 = V_1/m = 0.00103$ m^3/kg $\Rightarrow$ T_1 = **81.33°C**

Force balance on the combined set of pistons and spring.

$$P_{lift} = P_0 + \frac{(m_{p1}+m_{p2})g}{A_{cyl}} = 101.325 + \frac{100 \times 9.807}{7.012 \times 10^{-4} \times 10^3} = \mathbf{1500\ kPa}$$



To place the process line in the P-v diagram

1a: P_{lift} & line from (0,0) to state 1:

$$v_{1a} = \frac{v_1 P_{lift}}{P_1} = \frac{0.00103 \times 1500}{50} = 0.0309 \text{ m}^3\text{/kg}$$

2a: P_{lift} & at stop.

$$v_{2a} = \frac{V_{stop}}{m} = \frac{0.3}{2} = 0.15 \text{ m}^3\text{/kg}$$

check saturated vapor state at P_{lift} $\Rightarrow$ $v_g(P_{lift})$ = 0.13177 m^3/kg

$v_{2a} > v_g(P_{lift})$ so state 2a is superheated vapor.

$v_{1a} < v_g(P_{lift})$ so state 1a is reached before saturated vapor.

State 2: sat. vapor at P_{lift}, v_2 = 0.13177

$$W_{12} = W_{1\ 1a} + W_{1a\ 2} = \frac{1}{2} m(P_1 + P_{1a})(v_{1a} - v_1) + P_{1a} m(v_2 - v_{1a})$$

$$= \frac{1}{2} \times 2 \times (50 + 1500)(0.0309 - 0.00103)$$

$$+ 1500(2)(0.13177-0.0309) = 46.3 + 302.61 = \mathbf{348.91\ kJ}$$

4.47 The sun shines on a 150 m^2 road surface so it is at 45°C. Below the 5 cm thick asphalt, average conductivity of 0.06 W/m K, is a layer of compacted rubbles at a temperature of 15°C. Find the rate of heat transfer to the rubbles.

Solution :

This is steady one dimensional conduction through the asphalt layer.

$$\dot{Q} = k\ A\ \frac{\Delta T}{\Delta x} = 0.06 \times 150 \times \frac{45\text{-}15}{0.05} = \mathbf{5400W}$$

4.48 A pot of steel, conductivity 50 W/m K, with a 5 mm thick bottom is filled with 15°C liquid water. The pot has a diameter of 20 cm and is now placed on an electric stove that delivers 250 W as heat transfer. Find the temperature on the outer pot bottom surface assuming the inner surface is at 15°C.

Solution :

Steady conduction through the bottom of the steel pot. Assume the inside surface is at the liquid water temperature.

$$\dot{Q} = k\ A\ \frac{\Delta T}{\Delta x} \Rightarrow \Delta T = \dot{Q}\ \Delta x\ /\ kA$$

$$\Delta T = 250 \times 0.005/(50 \times \frac{\pi}{4} \times 0.2^2) = 0.796$$

$$T = 15 + 0.796 \cong \mathbf{15.8\ °C}$$

4.49 A water-heater is covered up with insulation boards over a total surface area of 3 m^2. The inside board surface is at 75°C and the outside surface is at 20°C and the board material has a conductivity of 0.08 W/m K. How thick a board should it be to limit the heat transfer loss to 200 W ?

Solution :

Steady state conduction through a single layer board.

$$\dot{Q}_{cond} = k\ A\ \frac{\Delta T}{\Delta x} \Rightarrow \Delta x = k\ A\ \Delta T/\dot{Q}$$

$$\Delta x = 0.08 \times 3 \times (75 - 20)/200 = \mathbf{0.066\ m}$$

4.50 You drive a car on a winter day with the atmospheric air at -15°C and you keep the outside front windshield surface temperature at +2°C by blowing hot air on the inside surface. If the windshield is 0.5 m^2 and the outside convection coefficient is 250 W/m^2K find the rate of energy loos through the front windshield.

Solution :

The heat transfer from the inside must match the loss on the outer surface to give a steady state (frost free) outside surface temperature.

$$\dot{Q}_{conv} = h\ A\ \Delta T = 250 \times 0.5 \times (2-(-15))$$

$$= 250 \times 0.5 \times 17 = \mathbf{2125\ W}$$

This is a substantial amount of power.

4.51 A large condenser (heat exchanger) in a power plant must transfer a total of 100 MW from steam running in a pipe to sea water being pumped through the heat exchanger. Assume the wall separating the steam and seawater is 4 mm of steel, conductivity 50 W/m K and that a maximum of 5°C difference between the two fluids is allowed in the design. Find the required minimum area for the heat transfer neglecting any convective heat transfer in the flows.

Solution :

Steady conduction through the 4 mm steel wall.

$$\dot{Q} = k\ A\ \frac{\Delta T}{\Delta x} \quad \Rightarrow \quad A = \dot{Q}\ \Delta x/k\Delta T$$

$$A = 100 \times 10^6 \times 0.004/(50 \times 5) = \mathbf{1600\ m^2}$$

4.52 The black grille on the back of a refrigerator has a surface temperature of 35°C with a total surface area of 1 m^2. Heat transfer to the room air at 20°C takes place with an average convective heat transfer coefficient of 15 W/m^2 K. How much energy can be removed during 15 minutes of operation?

Solution :

$$\dot{Q} = hA\Delta T; \qquad Q = \dot{Q}\ \Delta t = \ hA\ \Delta T\ \Delta t$$

$$Q = 15 \times 1 \times (35-20) \times 15 \times 60 = 202500\ J = \mathbf{202.5\ kJ}$$

4.53 Due to a faulty door contact the small light bulb (25 W) inside a refrigerator is kept on and limited insulation lets 50 W of energy from the outside seep into the refrigerated space. How much of a temperature difference to the ambient at 20°C must the refrigerator have in its heat exchanger with an area of 1 m^2 and an average heat transfer coefficient of 15 W/m^2 K to reject the leaks of energy.

Solution :

$$\dot{Q}_{tot} = 25 + 50 = 75 \text{ W to go out}$$

$$\dot{Q} = hA\Delta T = 15 \times 1 \times \Delta T = 75$$

$$\Delta T = \dot{Q} / hA = 75/(15\times1) = 5\ °C$$

OR T must be at least **25 °C**

4.54 The brake shoe and steel drum on a car continuously absorbs 25 W as the car slows down. Assume a total outside surface area of 0.1 m^2 with a convective heat transfer coefficient of 10 W/m^2 K to the air at 20°C. How hot does the outside brake and drum surface become when steady conditions are reached?

Solution :

$$\dot{Q} = hA\Delta T \quad \Rightarrow \quad \Delta T = \dot{Q} / hA$$

$$\Delta T = (T_{BRAKE} - 20) = 25/(10 \times 0.1) = \mathbf{25\ °C}$$

$$T_{BRAKE} = 20 + 25 = \mathbf{45\ °C}$$

4.55 A wall surface on a house is at 30°C with an emissivity of ε = 0.7. The surrounding ambient to the house is at 15°C, average emissivity of 0.9. Find the rate of radiation energy from each of those surfaces per unit area.

Solution :

$$\dot{Q} /A = \varepsilon\sigma AT^4, \quad \sigma = 5.67 \times 10^{-8}$$

a) $\dot{Q}/A = 0.7 \times 5.67 \times 10^{-8} \times (273.15 + 30)^4 = \mathbf{335\ W/m^2}$

b) $\dot{Q}/A = 0.9 \times 5.67 \times 10^{-8} \times 288.15^4 = \mathbf{352\ W/m^2}$

4.56 A log of burning wood in the fireplace has a surface temperature of 450°C. Assume the emissivity is 1 (perfect black body) and find the radiant emission of energy per unit surface area.

Solution :

$$\dot{Q}/A = 1 \times \sigma\ T^4 = 5.67 \times 10^{-8} \times (273.15 + 450)^4$$
$$= 15505\ W/m^2 = \mathbf{15.5\ kW/m^2}$$

4.57 A radiant heat lamp is a rod, 0.5 m long and 0.5 cm in diameter, through which 400 W of electric energy is deposited. Assume the surface has an emissivity of 0.9 and neglect incoming radiation. What will the rod surface temperature be ?

Solution :

For constant surface temperature outgoing power equals electric power.

$$\dot{Q}_{rad} = \varepsilon\sigma A T^4 = \dot{Q}_{el} \quad \Rightarrow$$

$$T^4 = \dot{Q}_{el} / \varepsilon\sigma A = 400 / (0.9 \times 5.67 \times 10^{-8} \times 0.5 \times \pi \times 0.005)$$

$$= 9.9803 \times 10^{11}\ K^4 \quad \Rightarrow \quad T \cong \mathbf{1000\ K \quad OR \quad 725\ °C}$$

4.58 Consider a window-mounted air conditioning unit used in the summer to cool incoming air. Examine the system boundaries for rates of work and heat transfer, including signs.

Solution : Air-conditioner unit, steady operation with no change of temperature of AC unit. - electrical work (power) input operates unit, +Q rate of heat transfer from the room, a larger -Q rate of heat transfer (sum of the other two energy rates) out to the outside air.

4.59 Consider a hot-air heating system for a home. Examine the following systems for heat transfer.

a) The combustion chamber and combustion gas side of the heat transfer area

Fuel and air enter, warm products of the combustion exit, large -Q to the air in the duct system, small -Q loss directly to the room.

b) The furnace as a whole, including the hot- and cold-air ducts and chimney

Fuel and air enter, warm products exit through the chimney, cool air into the cold air return duct, warm air exit hot-air duct to heat the house. Small heat transfer losses from furnace, chimney and ductwork to the house.

4.60 Consider a household refrigerator that has just been filled up with room-temperature food. Define a control volume (mass) and examine its boundaries for rates of work and heat transfer, including sign.

a. Immediately after the food is placed in the refrigerator

b. After a long period of time has elapsed and the food is cold

I. C.V. Food.

a) short term.: -Q from warm food to cold refrigerator air. Food cools.

b) Long term: -Q goes to zero after food has reached refrigerator T.

II. C.V. refrigerator space, not food, not refrigerator system

a) short term: +Q from the warm food, +Q from heat leak from room into cold space. -Q (sum of both) to refrigeration system. If not equal the refrigerator space initially warms slightly and then cools down to preset T.

b) long term: small -Q heat leak balanced by -Q to refrigeration system.

Note: For refrigeration system CV any Q in from refrigerator space plus electrical W input to operate system, sum of which is Q rejected to the room.

4.61 A room is heated with an electric space heater on a winter day. Examine the following control volumes, regarding heat transfer and work , including sign.

a) The space heater.

Electrical work (power) input, and equal (after system warm up) Q out to the room.

b) Room

Q input from the heater balances Q loss to the outside, for steady (no temperature change) operation.

c) The space heater and the room together

Electrical work input balances Q loss to the outside, for steady operation.

English Unit Problems

4.62E A cylinder fitted with a frictionless piston contains 10 lbm of superheated refrigerant R-134a vapor at 100 lbf/in.^{2}, 300 F. The setup is cooled at constant pressure until the water reaches a quality of 25%. Calculate the work done in the process.

Solution:

$v_1 = 0.76629$; $v_2 = 0.013331 + 0.25 \times 0.46652 = 0.12996$

$$W_{12} = \int_1^2 PdV = P(V_2 - V_1) = mP(v_2 - v_1)$$

$$= 10 \times 100 \times \frac{144}{778} \times (0.12996 - 0.76629) = \mathbf{-117.78\ Btu}$$

4.63E An escalator raises a 200 lbm bucket of sand 30 ft in 1 minute. Determine the total amount of work done and the instantaneous rate of work during the process.

Solution:

$$W = \int Fdx = F\int dx = F\,\Delta x$$

$$= 200 \times 30 = 6000 \text{ ft lbf } = (6000/778) \text{ Btu} = 7.71 \text{ Btu}$$

$$\dot{W} = W / \Delta t = 7.71 / 60 = \mathbf{0.129\ Btu/s}$$

4.64E A linear spring, $F = k_s(x - x_o)$, with spring constant $k_s = 35$ lbf/ft, is stretched until it is 2.5 in. longer. Find the required force and work input.

Solution:

$$F = k_s(x - x_0) = 35 \times 2.5/12 = 7.292 \text{ lbf}$$

$$W = \int Fdx = \int k_s(x - x_0)d(x - x_0) = \frac{1}{2}k_s(x - x_0)^2$$

$$= \frac{1}{2} \times 35 \times (2.5/12)^2 = 0.76 \text{ lbf•ft} = \mathbf{9.76{\times}10^{-4}\ Btu}$$

4.65E The piston/cylinder shown in Fig. P4.12 contains carbon dioxide at 50 lbf/in.^{2}, 200 F with a volume of 5 ft^3. Mass is added at such a rate that the gas compresses according to the relation $PV^{1.2}$ = constant to a final temperature of 350 F. Determine the work done during the process.

Solution:

From Eq. 4.4 for PV^n = const ($n \neq 1$)

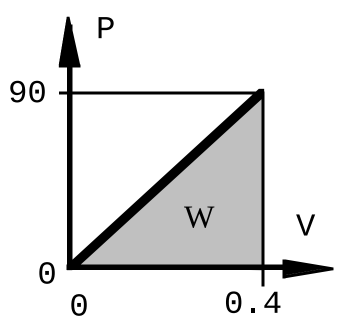
$$W_{12} = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1 - n} \quad \text{Assuming ideal gas, } PV = mRT$$

$$W_{12} = \frac{mR(T_2 - T_1)}{1 - n}, \text{ But } mR = \frac{P_1V_1}{T_1} = \frac{50 \times 144 \times 5}{659.7 \times 778} = 0.07014$$

$$W_{12} = \frac{0.07014(809.7 - 659.7)}{1 - 1.2} = \mathbf{-52.605\ Btu}$$

4.66E Consider a mass going through a polytropic process where pressure is directly proportional to volume (n = – 1). The process start with P = 0, V = 0 and ends with P = 90 lbf/in.^{2}, V = 0.4 ft^3.The physical setup could be as in Problem 2.22. Find the boundary work done by the mass.

Solution:



$$W = \int PdV = AREA$$

$$= \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(P_2 + 0)(V_2 - 0)$$

$$= \frac{1}{2} P_2 V_2 = \frac{1}{2} \times 90 \times 0.4 \times 144$$

= **2592 ft lbf = 3.33 Btu**

4.67E The gas space above the water in a closed storage tank contains nitrogen at 80 F, 15 lbf/in.^{2}. Total tank volume is 150 ft^3 and there is 1000 lbm of water at 80 F. An additional 1000 lbm water is now forced into the tank. Assuming constant temperature throughout, find the final pressure of the nitrogen and the work done on the nitrogen in this process.

Solution:

Water is compressed liquid, so it is incompressible

$$V_{H_2O\,1} = mv_1 = 1000 \times 0.016073 = 16.073 \text{ ft}^3$$

$$V_{N_2\,1} = V_{tank} - V_{H_2O\,1} = 150 - 16.073 = 133.93 \text{ ft}^3$$

$$V_{N_2\,2} = V_{tank} - V_{H_2O\,2} = 150 - 32.146 = 117.85 \text{ ft}^3$$

N_2 is an ideal gas so

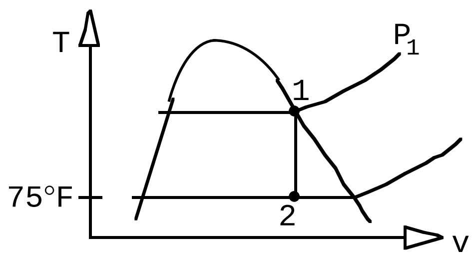
$$P_{N_2\,2} = P_{N_2\,1} \times V_{N_2\,1}/V_{N_2\,2} = 15 \times \frac{133.93}{117.85} = \mathbf{17.046\ lbf/in^2}$$

$$W_{12} = \int PdV = P_1V_1 \ln\frac{V_2}{V_1} = \frac{15 \times 144 \times 133.93}{778} \ln\frac{117.85}{133.93} = \mathbf{-47.5\ Btu}$$

4.68E A steam radiator in a room at 75 F has saturated water vapor at 16 lbf/in.^{2} flowing through it, when the inlet and exit valves are closed. What is the pressure and the quality of the water, when it has cooled to 75F? How much work is done?

Solution:

After the valve is closed no flow, constant V and m.



1: $x_1 = 1$, $P_1 = 16$ lbf/in^2

$\Rightarrow v_1 = v_{g1} = 24.754$ ft^3/lbm

2: $T_2 = 75°F$, $v_2 = v_1 = 24.754$

$P_2 = P_{g\,2} = \mathbf{0.43\ lbf/in^2}$

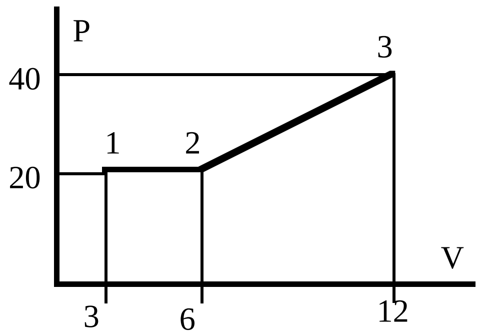
$$v_2 = 24.754 = 0.01606 + x_2(739.584 - 0.01606)$$

$x_2 = \mathbf{0.0334}$ $\qquad W_{12} = \int PdV = \mathbf{0}$

4.69E Consider a two-part process with an expansion from 3 to 6 ft^3 at a constant pressure of 20 lbf/in.^{2} followed by an expansion from 6 to 12 ft^3 with a linearly rising pressure from 20 lbf/in.^{2} ending at 40 lbf/in.^{2}. Show the process in a P-V diagram and find the boundary work.

Solution:

By knowing the pressure versus volume variation the work is found.



$$_1W_3 = {}_1W_2 + {}_2W_3$$

$$= \int_1^2 PdV + \int_2^3 PdV$$

$$= P_1 (V_2 - V_1)$$

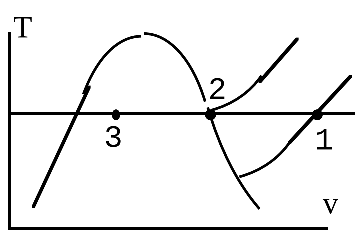
$$+ \frac{1}{2} (P_2 + P_3)(V_3 - V_2)$$

$$W = 20\ 144\ (6\text{-}3) + \frac{1}{2}(20+40)(12\text{-}6)\ 144 = 8640 + 25920 = 34560 \text{ ft lbf.}$$

$= (34560/778) =$ **44.42 Btu**

4.70E A cylinder having an initial volume of 100 ft^3 contains 0.2 lbm of water at 100 F. The water is then compressed in an isothermal quasi-equilibrium process until it has a quality of 50%. Calculate the work done in the process assuming water vapor is an ideal gas.

Solution:



$v_1 = V/m = \frac{100}{0.2} = 500 \text{ ft}^3/\text{lbm} \quad (> v_g)$

since P_g = 0.95 psia, very low so water is an ideal gas from 1 to 2.

$$P_1 = P_g \times \frac{v_g}{v_1} = 0.950 \times \frac{350}{500} = 0.6652 \text{ lbf/in}^2$$

$$V_2 = mv_2 = 0.2*350 = 70 \text{ ft}^3$$

$$v_3 = 0.01613 + 0.5\times(350 - 0.01613) = 175.0 \text{ ft}^3/\text{lbm}$$

$$W_{12} = \int PdV = P_1V_1 \ln\frac{V_2}{V_1} = 0.6652 \times \frac{144}{778} \times 100 \ln\frac{70}{100} = -4.33 \text{ Btu}$$

$$W_{23} = P_{2=3} \times m(v_3 - v_2) = 0.95 \times 0.2 \times (175 - 350) \times 144 / 778 = -6.16 \text{ Btu}$$

$W_{13} = - 6.16 - 4.33 =$ **-10.49 Btu**

4.71E Air at 30 lbf/in.^{2}, 85 F is contained in a cylinder/piston arrangement with initial volume 3.5 ft^3. The inside pressure balances ambient pressure of 14.7 lbf/in.^{2} plus an externally imposed force that is proportional to $V^{0.5}$. Now heat is transferred to the system to a final pressure of 40 lbf/in.^{2}. Find the final temperature and the work done in the process.

Solution:

C.V. Air. This is a control mass. Use initial state and process to find T_2

$$P_1 = P_0 + CV^{1/2}; \quad 30 = 14.7 + C(3.5)^{1/2}, \quad C = 8.1782 \Rightarrow$$

$$40 = 14.7 + CV_2^{1/2} \quad \Rightarrow \quad V_2 = [\ (40 - 14.7)/8.1782\ ]^2 = 9.57 \text{ ft}^3$$

$$P_2V_2 = mRT_2 = P_1V_1\, T_2 / T_1 \quad \Rightarrow$$

$$T_2 = (P_2V_2 / P_1V_1)\, T_1 = 40 \times 9.57 * 545 / (30 \times 3.5) = 1987 \text{ R}$$

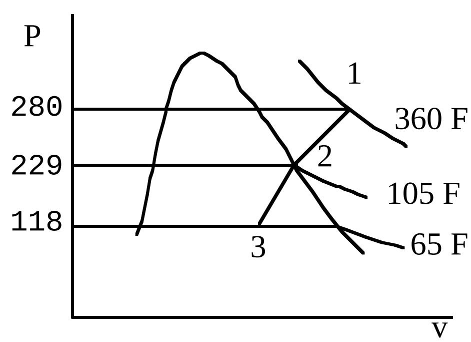
$$W_{12} = \int P\, dV = \int \left(P_0 + CV^{1/2}\right) dV$$

$$= P_0\,(V_2 - V_1) + C \times \frac{2}{3} \times (V_2^{3/2} - V_1^{3/2})$$

$$= [14.7\ (9.57 - 3.5) + \frac{2 \times 8.1782}{3} (0.957^{3/2} - 3.5^{3/2})\ ]\ \frac{144}{778} = \mathbf{10.85\ Btu}$$

4.72E A cylinder containing 2 lbm of ammonia has an externally loaded piston. Initially the ammonia is at 280 lbf/in.^{2}, 360 F and is now cooled to saturated vapor at 105 F, and then further cooled to 65 F, at which point the quality is 50%. Find the total work for the process, assuming a piecewise linear variation of *P* versus *V*.

Solution:



State 1: (T, P) Table C.9.2

$v_1 = 1.7672$ ft^3/lbm

State 2: (T, x) Table C.9.1 sat. vap.

$P_2 = 229$ psia, $v_2 = 1.311$ ft^3/lbm

State 3: (T, x) $P_3 = 118$ psia,

$v_3 = (0.02614+2.52895)/2 = 1.2775$

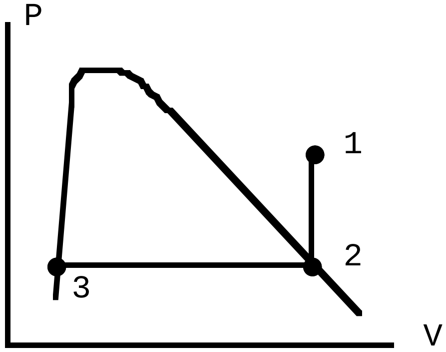
$$W_{13} = \int_1^3 PdV \approx \left(\frac{P_1 + P_2}{2}\right)m(v_2 - v_1) + \left(\frac{P_2 + P_3}{2}\right)m(v_3 - v_2)$$

$$= 2[(\frac{280 + 229}{2})(1.311 - 1.7672) + (\frac{229 + 118}{2})(1.2775 - 1.311)]\ \frac{144}{778} = \mathbf{-45.1\ Btu}$$

4.73E A piston/cylinder has 2 lbm of R-134a at state 1 with 200 F, 90 lbf/in.^{2}, and is then brought to saturated vapor, state 2, by cooling while the piston is locked with a pin. Now the piston is balanced with an additional constant force and the pin is removed. The cooling continues to a state 3 where the R-134a is saturated liquid. Show the processes in a P-V diagram and find the work in each of the two steps, 1 to 2 and 2 to 3.

Solution :

C.V. R-134a This is a control mass.



Properties from table C.11.1 and 11.2

State 1: (T,P) => $v = 0.7239 \text{ ft}^3/\text{lbm}$

State 2 given by fixed volume and $x_2 = 1.0$

State 2: $v_2 = v_1 = v_g$ => $\mathbf{{}_1W_2 = 0}$

$$T_2 = 50 + 10 \times \frac{0.7239 - 0.7921}{0.6632 - 0.7921} = 55.3 \text{ F}$$

$$P_2 = 60.311 + (72.271\text{-}60.311) \times 0.5291$$

$$= 66.64 \text{ ft}^3/\text{lbm}$$

State 3 reached at constant P (F = constant) state 3: $P_3 = P_2$ and

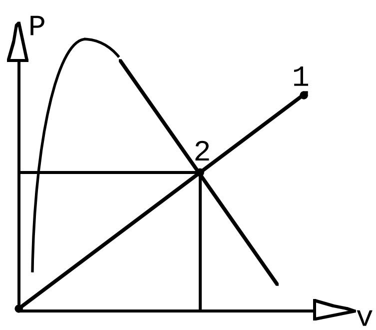
$$v_3 = v_f = 0.01271 + (0.01291 - 0.01271) \times 0.5291 = 0.01282 \text{ ft}^3/\text{lbm}$$

$${}_1W_3 = {}_1W_2 + {}_2W_3 = 0 + {}_2W_3 = \int P\, dV = P(V_3 - V_2) = mP(v_3 - v_2)$$

$$= 2\times 66.64\ (0.01282 - 0.7239)\ \frac{144}{778} = \mathbf{-17.54\ Btu}$$

4.74E Find the work for Problem 3.82.

Solution:



State 1: $v_1 = 1.7524 \text{ ft}^3/\text{lbm}$

$P = Cv \Rightarrow C = P_1/v_1 = 256.79$

State 2: sat. vap. $x_2 = 1$ and on line

Trial & error on T_2 or P_2

At 350 lbf/in^2: $P_g/v_g = 263.8 > C$

At 300 lbf/in^2: $P_g/v_g = 194.275 < C$

Interpolation: $P_2 \cong 345$ lbf/in^2 and $v_2 = v_g = 1.344 \text{ ft}^3/\text{lbm}$

$$\text{Process: } P = Cv \Rightarrow {}_1W_2 = \int P dv = \frac{1}{2}(P_1 + P_2)(v_2 - v_1)$$

$$= \frac{1}{2}(450 + 345)(1.344 - 1.7524)\ \frac{144}{778} = \mathbf{-30\ Btu/lbm}$$

4.75E Find the work for Problem 3.83.

Solution:

State 1: $P_1 = 274.6$ lbf/in^2 $v_1 = 0.1924$ ft^3/lbm

Process: $Pv = C = P_1v_1 = P_2v_2 \quad \Rightarrow \quad {}_1w_2 = \int P dv = C \int v^{-1} dv = C \ln \frac{v_2}{v_1}$

State 2: $P_2 = 30$ lbf/in^2; $v_2 = \frac{v_1P_1}{P_2} = 0.1924 \times 274.6 / 30 = 1.761$ ft^3/lbm

$$ {}_1w_2 = P_1v_1 \ln \frac{v_2}{v_1} = P_1v_1 \ln \frac{P_1}{P_2} = 274.6 \times 0.1924 \times 144 \ln \frac{274.6}{30} $$

$= 16845$ ft•lbf/lbm = **21.65 Btu/lbm**

4.76E A 1-ft-long steel rod with a 0.5-in. diameter is stretched in a tensile test. What is the required work to obtain a relative strain of 0.1%? The modulus of elasticity of steel is 30×10^6 lbf/in.^{2}.

Solution:

$$ -W_{12} = \frac{AEL_0}{2}(e)^2, \qquad A = \frac{\pi}{4}(0.5)^2 = \frac{\pi}{16} \text{ in}^2 $$

$$ -W_{12} = \frac{1}{2}\left(\frac{\pi}{16}\right) 30\times10^6 \times 1 \times (10^{-3})^2 = 2.94 \text{ ft•lbf} $$

4.77E The sun shines on a 1500 ft^2 road surface so it is at 115 F. Below the 2 inch thick asphalt, average conductivity of 0.035 Btu/h ft F, is a layer of compacted rubbles at a temperature of 60 F. Find the rate of heat transfer to the rubbles.

Solution:

$$ \dot{Q} = k \times A \times \frac{\Delta T}{\Delta x} = 0.035 \times 1500 \times \frac{115 - 60}{2/12} $$

= **17325** B**tu/h**

4.78E A water-heater is covered up with insulation boards over a total surface area of 30 ft^2. The inside board surface is at 175 F and the outside surface is at 70 F and the board material has a conductivity of 0.05 Btu/h ft F. How thick a board should it be to limit the heat transfer loss to 720 Btu/h ?

Solution:

$$\dot{Q} = k \times A \times \frac{\Delta T}{\Delta x} \quad \Rightarrow \quad \Delta x = kA\ \Delta T /\ O$$

$$\Delta x = 0.05 \times 30\ (175\ -70)/720 = 0.219\ \text{ft} = \mathbf{2.6\ in}$$

4.79E The black grille on the back of a refrigerator has a surface temperature of 95 F with a total surface area of 10 ft^2. Heat transfer to the room air at 70 F takes place with an average convective heat transfer coefficient of 3 Btu/h ft^2 R. How much energy can be removed during 15 minutes of operation?

Solution:

$$\dot{Q} = hA\ \Delta T; \qquad Q = \dot{Q}\ \Delta t = hA\ \Delta T\ \Delta t$$

$$Q = 3\ \times 10\ \times (95 - 70)\ \times (15/60)\ =\ \mathbf{187.5\ Btu}$$

CHAPTER 5

The correspondence between the new problem set and the previous 4th edition chapter 5 problem set.

New	Old	New	Old	New	Old
1	new	31	27	61	56
2	new	32	28	62	57
3	new	33	new	63	new
4	new	34	29	64	60 mod
5	new	35	41 new	65	61
6	4	36	30	66	62 mod
7	5	37	31	67	63
8	6	38	32 mod	68	64
9	7	39	33 mod	69	65
10	8	40	34 mod	70	66
11	9	41	new	71	67
12	10	42	35	72	68
13	11	43	36	73	69 mod
14	12	44	37	74	70
15	13	45	new	75	71 new
16	15	46	39	76	new
17	16	47	40	77	72
18	17	48	42	78	new
19	18	49	43	79	74
20	19	50	44	80	new
21	new	51	45 mod	81	new
22	20	52	46	82	76
23	new	53	48	83	77
24	new	54	new	84	78
25	new	55	new	85	79
26	22	56	51	86	1
27	23	57	53 mod	87	2
28	25	58	54	88	14
29	26	59	new	89	58 new
30	24	60	55 mod	90	59 mod

The problems that are labeled advanced are:

New	Old	New	Old	New	Old
91	21	95	50	99	73
92	38	96	new	100	82
93	47	97	new	101	new
94	49	98	new		

The English unit problems are:

New	Old	New	Old	New	Old
102	new	114	153	126	167
103	new	115	154 new	127	169 mod
104	141 mod	116	156	128	170 new
105	142 mod	117	157	129	171
106	143 mod	118	160 mod	130	173
107	144 mod	119	new	131	new
108	146	120	161	132	new
109	148	121	163 mod	133	174
110	149	122	new	134	175
111	new	123	164 mod	135	140
112	151	124	165	136	162 mod
113	new	125	166		

5.1 A hydraulic hoist raises a 1750 kg car 1.8 m in an auto repair shop. The hydraulic pump has a constant pressure of 800 kPa on its piston. What is the increase in potential energy of the car and how much volume should the pump displace to deliver that amount of work?

Solution: C.V. Car.

No change in kinetic or internal energy of the car, neglect hoist mass.

$E_2 - E_1 = PE_2 - PE_1 = mg\,(Z_2 - Z_1) = 1750 \times 9.80665 \times 1.8 = \mathbf{30891\ \ J}$

The increase in potential energy is work into car from pump at constant P.

$W = E_2 - E_1 = \int P\,dV = P\,\Delta V \qquad \Rightarrow$

$\Delta V = (E_2 - E_1) / P = 30891/(800 \times 1000) = \mathbf{0.0386\ m^3}$

5.2 Airplane takeoff from an aircraft carrier is assisted by a steam driven piston/cylinder with an average pressure of 750 kPa. A 3500 kg airplane should be accelerated from zero to a speed of 30 m/s with 25% of the energy coming from the steam piston. Find the needed piston displacement volume.

Solution: C.V. Airplane.

$E_2 - E_1 = m\,(1/2)\,(V_2^2\ - 0) = 3500 \times (1/2) \times 30^2 = 1575000\ J = 1575\ kJ$

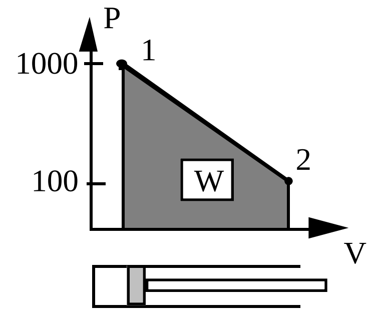
The work supplied by the piston is 25% of energy increase.

$W = \int P\,dv = P_{avg}\ \Delta V = 0.25\,(E_2 - E_1) = 0.25 \times 1575 = 393.75\ kJ$

$\Delta V = 393.75/750 = \mathbf{0.525\ m^3}$

5.3 Solve Problem 5.2, but assume the steam pressure in the cylinder starts at 1000 kPa, dropping linearly with volume to reach 100 kPa at the end of the process.

Solution: C.V. Airplane.



$E_2 - E_1 = m\,(1/2)\,(V_2^2\ - 0)$

$= 3500 \times (1/2) \times 30^2$

$= 1575000\ J = 1575\ kJ$

$W = \int P\,dv = (1/2)(P_{beg} + P_{end})\,\Delta V$

$= 0.25 \times 1575 = 393.75\ kJ$

$\Delta V = 393.75/[\ (1/2)(1000 + 100)\ ] = \mathbf{0.716\ m^3}$

5.4 A piston motion moves a 25 kg hammerhead vertically down 1 m from rest to a velocity of 50 m/s in a stamping machine. What is the change in total energy of the hammerhead?

Solution: C.V. Hammerhead

The hammerhead does not change internal energy i.e. same P,T

$E_2 – E_1 = m(u_2 – u_1) + m((1/2)V_2^{\,2} - 0) + mg\,(h_2 - 0)$

$= 0 + 25 \text{ x } (1/2) \text{ x } 50^2 + 25 \text{ x } 9.80665 \text{ x } (-1)$

$= 31250 – 245.17 = 31005$ J = **31 kJ**

5.5 A 25 kg piston is above a gas in a long vertical cylinder. Now the piston is released from rest and accelerates up in the cylinder reaching the end 5 m higher at a velocity of 25 m/s. The gas pressure drops during the process so the average is 600 kPa with an outside atmosphere at 100 kPa. Neglect the change in gas kinetic and potential energy, and find the needed change in the gas volume.

Solution: C.V. Piston

$(E_2 – E_1)_{PIST.} = m(u_2 – u_1) + m[(1/2)V_2^{\,2} - 0] + mg\,(h_2 - 0)$

$= 0 + 25 \text{ x } (1/2) \text{ x } 25^2 + 25 \text{ x} 9.80665 \text{ x } 5$

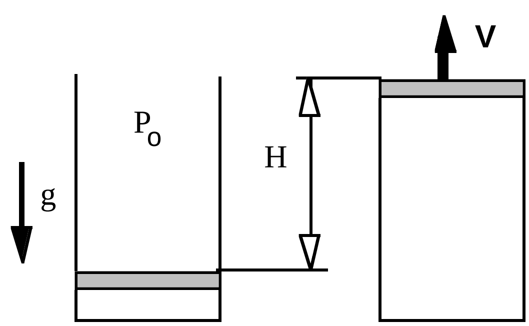
$= 7812.5 + 1225.8 = 9038.3$ J = 9.038 kJ

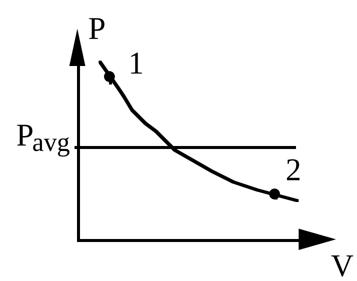
Energy equation for the piston is:

$E_2 – E_1 = W_{gas} - W_{atm} = P_{avg}\ \Delta V_{gas} – P_o\ \Delta V_{gas}$

(remark $\Delta V_{atm} = – \Delta V_{gas}$ so the two work terms are of opposite sign)

$\Delta V_{gas} = 9.038/(600 – 100) =$ **0.018 m³**





5.6 Find the missing properties

a.	H_2O	$T = 250°C$, $v = 0.02$ m^3/kg	$P = ?$ $u = ?$
b.	N_2	$T = 277°C$, $P = 0.5$ MPa	$x = ?$ $h = ?$
c.	H_2O	$T = -2°C$, $P = 100$ kPa	$u = ?$ $v = ?$
d.	R-134a	$P = 200$ kPa, $v = 0.12$ m^3/kg	$u = ?$ $T = ?$
e.	NH_3	$T = 65°C$, $P = 600$ kPa	$u = ?$ $v = ?$

Solution:

a) Table B.1.1 $v_f < v < v_g$ $\Rightarrow$ P = Psat = **3973 kPa**

$x = (v - v_f)/ v_{fg} = (0.02 – 0.001251)/0.04887 = 0.383$

$u = u_f + x\ u_{fg} = 1080.37 + 0.38365 \times 1522.0 =$ **1664.28 kJ/kg**

b) T= 277°C = 550 K > Tc so this is an ideal gas => x = **undef.**

Table C.7 h = [(1/2) x 5911 + (1/2) x 8894]/28.013 = **264.25 kJ/kg**

Conversion to mass base from mole base with the molecular weight.

c) Table B.1.1 : $T < T_{\text{triple point}}$ => B.1.5: P > Psat so compressed solid

$u \cong u_i =$ **-337.62 kJ/kg** $v \cong v_i =$ **1.09x10^{-3} m^3/kg**

approximate compressed solid with saturated solid properties at same T.

d) Table B.5.1 $v > v_g$ superheated vapor => B.5.2.

T ~ **32.5°C** = 30 + (40 – 30) x (0.12 – 0.11889)/(0.12335 - 0.11889)

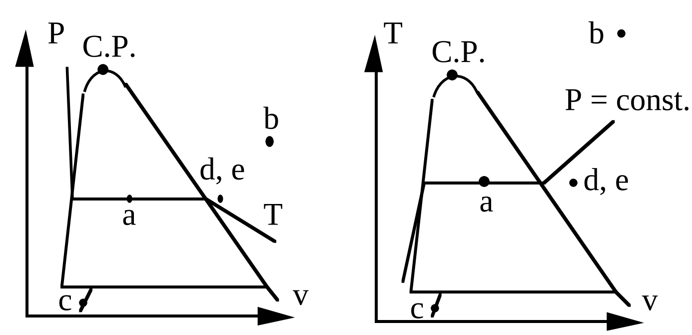
u = h - Pv = 429.07 - 200 x 0.12 = 405.07 kJ/kg

e) Table B.2.1 P < Psat => superheated vapor B.2.2:

v = 0.5*0.25981 + 0.5 x 0.26888 = **0.2645 m^3/kg**

u = h - Pv = 1594.65 - 600 x 0.2645 = **1435.95 kJ/kg**

States shown are placed relative to the two-phase region, not to each other.



5.7 Find the missing properties and give the phase of the substance

a. H_2O u = 2390 kJ/kg, T = 90°C h = ? v = ? x = ?

b. H_2O u = 1200 kJ/kg, P = 10 MPa T = ? x = ? v = ?

c. R-12 T = −5°C, P = 300 kPa h = ? x = ?

d. R-134a T = 60°C, h = 430 kJ/kg v = ? x = ?

e. NH_3 T = 20°C, P = 100 kPa u = ? v = ? x = ?

Solution:

a) Table B.1.1: $u_f < u < u_g$ => 2-phase mixture of liquid and vapor

$x = (u - u_f)/ u_{fg} = (2390 - 376.82)/2117.7 = \mathbf{0.9506}$

$v = v_f + x\ v_{fg} = 0.001036 + 0.9506 \times 2.35953 = \mathbf{2.244\ m^3/kg}$

$h = h_f + x\ h_{fg} = 376.96 + 0.9506 \times 2283.19 = \mathbf{2547.4\ kJ/kg}$

b) Table B.1.2: $u < u_f$ so compressed liquid B.1.4, x = **undefined**

$$T \cong 260 + (280 - 260) \times \frac{1200\text{-}1121.03}{1220.9\text{-}1121.03} = \mathbf{275.8°C}$$

$$v = 0.001265 + 0.000057 \times \frac{1200\text{-}1121.03}{1220.9\text{-}1121.03} = \mathbf{0.0013096\ m^3/kg}$$

c) Table B.3.1: P > Psat => x = **undef**, **compr. liquid**

Approximate as saturated liquid at same T, $h = h_f$ = **31.45 kJ/kg**

d) Table B.5.1: h > hg => x = **undef**, **superheated vapor** B.5.2,

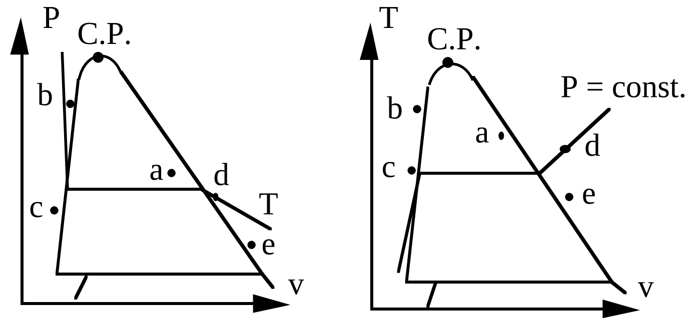
find it at given T between 1400 kPa and 1600 kPa to match h:

$$v \cong 0.01503 + (0.01239\text{-}0.01503) \times \frac{430\text{-}434.08}{429.32\text{-}434.08} = \mathbf{0.01269\ m^3/kg}$$

e) Table B.2.1: P < Psat => x = **undef**, **superheated vapor**, from B.2.2:

$v = \mathbf{1.4153\ m^3/kg}$; $u = h - Pv = 1516.1 - 100 \times 1.4153 = \mathbf{1374.6\ kJ/kg}$

States shown are placed relative to the two-phase region, not to each other.



5.8 Find the missing properties and give the phase of the substance

a.	H_2O	$T = 120°C$, $v = 0.5\ m^3/kg$	$u = ?$ $P = ?$ $x = ?$
b.	H_2O	$T = 100°C$, $P = 10$ MPa	$u = ?$ $x = ?$ $v = ?$
c.	N_2	$T = 800$ K, $P = 200$ kPa	$v = ?$ $u = ?$
d.	NH_3	$T = 100°C$, $v = 0.1\ m^3/kg$	$P = ?$ $x = ?$
e.	CH_4	$T = 190$ K, $x = 0.75$	$v = ?$ $u = ?$

Solution:

a) Table B.1.1: $v_f < v < v_g$ => L+V mix, P = **198.5 kPa**,

x = (0.5 - 0.00106)/0.8908 = **0.56**,

u = 503.48 + 0.56 × 2025.76 = **1637.9 kJ/kg**

b) Table B.1.4: compressed liquid, v = 0**.001039 m³/kg**, u = **416.1 kJ/kg**

c) Table A.2: T >> Tcrit. => sup. vapor, ideal gas, R from Table A.5

v = RT/P = 0.18892 x 800/200 = **0.7557 m³/kg**

Table A.8: $u = h - Pv = \frac{22806}{44.01} - 200 \times 0.7557 = \mathbf{367\ kJ/kg}$

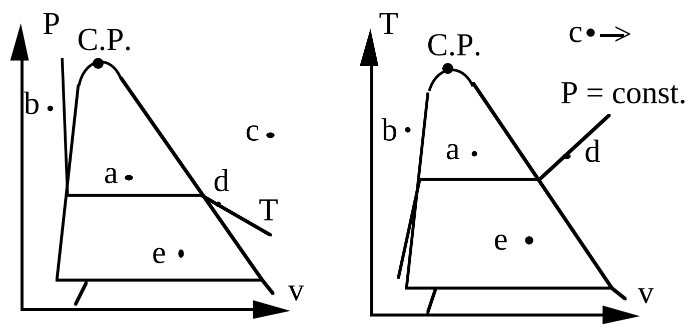
d) Table B.2.1: $v > v_g$ => sup. vapor, x = **undefined**

B.2.2: $P = 1600 + 200 \times \frac{0.1 - 0.10539}{0.09267-0.10539} = \mathbf{1685\ kPa}$

e) Table B.7.1: L+V mix, v = 0.00497 + 0.75 × 0.003 = **0.00722 m³/kg**

u = 69.1 + 0.75 x 67.01 = **119.36 kJ/kg**

States shown are placed relative to the two-phase region, not to each other.



5.9 Find the missing properties among (*P*, *T*, *v*, *u*, *h*) together with *x* if applicable and give the phase of the substance.

a. R-22 $T = 10°C$, $u = 200$ kJ/kg

b. H_2O $T = 350°C$, $h = 3150$ kJ/kg

c. R-12 $P = 600$ kPa, $h = 230$ kJ/kg

d. R-134a $T = 40°C$, $u = 407$ kJ/kg

e. NH_3 $T = 20°C$, $v = 0.1\ m^3/kg$

Solution:

a) Table B.4.1: $u < u_g$ => L+V mixture, P = **680.7 kPa**

$x = (200 - 55.92)/173.87 =$ **0.8287**,

$v = 0.0008 + 0.8287 \times 0.03391 =$ **0.0289 m³/kg**,

$h = 56.46 + 0.8287 \times 196.96 =$ **219.7 kJ/kg**

b) Table B.1.1: $h > h_g$ => superheated vapor follow 350°C in B.1.3

P ~ 1375 kPa, v = **0.204 m³/kg,** u = **2869.5 kJ/kg**

c) Table B.3.1: $h > h_g$ = > **sup. vapor**,

T = **69.7°C**, v = **0.03624 m³/kg**, u = **208.25 kJ/kg**

d) Table B.5.1: $u > u_g$ => **sup. vap.,** calculate u at some P to end with

P = **500 kPa**, v = **0.04656 m³/kg,** h = **430.72 kJ/kg**

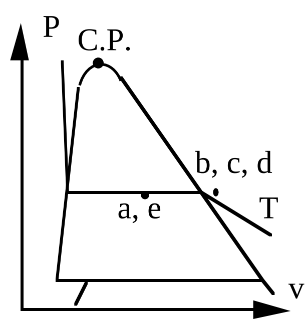
e) Table B.2.1: $v < v_g$ => L+V mixture, P = **857.22 kPa**

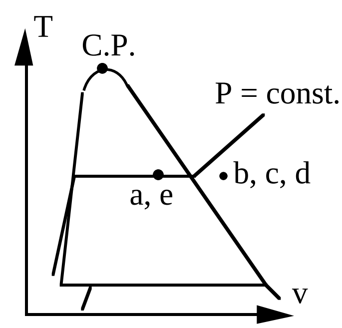
$x = (0.1 - 0.001638)/0.14758 =$ **0.666**

$h = 274.3 + 0.666 \times 1185.9 =$ **1064.1 kJ/kg**

$u = h - Pv =$ **978.38 kJ/kg** $(= 272.89 + 0.666 \times 1059.3)$

States shown are placed relative to the two-phase region, not to each other.





5.10 A 100-L rigid tank contains nitrogen (N_2) at 900 K, 6 MPa. The tank is now cooled to 100 K. What are the work and heat transfer for this process?

C.V.: Nitrogen in tank. $m_2 = m_1$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: V = constant, $v_2 = v_1 = V/m$ => $\mathbf{{}_1W_2 = 0}$

Table B.6.2: State 1: $v_1 = 0.045514$ => $m = V/v_1 = 2.197$ kg

$$u_1 = h_1 - P_1v_1 = 963.59 – 6000 \text{ x } 0.045514 = 690.506$$

State 2: 100 K, $v_2 = v_1 = V/m$, look in table B.6.2 at 100 K

500 kPa: v= 0.05306 ; h = 94.46, 600 kPa: v = 0.042709, h = 91.4

so a linear interpolation gives: $P_2 = 572.9$ kPa, $h_2 = 92.265$ kJ/kg,

$$u_2 = h_2 - P_2v_2 = 92.265 - 572.9 \times 0.04551 = 66.19 \text{ kJ/kg}$$

${}_1Q_2 = m(u_2 - u_1) = 2.197\ (66.19 – 690.506) =$ **-1372 kJ**

5.11 Water in a 150-L closed, rigid tank is at 100°C, 90% quality. The tank is then cooled to −10°C. Calculate the heat transfer during the process.

Solution:

C.V.: Water in tank. $m_2 = m_1$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: V = constant, $v_2 = v_1$, ${}_1W_2 = 0$

State 1: $v_1 = 0.001044 + 0.9 \text{ x } 1.6719 = 1.5057 \text{ m}^3\text{/kg}$

$u_1 = 418.94 + 0.9 \text{ x } 2087.6 = 2297.8$ kJ/kg

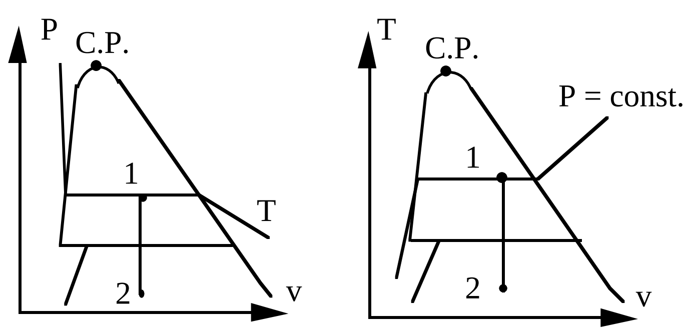
State 2: T_2, $v_2 = v_1$ $\Rightarrow$ mix of sat. solid + vap. Table B.1.5

$v_2 = 1.5057 = 0.0010891 + x_2 \text{ x } 466.7$ => $x_2 = 0.003224$

$u_2 = -354.09 + 0.003224 \text{ x } 2715.5 = -345.34$ kJ/kg

$m = V/v_1 = 0.15/1.5057 = 0.09962$ kg

${}_1Q_2 = m(u_2 - u_1) = 0.09962(-345.34 - 2297.8) =$ **-263.3 kJ**

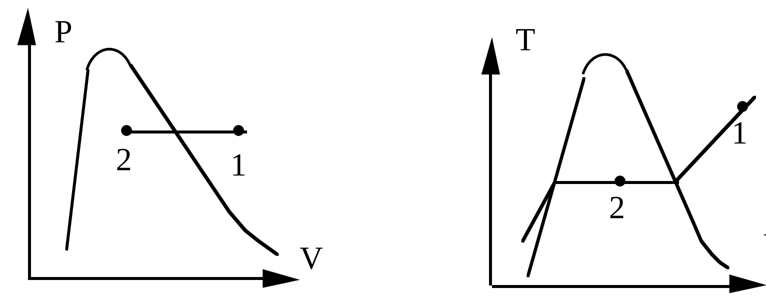


5.12 A cylinder fitted with a frictionless piston contains 2 kg of superheated refrigerant R-134a vapor at 350 kPa, 100°C. The cylinder is now cooled so the R-134a remains at constant pressure until it reaches a quality of 75%. Calculate the heat transfer in the process.

Solution:

C.V.: R-134a $m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: P = const. $\Rightarrow {}_1W_2 = \int PdV = P\Delta V = P(V_2 - V_1) = Pm(v_2 - v_1)$



State 1: Table B.5.2 $h_1 = (490.48 + 489.52)/2 = 490$ kJ/kg

State 2: Table B.5.1 $h_2 = 206.75 + 0.75 \times 194.57 = 352.7$ kJ/kg (350.9 kPa)

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(u_2 - u_1) + Pm(v_2 - v_1) = m(h_2 - h_1)$

${}_1Q_2 = 2 \times (352.7 - 490) =$ **-274.6 kJ**

5.13 A test cylinder with constant volume of 0.1 L contains water at the critical point. It now cools down to room temperature of 20°C. Calculate the heat transfer from the water.

Solution:

C.V.: Water

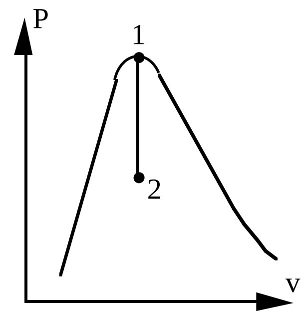
$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: Constant volume $\Rightarrow v_2 = v_1$

Properties from Table B.1.1

State 1: $v_1 = v_c = 0.003155$ $u_1 = 2029.6$

$m = V/v_1 = 0.0317$ kg



State 2: T_2, $v_2 = v_1 = 0.001002 + x_2$ x 57.79

$x_2 = 3.7\text{x}10^{-5}$, $u_2 = 83.95 + x_2$ x 2319 = 84.04

Constant volume => ${}_1W_2 = \emptyset$

${}_1Q_2 = m(u_2 - u_1) = 0.0317(84.04 - 2029.6) =$ **-61.7 kJ**

5.14 Ammonia at 0°C, quality 60% is contained in a rigid 200-L tank. The tank and ammonia is now heated to a final pressure of 1 MPa. Determine the heat transfer for the process.

Solution:

C.V.: NH_3

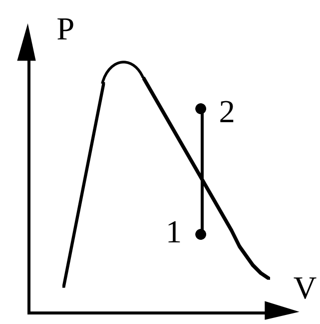
$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: Constant volume $\Rightarrow v_2 = v_1$ & ${}_1W_2 = \emptyset$

State 1: Table B.2.1

$v_1 = 0.001566 + x_1$ x $0.28783 = 0.17426$ m^3/kg

$u_1 = 179.69 + 0.6$ x $1138.3 = 862.67$ kJ/kg



$m = V/v_1 = 0.2/0.17426 = 1.148$ kg

State 2: P_2 , $v_2 = v_1$ superheated vapor Table B.2.2

$\Rightarrow T_2 \cong 100$°C, $u_2 = 1664.3 - 1000$ x $0.174 = 1490.3$ kJ/kg

${}_1Q_2 = 1.148(1490.3 - 862.67) =$ **720.52 kJ**

5.15 A 10-L rigid tank contains R-22 at −10°C, 80% quality. A 10-A electric current (from a 6-V battery) is passed through a resistor inside the tank for 10 min, after which the R-22 temperature is 40°C. What was the heat transfer to or from the tank during this process?

Solution:

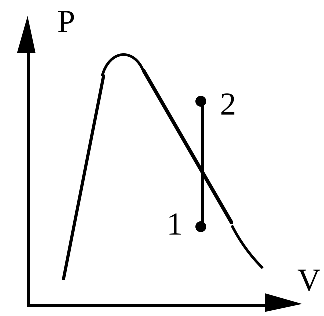
C.V. R-22 in tank. Control mass at constant V.

$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: Constant V $\Rightarrow$ $v_2 = v_1$

=> no boundary work, but electrical work

State 1 from table B.4.1



$v_1 = 0.000759 + 0.8 \times 0.06458 = 0.05242\ m^3/kg$

$u_1 = 32.74 + 0.8 \times 190.25 = 184.9\ kJ/kg$

$m = V/v = 0.010/0.05242 = 0.1908\ kg$

State 2: Table B.4.2 at 40°C and $v_2 = v_1 = 0.05242\ m^3/kg$ => sup.vap.

$P_2 = 500 + 100 \times (0.05242\text{-}0.05636)/(0.04628\text{-}0.05636) = 535\ kPa$,

$u_2 = h_2 - P_2v_2 = [278.69 + 0.35 \times (-1.44)] - 535 \times 0.05242 = 250.2\ kJ/kg$

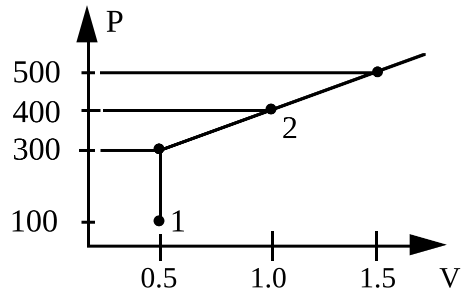
$${}_1W_{2\ elec} = \text{-power} \times \Delta t = \text{-Amp} \times \text{volts} \times \Delta t = -\frac{10 \text{ x } 6 \text{ x } 10 \text{ x } 60}{1000} = -36\ kJ$$

${}_1Q_2 = m(u_2\text{-}u_1) + {}_1W_2 = 0.1908\ (250.2\text{-}\ 184.9) - 36 =$ **-23.5 kJ**

5.16 A piston/cylinder arrangement contains 1 kg of water, shown in Fig. P5.16. The piston is spring loaded and initially rests on some stops. A pressure of 300 kPa will just float the piston and, at a volume of 1.5 m^3, a pressure of 500 kPa will balance the piston. The initial state of the water is 100 kPa with a volume of 0.5 m^3. Heat is now added until a pressure of 400 kPa is reached.

a. Find the initial temperature and the final volume.

b. Find the work and heat transfer in the process and plot the *P–V* diagram.



C.V.: H_2O

Cont.: $m_2 = m_1 = 1$ kg

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Straight line (linear spring):

From (0.5, 300) to (1.5, 500)

The initial pressure can not lift the piston.

1: 100 kPa, $v_1 = V_1/m_1 = 0.5\ m^3/kg < v_g$; => $T_1 =$ **99.6°C**

$x_1 = (0.5 - 0.001043)/1.69296 = 0.2947$

$u_1 = 417.33 + 0.2947 \times 2088.72 = 1032.9$ kJ/kg

2: 400 kPa and on line, see figure => $V_2 = \mathbf{1.0\ m^3}$, $v_2 = V_2/m_1 = 1.0\ m^3/kg$

Superheated vapor Table B.1.2: $T_2 = 595°C$, $u_2 = 3292$ kJ/kg

$${}_1W_2 = \int P\,dV = \text{AREA} = \frac{1}{2}(300 + 400)(1.0 - 0.5) = \mathbf{175\ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1(3292 - 1032.9) + 175 = \mathbf{2434\ kJ}$$

5.17 A closed steel bottle contains ammonia at −20°C, $x = 20\%$ and the volume is 0.05 m^3. It has a safety valve that opens at a pressure of 1.4 MPa. By accident, the bottle is heated until the safety valve opens. Find the temperature and heat transfer when the valve first opens.

C.V.: NH_3 : $m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

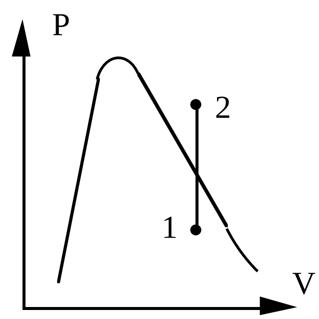
Process: constant volume process $\Rightarrow {}_1W_2 = 0$

State 1: $v_1 = 0.001504 + 0.2 \times 0.62184 = 0.1259$

=> $m = V/v_1 = 0.05/0.1259 = 0.397$ kg

$u_1 = 88.76 + 0.2 \times 1210.7 = 330.9$ kJ/kg

State 2: P_2 , $v_2 = v_1$ => superheated vapor



T ≅ 110°C, $u_2 = h_2 - P_2v_2 = 1677.6 - 1400 \times 0.1259 = 1501.34$

$${}_1Q_2 = m(u_2 - u_1) = 0.397(1501.34 - 330.9) = \mathbf{464.7\ kJ}$$

5.18 A piston/cylinder arrangement B is connected to a 1-m^3 tank A by a line and valve, shown in Fig. P5.18. Initially both contain water, with A at 100 kPa, saturated vapor and B at 400°C, 300 kPa, 1 m^3. The valve is now opened and, the water in both A and B comes to a uniform state.

a. Find the initial mass in A and B.

b. If the process results in T_2 = 200°C, find the heat transfer and work.

Solution:

C.V.: A + B. This is a control mass.

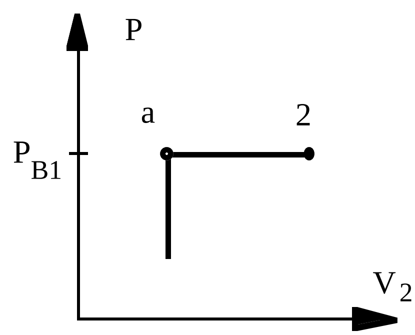
Continuity equation: $m_2 - (m_{A1} + m_{B1}) = 0$;

Energy: $m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = {}_1Q_2 - {}_1W_2$

System: if $V_B \geq 0$ piston floats $\Rightarrow$ $P_B = P_{B1}$ = const.

if $V_B = 0$ then $P_2 < P_{B1}$ and $v = V_A/m_{tot}$ see P-V diagram

$${}_1W_2 = \int P_B dV_B = P_{B1}(V_2 - V_1)_B = P_{B1}(V_2 - V_1)_{tot}$$



State A1: Table B.1.1, x = 1

v_{A1} = 1.694 m^3/kg, u_{A1} = 2506.1 kJ/kg

$m_{A1} = V_A/v_{A1}$ = **0.5903 kg**

State B1: Table B.1.2 sup. vapor

v_{B1} = 1.0315 m^3/kg, u_{B1} = 2965.5 kJ/kg

$m_{B1} = V_{B1}/v_{B1}$ = **0.9695 kg**

$m_2 = m_{TOT}$ = 1.56 kg

* At (T_2, P_{B1}) $v_2 = 0.7163 > v_a = V_A/m_{tot} = 0.641$ so $V_{B2} > 0$

so now state 2: $P_2 = P_{B1}$ = 300 kPa, T_2 = 200 °C

=> u_2 = 2650.7 kJ/kg and $V_2 = m_2 v_2 = 1.56 \times 0.7163 = 1.117$ m^3

(we could also have checked T_a at: 300 kPa, 0.641 m^3/kg => T = 155 °C)

${}_1W_2 = P_{B1}(V_2 - V_1)$ = **-264.82 kJ**

${}_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} + {}_1W_2$ = **-484.7 kJ**

5.19 Consider the same setup and initial conditions as in the previous problem. Assuming that the process is adiabatic, find the final temperature and work.

See **5.18** solution up to *, then:

$_1W_2 = P_{B1}(V_2 - V_1)$; $V_2 \ge V_A$ if > then $P_2 = P_{B1}$ piston floats

Energy: $m_2u_2 + {}_1W_2 = m_{A1}u_{A1} + m_{B1}u_{B1} = m_2u_2 + P_2V_2 - P_{B1}V_1$

$\Rightarrow m_2h_2 = m_{A1}u_{A1} + m_{B1}u_{B1} + P_{B1}V_1$

$= 0.5903 \times 2506.1 + 0.9695 \times 2965.5 + 300 \times 2 = 4954$ kJ

$h_2 = 4954/1.5598 = 3176.3 \Rightarrow$ Table B.1.2 : $v_2 = 0.95717 > v_a = 0.641$

$(P_{B1}, h_2) \Rightarrow T_2 =$ **352°C** and $V_2 = 1.56 \times 0.9572 = 1.493$ m^3

$_1W_2$= 300 (1.493 - 2) = **-152.1 kJ**

5.20 A vertical cylinder fitted with a piston contains 5 kg of R-22 at 10°C, shown in Fig. P5.20. Heat is transferred to the system, causing the piston to rise until it reaches a set of stops at which point the volume has doubled. Additional heat is transferred until the temperature inside reaches 50°C, at which point the pressure inside the cylinder is 1.3 MPa.

a. What is the quality at the initial state?

b. Calculate the heat transfer for the overall process.

Solution:

C.V. R-22. Control mass goes through process: 1 -> 2 -> 3

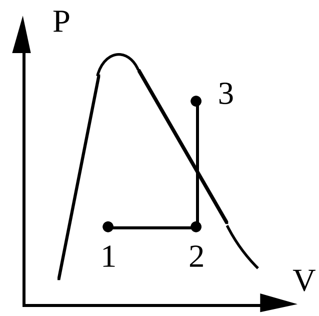
As piston floats pressure is constant (1 -> 2) and the volume is constant for the second part (2 -> 3)

So we have: $v_3 = v_2 = 2 \times v_1$

State 3: Table B.4.2 (P,T) $v_3 = 0.02015$

$u_3 = h - Pv = 274.39 - 1300 \times 0.02015 = 248.2$ kJ/kg

So we can then determine state 1 and 2 Table B.4.1:



$v_1 = 0.010075 = 0.0008 + x_1 \times 0.03391$ => $x_1 =$ **0.2735**

b) $u_1 = 55.92 + 0.271 \times 173.87 = 103.5$

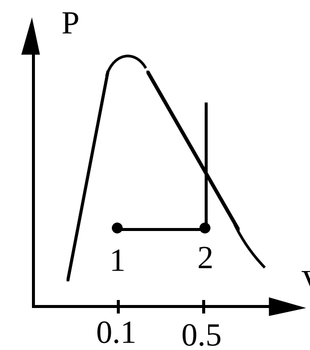
State 2: $v_2 = 0.02015$, $P_2 = P_1 = 681$ kPa this is still 2-phase.

$$_1W_3 = {}_1W_2 = \int_1^2 PdV = P_1(V_2 - V_1) = 681 \times 5\,(0.02 - 0.01) = \mathbf{34.1\ kJ}$$

$$_1Q_3 = m(u_3 - u_1) + {}_1W_3 = 5(248.2-103.5) + 34.1 = \mathbf{757.6\ kJ}$$

5.21 A piston/cylinder contains 50 kg of water at 200 kPa with a volume of 0.1 m^3. Stops in the cylinder are placed to restrict the enclosed volume to 0.5 m^3 similar to Fig. P5.20. The water is now heated until the piston reaches the stops. Find the necessary heat transfer.

Solution:



C.V. H_2O m = constant

$m(e_2 - e_1) = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process : P = constant (forces on piston constant)

$\Rightarrow {}_1W_2 = \int P\, dV = P_1 (V_2 - V_1)$

${}_1Q_2 = m(u_2 - u_1) + P_1 (V_2 - V_1) = m(h_2 - h_1)$

Properties from Table B.1.1

State 1 : $v_1 = 0.1/50 = 0.002\ m^3/kg$ => 2-phase

$x = (0.002 - 0.001061)/0.88467 = 0.001061$

$h = 504.68 + 0.001061 \times 2201.96 = 507.02$ kJ/kg

State 2 : $v_2 = 0.5/50 = 0.01\ m^3/kg$ also 2-phase same P

$x_2 = (0.01 - 0.001061)/0.88467 = 0.01010$

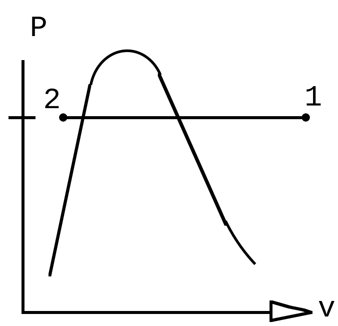
$h_2 = 504.68 + 0.01010 \times 2201.96 = 526.92$ kJ/kg

${}_1Q_2 = 50 \times (526.92 - 507.02) =$ **995 kJ**

[${}_1W_2 = P_1 (V_2 - V_1) = 200 \times (0.5 - 0.1) =$ **80 kJ**]

5.22 Ten kilograms of water in a piston/cylinder with constant pressure is at 450°C and a volume of 0.633 m^3. It is now cooled to 20°C. Show the *P–v* diagram and find the work and heat transfer for the process.

Solution:



Constant pressure $\Rightarrow {}_1W_2 = mP(v_2 - v_1)$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1)$

Properties from Table B.1.3 and B.1.4

State 1: $v_1 = 0.633/10 = 0.0633\ m^3/kg$

$P_1 = 5$ Mpa, $h_1 = 3316.2$ kJ/kg

State 2: 5 MPa, 20°C $\Rightarrow v_2 = 0.0009995$

$h_2 = 88.65$ kJ/kg

${}_1W_2 = 10 \times 5000 \times (0.0009995 - 0.0633) =$ **-3115 kJ**

${}_1Q_2 = 10 \times (88.65 - 3316.2) =$ **-32276 kJ**

5.23 Find the heat transfer in Problem 4.10.

Solution:

Take CV as the water. Properties from table B.1

$$m_2 = m_1 = m \; ; \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: Compressed liq. $v = v_f\,(20) = 0.001002$, $u = u_f = 83.94$

State 2: Since $P > P_{lift}$ then $v = v_{stop} = 0.002$ and $P = 600$ kPa

For the given P : $v_f < v < v_g$ so 2-phase $T = T_{sat} = 158.85$ °C

$$v = 0.002 = 0.001101 + x \times (0.3157 - 0.001101) \;\Rightarrow\; x = 0.002858$$

$$u = 669.88 + 0.002858 \times 1897.5 = 675.3 \text{ kJ/kg}$$

Work is done while piston moves at P_{lift} = constant = 300 kPa so we get

$${}_1W_2 = \int P\,dV = m\,P_{lift}\,(v_2 - v_1) = 1 \times 300(0.002 - 0.001002) = \mathbf{0.299\ kJ}$$

Heat transfer is found from energy equation

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1(675.3 - 83.94) + 0.299 = \mathbf{591.66\ kJ}$$

5.24 Find the heat transfer in Problem 4.24.

Solution:

C.V. Water. This is a control mass.

$$m_2 = m_1 = m \; ; \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: 20 C, $v_1 = V/m = 0.1/1 = 0.1\ m^3/kg$

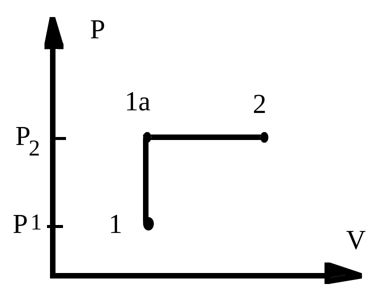
$x = (0.1 - 0.001002)/57.789 = 0.001713$

$u_1 = 83.94 + 0.001713 \times 2318.98 = 87.92$ kJ/kg

To find state 2 check on state 1a:

$P = 400$ kPa, $v = v_1 = 0.1\ m^3/kg$

Table B.1.2: $v_f < v < v_g = 0.4625$



State 2 is saturated vapor at 400 kPa since state 1a is two-phase.

$v_2 = v_g = 0.4625\ m^3/kg$, $V_2 = m\,v_2 = 0.4625\ m^3$, $u_2 = u_g = 2553.6$ kJ/kg

Pressure is constant as volume increase beyond initial volume.

$${}_1W_2 = \int P\,dV = P\,(V_2 - V_1) = P_{lift}\,(V_2 - V_1) = 400\,(0.4625 - 0.1) = 145 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1\,(2553.6 - 87.92) + 145 = \mathbf{2610.7\ kJ}$$

5.25 A piston/cylinder contains 1 kg of liquid water at 20°C and 300 kPa. There is a linear spring mounted on the piston such that when the water is heated the pressure reaches 3 MPa with a volume of 0.1 m^3.

a. Find the final temperature and plot the *P-v* diagram for the process.

b. Calculate the work and heat transfer for the process.

Solution:

Take CV as the water.

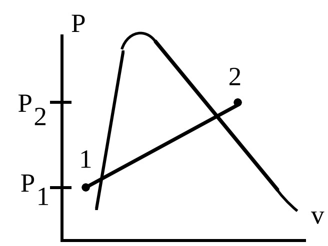
$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: Compr. liq., use sat. liq. same T, Table B.1.1

$v = v_f\,(20) = 0.001002$, $u = u_f = 83.94$ kJ/kg

State 2: $v = V/m = 0.1/1 = 0.1\ m^3/kg$ and P = 3 MPa

=> Sup. vapor T = 400 C ; u = 2932.7 kJ/kg



Work is done while piston moves at linearly varying pressure, so we get

${}_1W_2 = \int P\,dV = P_{avg}(V_2 - V_1) = 0.5x(300+3000)(0.1 - 0.001) =$ **163.35 kJ**

Heat transfer is found from energy equation

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1 \text{ x } (2932.7 - 83.94) + 163.35 =$ **3012 kJ**

5.26 An insulated cylinder fitted with a piston contains R-12 at 25°C with a quality of 90% and a volume of 45 L. The piston is allowed to move, and the R-12 expands until it exists as saturated vapor. During this process the R-12 does 7.0 kJ of work against the piston. Determine the final temperature, assuming the process is adiabatic.

Solution:

Take CV as the R-12. $m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: (T, x) Tabel B.3.1 =>

$v_1 = 0.000763 + 0.9 \text{ x } 0.02609 = 0.024244\ m^3/kg$

$m = V_1/v_1 = 0.045/0.024244 = 1.856$ kg

$u_1 = 59.21 + 0.9 \text{ x } 121.03 = 168.137$ kJ/kg

${}_1Q_2 = \emptyset = m(u_2 - u_1) + {}_1W_2 = 1.856 \text{ x } (u_2 - 168.137) + 7.0$

=> $u_2 = 164.365 = u_g$ at T_2

Table B.3.1 gives u_g at different temperatures: $T_2 \cong$ **-15°C**

5.27 Two kilograms of nitrogen at 100 K, x = 0.5 is heated in a constant pressure process to 300 K in a piston/cylinder arrangement. Find the initial and final volumes and the total heat transfer required.

Solution:

Take CV as the nitrogen.

$$m_2 = m_1 = m \; ; \qquad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: Table B.6.1

$$v_1 = 0.001452 + 0.5 \times 0.02975 = 0.01633 \text{ m}^3\text{/kg}, \quad V_1 = \mathbf{0.0327 \ m^3}$$

$$h_1 = -73.20 + 0.5 \times 160.68 = 7.14 \text{ kJ/kg}$$

State 2: P = 779.2 kPa , 300 K => sup. vapor interpolate in Table B.6.2

$$v_2 = 0.14824 + (0.11115\text{-}0.14824)\times 179.2/200 = 0.115 \text{ m}^3\text{/kg}, \; V_2 = \mathbf{0.23 \ m^3}$$

$$h_2 = 310.06 + (309.62\text{-}310.06) \times 179.2/200 = 309.66 \text{ kJ/kg}$$

Process: P = const. $\Rightarrow {}_1W_2 = \int PdV = Pm(v_2 - v_1)$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1) = 2 \text{ x } (309.66 - 7.14) = \mathbf{605 \ kJ}$$

5.28 A piston/cylinder arrangement has the piston loaded with outside atmospheric pressure and the piston mass to a pressure of 150 kPa, shown in Fig. P5.28. It contains water at −2°C, which is then heated until the water becomes saturated vapor. Find the final temperature and specific work and heat transfer for the process.

Solution:

C.V. Water in the piston cylinder.

Continuity: $m_2 = m_1$, Energy: $u_2 - u_1 = {}_1q_2 - {}_1w_2$

Process: P = const. = P_1, => ${}_1w_2 = \int_1^2 P \, dv = P_1(v_2 - v_1)$

State 1: T_1 , P_1 => Table B.1.5 compressed solid, take as saturated solid.

$$v_1 = 1.09\text{x}10^{-3} \text{ m}^3\text{/kg}, \quad u_1 = -337.62 \text{ kJ/kg}$$

State 2: x = 1, $P_2 = P_1$ = 150 kPa due to process => Table B.1.2

$$v_2 = v_g(P_2) = 1.1593 \text{ m}^3\text{/kg}, \quad T_2 = \mathbf{111.37°C} \; ; \quad u_2 = 2519.7 \text{ kJ/kg}$$

$${}_1w_2 = P_1(v_2 - v_1) = 150(1.1593 - 1.09\text{x}10^{-3}) = \mathbf{173.7 \ kJ/kg}$$

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = 2519.7 - (-337.62) + 173.7 = \mathbf{3031 \ kJ/kg}$$

5.29 Consider the system shown in Fig. P5.29. Tank A has a volume of 100 L and contains saturated vapor R-134a at 30°C. When the valve is cracked open, R-134a flows slowly into cylinder B. The piston mass requires a pressure of 200 kPa in cylinder B to raise the piston. The process ends when the pressure in tank A has fallen to 200 kPa. During this process heat is exchanged with the surroundings such that the R-134a always remains at 30°C. Calculate the heat transfer for the process.

Solution:

C.V. The R-134a. This is a control mass.

$$m_2 = m_1 = m \; ; \qquad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: 30°C, x = 1. Table B.5.1: $v_1 = 0.02671\ m^3/kg$, $u_1 = 394.48$ kJ/kg

$$m = V/v_1 = 0.1 / 0.02671 = 3.744 \text{ kg}$$

State 2: 30°C, 200 kPa superheated vapor Table B.5.2

$$v_2 = 0.11889\ m^3/kg, \quad u_2 = 426.87 - 200 \times 0.11889 = 403.09 \text{ kJ/kg}$$

Work done in B against constant external force (equilibrium P in cyl. B)

$${}_1W_2 = \int P_{ext}\, dV = P_{ext} m(v_2 - v_1) = 200 x 3.744 x(0.11889 - 0.02671) = 69.02 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 3.744 x(403.09 - 394.48) + 69.02 = \mathbf{101.26\ kJ}$$

5.30 A spherical balloon contains 2 kg of R-22 at 0°C, 30% quality. This system is heated until the pressure in the balloon reaches 600 kPa. For this process, it can be assumed that the pressure in the balloon is directly proportional to the balloon diameter. How does pressure vary with volume and what is the heat transfer for the process?

Solution: C.V. R-22 which is a control mass.

$$m_2 = m_1 = m \; ; \qquad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: 0°C, x = 0.3. Table B.4.1 gives $P_1 = 497.6$ kPa

$$v_1 = 0.000778 + 0.3 \times 0.04636 = 0.014686\ m^3/kg$$

$$u_1 = 44.2 + 0.3 \text{ x } 182.3 = 98.9 \text{ kJ/kg}$$

Process: $P \propto D$, $V \propto D^3$ => $PV^{-1/3}$ = constant, polytropic n = -1/3.

$$=> \quad V_2 = mv_2 = V_1 (P_2 /P_1)^3 = mv_1 (P_2 /P_1)^3$$

$$v_2 = v_1 (P_2 /P_1)^3 = 0.014686 \times (600 / 497.6)^3 = 0.02575\ m^3/kg$$

State 2: $P_2 = 600$ kPa, process : $v_2 = 0.02575 \;\rightarrow\; x_2 = 0.647$, $u_2 = 165.8$

$${}_1W_2 = \int P\, dV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{600 \text{ x } 0.05137 - 498 \text{ x } 0.02937}{1 - (-1/3)} = 12.1 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2(165.8 - 98.9) + 12.1 = \mathbf{145.9\ kJ}$$

5.31 A piston held by a pin in an insulated cylinder, shown in Fig. P5.31, contains 2 kg water at 100°C, quality 98%. The piston has a mass of 102 kg, with cross-sectional area of 100 cm^2, and the ambient pressure is 100 kPa. The pin is released, which allows the piston to move. Determine the final state of the water, assuming the process to be adiabatic.

$$P_2 = P_{ext} = P_0 + m_p g/A = 100 + \frac{102 \text{ x } 9.807}{100\text{x}10^{-4} \text{ x } 10^3} = 200 \text{ kPa}$$

$${}_1W_2 = \int P_{ext} dV = P_{ext} m(v_2 - v_1)$$

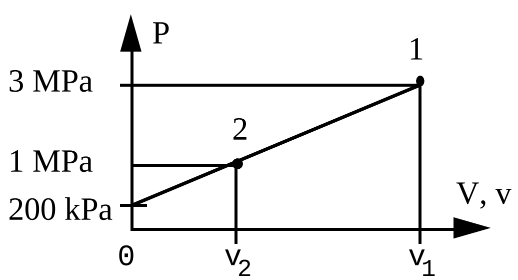
$${}_1q_2 = \emptyset = u_2 - u_1 + P_2v_2 - P_2v_1 = h_2 - u_1 - P_2v_1$$

$$h_2 = u_1 + P_2v_1 = 2464.8 + 200 \text{ x } 1.6395 = 2792.7 \text{ kJ/kg}$$

State 2: (P_2 , h_2) Table B.1.3 => $T_2 \cong$ **161.75°C**

5.32 A piston/cylinder arrangement has a linear spring and the outside atmosphere acting on the piston, shown in Fig. P5.32. It contains water at 3 MPa, 400°C with the volume being 0.1 m^3. If the piston is at the bottom, the spring exerts a force such that a pressure of 200 kPa inside is required to balance the forces. The system now cools until the pressure reaches 1 MPa. Find the heat transfer for the process.

Solution:



C.V. Water.

State 1: Table B.1.3

$v_1 = 0.09936 \text{ m}^3\text{/kg}, \; u_1 = 2932.8 \text{ kJ/kg}$

$m = V/v_1 = 0.1/0.09936 = 1.006 \text{ kg}$

Process: Linear spring so P linear in v.

$$P = P_0 + (P_1 - P_0)v/v_1$$

$$v_2 = \frac{(P_2 - P_0)v_1}{P_1 - P_0} = \frac{(1000 - 200)0.09936}{3000 - 200} = 0.02839 \text{ m}^3\text{/kg}$$

State 2: P_2 , v_2 $\Rightarrow$ $x_2 = (v_2 - 0.001127)/0.19332 = 0.141$, $T_2 = 179.91°C$,

$$u_2 = 761.62 + x_2 \times 1821.97 = 1018.58 \text{ kJ/kg}$$

Process => $${}_1W_2 = \int PdV = \frac{1}{2} m(P_1 + P_2)(v_2 - v_1)$$

$$= \frac{1}{2} 1.006 \, (3000 + 1000)(0.02839 - 0.09936) = -142.79 \text{ kJ}$$

Heat transfer from the energy equation

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1.006(1018.58 - 2932.8) - 142.79 =$ **-2068.5 kJ**

5.33 A vertical piston/cylinder has a linear spring mounted as shown in Fig. P5.32. The spring is mounted so at zero cylinder volume a balancing pressure inside is 100 kPa. The cylinder contains 0.5 kg of water at 125°C, 70% quality. Heat is now transferred to the water until the cylinder pressure reaches 300 kPa. How much work is done by the water during this process and what is the heat transfer?

Solution:

C.V. The 0.5 kg of water. This is a control mass.

Conservation of mass: $m_2 = m_1 = m$;

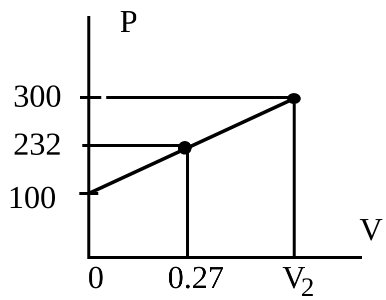
Energy eq.: $m(u_2 - u_1) + = {}_1Q_2 - {}_1W_2$

Process: Linear spring => $P = P_0 + C(V - 0)$

$P_o = 100$ kPa $F_{spr} = 0$ at $V_o = 0$, Q to $P_2 = 300$ kPa

State 1: Two phase table B.1.1, $P_1 = P_{g\ 125C} = 232.1$ kPa

$$v_1 = 0.001065 + 0.7(0.77059 - 0.001065) = 0.53973$$



$u_1 = 534.7 + 0.7 \times 2009.9 = 1931.6$ kJ/kg

$V_1 = mv_1 = 0.27\ m^3$

$$300 = 232.1 + \frac{232.1\text{-}100}{0.27\text{-}0}(V_2 - 0.27)$$

$$67.9 = 489.259V_2 - 132.1$$

$$\Rightarrow \quad V_2 = 0.4088\ m^3$$

State 2: Table B.1.3 $v_2 = V_2/m = 0.81756\ m^3/kg$, $T_2 = 263.4$ C, $u_2 = 2749.7$

$${}_1W_2 = \int_1^2 P\,dV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{232.1 + 300}{2}(0.4088 - 0.27)$$

${}_1W_2 =$ **36.9kJ**

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.5(2749.7 - 1931.6) + 36.9 = 409.1 + 36.9$

${}_1Q_2 =$ **446.0kJ**

5.34 Two heavily insulated tanks are connected by a valve, as shown in Fig. P5.34. Tank A contains 0.6 kg of water at 300 kPa, 300°C. Tank B has a volume of 300 L and contains water at 600 kPa, 80% quality. The valve is opened, and the two tanks eventually come to a uniform state. Assuming the process to be adiabatic, show the final state (u,v) is two-phase and iterate on final pressure to match required internal energy.

Solution:

C.V.: Both tanks

$m_2 = m_{A1} + m_{B1}$; $\quad m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = {}_1Q_2 - {}_1W_2 = \emptyset$

State 1A: Table B.1.3 $\quad v_{A1} = 0.8753\ m^3/kg, \quad u_{A1} = 2806.7\ kJ/kg$

State 1B: Table B.1.2 $\quad v_{B1} = 0.001101 + 0.8 \times 0.31457 = 0.25278\ m^3/kg$

$u_{B1} = 669.88 + 0.8 \times 1897.52 = 2187.9\ kJ/kg$

$m_{B1} = V_B/v_{B1} = 0.3/0.25278 = 1.187\ kg$

Continuity eq.: $\quad \Rightarrow m_2 = m_{A1} + m_{B1} = 1.787\ kg$

$m_2u_2 = 0.6 \text{ x } 2806.7 + 1.187 \text{ x } 2187.9 = 4281\ kJ \quad \Rightarrow \quad u_2 = 2395.67\ kJ/kg$

$v_2 = V_{tot}/m_2 = (0.6 \text{ x } 0.8753 + 0.3)/1.787 = 0.462\ m^3/kg$

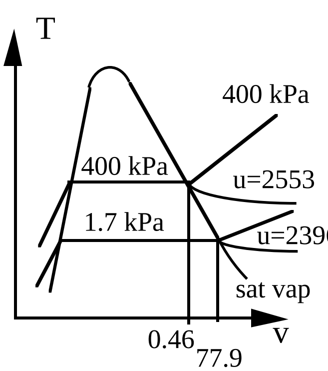
State 2: u_2 , v_2 Table B.1.1 see Fig.

$\Rightarrow$ state is two-phase

Trial & error $\quad v = v_f + xv_{fg}$; $u = u_f + xu_{fg}$

$$\Rightarrow u_2 = 2395.67 = u_f + \frac{v_2 - v_f}{v_{fg}} u_{fg}$$

Compute RHS for a guessed pressure:



From Table B.1.2 we see that $u < 2553$ for given v so we know $P < 400$ kPa.

P = 350 kPa: RHS = 583.93 + [(0.462-0.001079)/0.52317]*1964.98 = 2315.1

P = 375 kPa: RHS = 594.38 + [(0.462-0.001081)/0.49029]*1956.93 = 2434.1

Interpolate to match correct u: $\quad$ $\mathbf{P_2 \cong 367\ kPa}$

Notice the RHS is fairly sensitive to choice of P.

5.35 A piston/cylinder contains 1 kg of ammonia at 20°C with a volume of 0.1 m^3, shown in Fig. P5.35. Initially the piston rests on some stops with the top surface open to the atmosphere, *P*o, so a pressure of 1400 kPa is required to lift it. To what temperature should the ammonia be heated to lift the piston? If it is heated to saturated vapor find the final temperature, volume, and the heat transfer.

Solution:

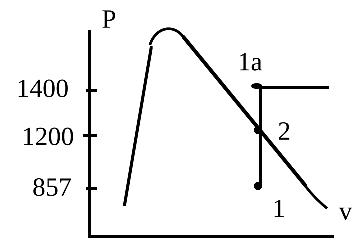
C.V. Ammonia which is a control mass.

$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: 20°C; $v_1 = 0.10 < v_g \Rightarrow x_1 = (0.1 - 0.001638)/0.14758 = 0.6665$

$u_1 = u_f + x_1 u_{fg} = 272.89 + 0.6665 \times 1059.3 = 978.9$

Process: Piston starts to lift at state 1a (P_{lift}, v_1)



State 1a: 1400 kPa, v_1 Table B.2.2 (sup.vap.)

$$T_a = 50 + (60 - 50)\frac{0.1 - 0.09942}{0.10423 - 0.09942} = 51.2\ °C$$

State 2: x = 1.0, $v = v_1$ => V = mv = **0.1 m^3**

$T_2 = 30 + (0.1 - 0.11049) \times 5/(0.09397 - 0.11049) =$ **33.2 °C**

$u_2 = 1338.7$; ${}_1W_2 = 0$; ${}_1q_2 = u_2 - u_1 =$ **359.8 kJ/kg**

5.36 A cylinder/piston arrangement contains 5 kg of water at 100°C with $x = 20\%$ and the piston, $m_P = 75$ kg, resting on some stops, similar to Fig. P5.35. The outside pressure is 100 kPa, and the cylinder area is $A = 24.5\ cm^2$. Heat is now added until the water reaches a saturated vapor state. Find the initial volume, final pressure, work, and heat transfer terms and show the *P–v* diagram.

C.V. The 5 kg water.

Continuty: $m_2 = m_1 = m$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: V = constant if $P < P_{lift}$ otherwise $P = P_{lift}$ see P-v diagram.

$$P_3 = P_2 = P_{lift} = P_0 + m_p g / A_p = 100 + \frac{75 \times 9.807}{0.00245 \times 1000} = \textbf{400 kPa}$$

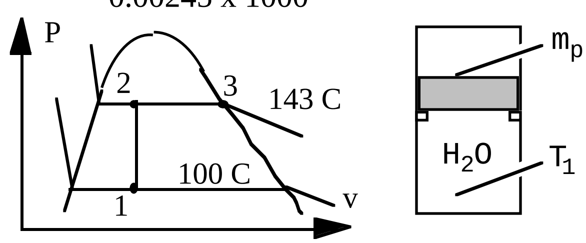
State 1: (T,x) Table B.1.1

$v_1 = 0.001044 + 0.2 \times 1.6719$

$V_1 = mv_1 = 5 \times 0.3354 =$ **1.677 m^3**

$u_1 = 418.91 + 0.2 \times 2087.58$

$= 836.4$ kJ/kg



State 3: (P, x = 1) Table B.1.1 => $v_3 = 0.4625 > v_1$, $u_3 = 2553.6$ kJ/kg

${}_1W_3 = {}_2W_3 = P_{ext}m(v_3 - v_2) = 400 \times 5(0.46246 - 0.3354) =$ **254.1 kJ**

${}_1Q_3 = 5\ (2553.6 - 836.4) + 254.1 =$ **8840 kJ**

5.37 A rigid tank is divided into two rooms by a membrane, both containing water, shown in Fig. P5.37. Room A is at 200 kPa, $v = 0.5$ m^3/kg, $V_A = 1$ m^3, and room B contains 3.5 kg at 0.5 MPa, 400°C. The membrane now ruptures and heat transfer takes place so the water comes to a uniform state at 100°C. Find the heat transfer during the process.

C.V.: Both rooms in tank.

$m_2 = m_{A1} + m_{B1}$; $\quad m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = {}_1Q_2 - {}_1W_2$

State 1A: (P, v) Table B.1.2, $\quad m_{A1} = V_A/v_{A1} = 1/0.5 = 2$ kg

$x_{A1} = (0.5 - 0.001061)/0.88467 = 0.564$

$u_{A1} = 504.47 + 0.564 \times 2025.02 = 1646.6$ kJ/kg

State 1B: Table B.1.3, $v_{B1} = 0.6173$, $u_{B1} = 2963.2$, $V_B = m_{B1}v_{B1} = 2.16$ m^3

Process constant total volume: $\quad V_{tot} = V_A + V_B = 3.16$ m^3 and ${}_1W_2 = \emptyset$

$m_2 = m_{A1} + m_{B1} = 5.5$ kg $\quad => \quad v_2 = V_{tot}/m_2 = 0.5746$ m^3/kg

State 2: T_2 , v_2 $\Rightarrow$ Table B.1.1 $\quad x_2 = (0.5746 - 0.001044)/1.67185 = 0.343$,

$u_2 = 418.91 + 0.343*2087.58 = 1134.95$ kJ/kg

${}_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} =$ **-7421 kJ**

5.38 Two tanks are connected by a valve and line as shown in Fig. P5.38. The volumes are both 1 m^3 with R-134a at 20°C, quality 15% in A and tank B is evacuated. The valve is opened and saturated vapor flows from A into B until the pressures become equal. The process occurs slowly enough that all temperatures stay at 20°C during the process. Find the total heat transfer to the R-134a during the process.

C.V.: A + B

State 1A: $v_{A1} = 0.000817 + 0.15 \text{ x } 0.03524 = 0.006103$

$u_{A1} = 227.03 + 0.15 \text{ x } 162.16 = 251.35$

$m_{A1} = V_A/v_{A1} = 163.854$ kg

Process: Constant temperature and total volume.

$m_2 = m_{A1}$; $V_2 = V_A + V_B = 2$ m^3 ; $v_2 = V_2/m_2 = 0.012206$ m^3/kg

State 2: T_2 , v_2 $\Rightarrow$ $x_2 = (0.012206 – 0.000817)/0.03524 = 0.3232$

$u_2 = 227.03 + 0.3232 \text{ x } 162.16 = 279.44$ kJ/kg

${}_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} + {}_1W_2 = m_2(u_2 - u_{A1})$

$= 163.854 \text{ x } (279.44 - 251.35) =$ **4603 kJ**

5.39 Consider the same system as in the previous problem. Let the valve be opened and transfer enough heat to both tanks so all the liquid disappears. Find the necessary heat transfer.

C.V. A + B, so this is a control mass.

State 1A: $v_{A1} = 0.000817 + 0.15 \times 0.03524 = 0.006103$

$u_{A1} = 227.03 + 0.15 \times 162.16 = 251.35$

$m_{A1} = V_A/v_{A1} = 163.854 \text{ kg}$

Process: Constant temperature and total volume.

$m_2 = m_{A1}$; $V_2 = V_A + V_B = 2 \text{ m}^3$; $v_2 = V_2/m_2 = 0.012206 \text{ m}^3\text{/kg}$

State 2: $x_2 = 100\%$, $v_2 = 0.012206$

$\Rightarrow \quad T_2 = 55 + 5 \times (0.012206 – 0.01316)/(0.01146 – 0.01316) = 57.8°\text{C}$

$u_2 = 406.01 + 0.56 \times (407.85 – 406.01) = 407.04 \text{ kJ/kg}$

${}_1Q_2 = m_2(u_2 - u_{A1}) = 163.854 \times (407.04 - 251.35) = \mathbf{25510 \text{ kJ}}$

5.40 A cylinder having a piston restrained by a linear spring contains 0.5 kg of saturated vapor water at 120°C, as shown in Fig. P5.40. Heat is transferred to the water, causing the piston to rise, and with a spring constant of 15 kN/m, piston cross-sectional area 0.05 m^2, the presure varies linearly with volume until a final pressure of 500 kPa is reached. Find the final temperature in the cylinder and the heat transfer for the process.

C.V. Water in cylinder.

Continuity: $m_2 = m_1 = m$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: (T, x) Table B.1.1 => $v_1 = 0.89186 \text{ m}^3\text{/kg}$, $u_1 = 2529.2 \text{ kJ/kg}$

Process: $P_2 = P_1 + \dfrac{k_s m}{A_p^2}(v_2 - v_1) = 198.5 + \dfrac{15 \times 0.5}{(0.05)^2}(v_2 - 0.89186)$

State 2: $P_2 = 500$ kPa and on the process curve (see above).

=> $v_2 = 0.89186 + (500 - 198.5) \times (0.05^2/7.5) = 0.9924 \text{ m}^3\text{/kg}$

(P, v) Table B.1.3 => $T_2 = 803°\text{C}$; $u_2 = 3668 \text{ kJ/kg}$

$$W_{12} = \int P dV = \left(\frac{P_1 + P_2}{2}\right) m(v_2 - v_1)$$

$$= \left(\frac{198.5 + 500}{2}\right) \times 0.5 \times (0.9924 - 0.89186) = 17.56 \text{ kJ}$$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.5 \times (3668 - 2529.2) + 17.56 = \mathbf{587 \text{ kJ}}$

5.41 A water-filled reactor with volume of 1 m^3 is at 20 MPa, 360°C and placed inside a containment room as shown in Fig. P5.41. The room is well insulated and initially evacuated. Due to a failure, the reactor ruptures and the water fills the containment room. Find the minimum room volume so the final pressure does not exceed 200 kPa.

Solution:

C.V.: Containment room and reactor.

Mass: $m_2 = m_1 = V_{reactor}/v_1 = 1/0.001823 = 548.5$ kg

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = 0 - 0 = 0 \quad \Rightarrow \quad u_2 = u_1 = 1702.8$ kJ/kg

State 2: $P_2 = 200$ kPa, $u_2 < u_g$ => Two-phase Table B.1.2

$x_2 = (u_2 - u_f)/ u_{fg} = (1702.8 – 504.47)/2025.02 = 0.59176$

$v_2 = 0.001061 + 0.59176 \times 0.88467 = 0.52457$ m^3/kg

$V_2 = m_2 v_2 = 548.5 \times 0.52457 =$ **287.7 m³**

5.42 Assume the same setup as the previous problem, but the room has a volume of 100 m^3. Show that the final state is two-phase and find the final pressure by trial and error.

C.V.: Containment room and reactor.

Mass: $m_2 = m_1 = V_{reactor}/v_1 = 1/0.001823 = 548.5$ kg

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = 0 - 0 = 0 \Rightarrow \quad u_2 = u_1 = 1702.8$

Total volume and mass => $v_2 = V_{room}/m_2 = 0.1823$ m^3/kg

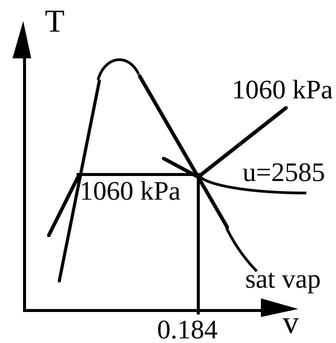
State 2: u_2 , v_2 Table B.1.1 see Fig.

$\Rightarrow$ state is two-phase (notice $u_2 << u_g$

Trial & error $v = v_f + xv_{fg}$; $u = u_f + xu_{fg}$

$$\Rightarrow u_2 = 1702.8 = u_f + \frac{v_2 - v_f}{v_{fg}} u_{fg}$$

Compute RHS for a guessed pressure P_2:



$P_2 = 600$ kPa: RHS $= 669.88 + \dfrac{0.1823\text{-}0.001101}{0.31457} \times 1897.52 = 1762.9$ too large

$P_2 = 550$ kPa: RHS $= 655.30 + \dfrac{0.1823\text{-}0.001097}{0.34159} \times 1909.17 = 1668.1$ too small

Linear interpolation to match u = 1702.8 gives $P_2 \cong$ **568.5 kPa**

5.43 Refrigerant-12 is contained in a piston/cylinder arrangement at 2 MPa, 150°C with a massless piston against the stops, at which point $V = 0.5\ m^3$. The side above the piston is connected by an open valve to an air line at 10°C, 450 kPa, shown in Fig. P5.43. The whole setup now cools to the surrounding temperature of 10°C. Find the heat transfer and show the process in a *P–v* diagram.

C.V.: R-12. Control mass.

Continuity: m = constant, Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: $F\downarrow = F\uparrow = P \bullet A = P_{air}A + F_{stop}$; if $V < V_{stop} \Rightarrow F_{stop} = \emptyset$

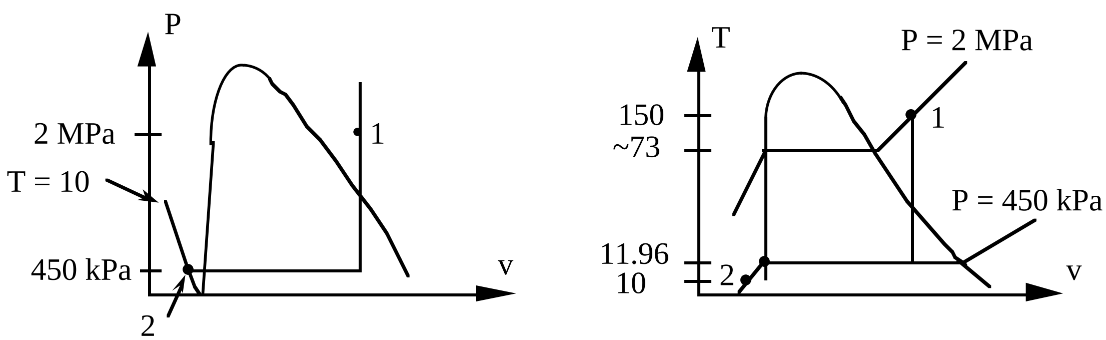
This is illustrated in the P-v diagram shown below.

State 1: $v_1 = 0.01265\ m^3/kg$, $u_1 = 277 - 2000*0.01265 = 252.1$ kJ/kg

$\Rightarrow$ m = V/v = **39.523 kg**

State 2: T_2 and on line $\Rightarrow$ compressed liquid, see figure below.

$v_2 \cong v_f = 0.000733 \Rightarrow V_2 = 0.02897$; $u_2 = u_f - = 45.06$



${}_1W_2 = \int PdV = P_{lift}(V_2 - V_1) = 450(0.02897 - 0.5) = -212.0$ kJ ;

Energy eq. $\Rightarrow$ ${}_1Q_2 = 39.526(45.06 - 252.1) - 212 =$ **-8395 kJ**

5.44 A 10-m high open cylinder, A_{cyl} = 0.1 m^2, contains 20°C water above and 2 kg of 20°C water below a 198.5-kg thin insulated floating piston, shown in Fig. P5.44. Assume standard *g*, *Po*. Now heat is added to the water below the piston so that it expands, pushing the piston up, causing the water on top to spill over the edge. This process continues until the piston reaches the top of the cylinder. Find the final state of the water below the piston (*T*, *P*, *v*) and the heat added during the process.

Solution:

C.V. Water below the piston.

Piston force balance at initial state: $F\uparrow = F\downarrow = P_A A = m_p g + m_B g + P_0 A$

State $1_{A,B}$: Comp. Liq. $\Rightarrow$ $v \cong v_f = 0.001002$ m^3/kg; u_{1A} = 83.95 kJ/kg

$V_{A1} = m_A v_{A1} = 0.002$ m^3; $m_{tot} = V_{tot}/v = 1/0.001002 = 998$ kg

mass above the piston $m_{B1} = m_{tot} - m_A =$ **996 kg**

$$P_{A1} = P_0 + (m_p + m_B)g/A = 101.325 + \frac{(198.5+996)*9.807}{0.1*1000} = \mathbf{218.5\ kPa}$$

$$\text{State } 2_A: \quad P_{A2} = P_0 + \frac{m_p g}{A} = \mathbf{120.82\ kPa}\ ; \quad v_{A2} = V_{tot}/m_A = \mathbf{0.5\ m^3/kg}$$

$x_{A2} = (0.5 - 0.001047)/1.4183 = 0.352$; $T_2 =$ **105°C**

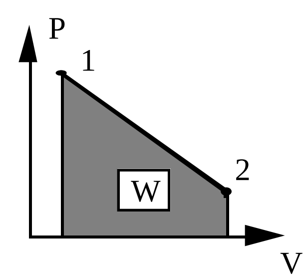
$u_{A2} = 440.0 + 0.352 \times 2072.34 = 1169.5$ kJ/kg

Continuity eq. in A: $m_{A2} = m_{A1}$

Energy: $m_A(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: P linear in V as m_B is linear with V

$${}_1W_2 = \int PdV = \frac{1}{2}(218.5 + 120.82)(1 - 0.002) = \mathbf{169.32\ kJ}$$



$${}_1Q_2 = m_A(u_2 - u_1) + {}_1W_2 = 2170.14 + 169.32 = \mathbf{2340.4\ kJ}$$

5.45 A rigid container has two rooms filled with water, each 1 m^3 separated by a wall. Room A has P = 200 kPa with a quality x = 0.80. Room B has P = 2 MPa and T = 400°C. The partition wall is removed and the water comes to a uniform state which after a while due to heat transfer has a temperature of 200°C. Find the final pressure and the heat transfer in the process.

C.V. A + B. Constant total mass and constant total volume.

Continuity: $m_2 - m_{A1} - m_{B1} = 0$; $V_2 = V_A + V_B = 2\ m^3$

Energy: $m_2u_2 - m_{A1}u_{A1} - m_{A1}u_{A1} = {}_1Q_2 - {}_1W_2 = {}_1Q_2$

State 1A: Table B.1.2 $u_{A1} = 504.47 + 0.8 \times 2025.02 = 2124.47$,

$v_{A1} = 0.001061 + 0.8 \times 0.88467 = 0.70877 \Rightarrow m_{A1} = 1/v_{A1} = 1.411$ kg

State 1B: $u_{B1} = 2945.2$, $v_{B1} = 0.1512 \Rightarrow m_{B1} = 1/v_{B1} = 6.614$ kg

State 2: T_2, $v_2 = V_2/m_2 = 2/(1.411 + 6.614) = 0.24924\ m^3/kg$

Table B.1.3 superheated vapor. 800 kPa < P_2 < 1 MPa

$$P_2 \cong 800 + \frac{0.24924\text{-}0.2608}{0.20596\text{-}0.2608} \times 200 = \mathbf{842\ kPa} \qquad u_2 \cong 2628.8 \text{ kJ/kg}$$

${}_1Q_2 = 8.025 \text{ x } 2628.8 - 1.411 \text{ x } 2124.47 - 6.614 \text{ x } 2945.2 =$ **- 1381 kJ**

5.46 A piston/cylinder arrangement of initial volume 0.025 m^3 contains saturated water vapor at 180°C. The steam now expands in a polytropic process with exponent *n* = 1 to a final pressure of 200 kPa, while it does work against the piston. Determine the heat transfer in this process.

Solution:

C.V. Water. This is a control mass.

State 1: Table B.1.1 P = 1002.2 kPa, $v_1 = 0.19405$, $u_1 = 2583.7$ kJ/kg ,

$m = V/v_1 = 0.025/0.19405 = 0.129$ kg

Process: $Pv = \text{const.} = P_1v_1 = P_2v_2$; polytropic process n=1.

$\Rightarrow v_2 = v_1P_1/P_2 = 0.19405 \text{ x } 1002.1/200 = 0.9723\ m^3/kg$

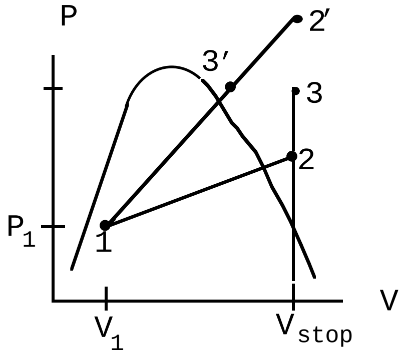
State 2: P_2 , $v_2 \Rightarrow$ Table B.1.3 $T_2 \cong 155°C$, $u_2 = 2585$

$${}_1W_2 = \int PdV = P_1V_1 \ln\frac{v_2}{v_1} = 1002.2 \text{ x } 0.025 \ln\frac{0.9723}{0.19405} = 40.37 \text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.129(2585 - 2583.7) + 40.37 = \mathbf{40.54\ kJ}$$

5.47 Calculate the heat transfer for the process described in Problem 4.23.

Solution:



State 1: $v_1 = V/m = 0.2 / 2 = 0.1\ m^3/kg$

$x_1 = 0.058$, $u_1 = 539.45$ kJ/kg

Process: $1 \rightarrow 2 \rightarrow 3$ or $1 \rightarrow 3'$

State at stops: 2 or 2'

$v_2 = V_{stop}/m = 0.4\ m^3/kg$ & $T_2 = 600°C$

Table B.1.3 $\Rightarrow$ $P_{stop} = 1$ MPa $< P_3$

since $P_{stop} < P_3$ the process is as $1 \rightarrow 2 \rightarrow 3$

State 3: $P_3 = 1.2$ MPa, $v_3 = v_2 = 0.4\ m^3/kg$ $\Rightarrow$ $T_3 \cong$ **770°C**; $u_3 = 3603.5$ kJ/kg

$$W_{13} = W_{12} + W_{23} = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) + 0 = \frac{1}{2}(100 + 1000)(0.8 - 0.2)$$

$= \mathbf{330\ kJ}$

${}_1Q_3 = m(u_3 - u_1) + {}_1W_3 = 2 \times (3603.5 - 539.45) + 330 = \mathbf{6458\ kJ}$

5.48 Consider the piston/cylinder arrangement shown in Fig. P5.48. A frictionless piston is free to move between two sets of stops. When the piston rests on the lower stops, the enclosed volume is 400 L. When the piston reaches the upper stops, the volume is 600 L. The cylinder initially contains water at 100 kPa, 20% quality. It is heated until the water eventually exists as saturated vapor. The mass of the piston requires 300 kPa pressure to move it against the outside ambient pressure. Determine the final pressure in the cylinder, the heat transfer and the work for the overall process.

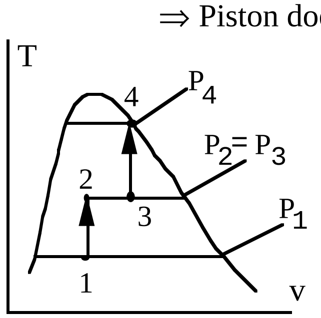
C.V. Water. Check to see if piston reaches upper stops.

State 1: $v_1 = 0.001043 + 0.2\text{x}1.693 = 0.33964$; $m = V_1/v_1 = \dfrac{0.4}{0.33964} = 1.178$ kg

$u_1 = 417.36 + 0.2 \times 2088.7 = 835.1$ kJ/kg

State 3: $v_3 = \dfrac{0.6}{1.178} = 0.5095 < v_G = 0.6058$ at $P_3 = 300$ kPa

$\Rightarrow$ Piston does reach upper stops.



$v_4 = v_3 = 0.5095 = v_G$ at P_4 From Table B.1.2

=> $P_4 =$ **361 kPa,** $u_4 = 2550.0$ kJ/kg

${}_1W_4 = {}_1W_2 + {}_2W_3 + {}_3W_4 = 0 + {}_2W_3 + 0$

${}_1W_4 = P_2(V_3 - V_2) = 300 \times (0.6 - 0.4) = \mathbf{60\ kJ}$

${}_1Q_4 = m(u_4 - u_1) + {}_1W_4$

$= 1.178(2550.0 - 835.1) + 60 = \mathbf{2080\ kJ}$

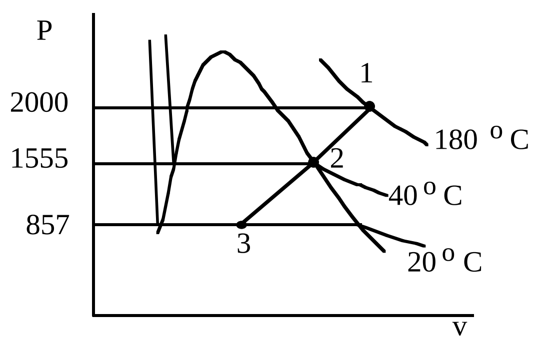
5.49 Calculate the heat transfer for the process described in Problem 4.30.

A cylinder containing 1 kg of ammonia has an externally loaded piston. Initially the ammonia is at 2 MPa, 180°C and is now cooled to saturated vapor at 40°C, and then further cooled to 20°C, at which point the quality is 50%. Find the total work for the process, assuming a piecewise linear variation of *P* versus *V*.

Solution:

C.V. Ammonia going through process 1 - 2 - 3. Control mass.

Continuity: m = constant, Energy: $m(u_3 - u_1) = {}_1Q_3 - {}_1W_3$



State 1: (T, P) Table B.2.2

$v_1 = 0.10571,\ u_1 = 1630.7$ kJ/kg

State 2: (T, x) Table B.2.1 sat. vap.

$P_2 = 1555$ kPa, $v_2 = 0.08313$

State 3: (T, x) $P_3 = 857$ kPa,

$v_3 = (0.001638+0.14922)/2 = 0.07543$

$u_3 = (272.89 + 1332.2)/2 = 802.7$ kJ/kg

Process: piecewise linear P versus V, see diagram. Work is area as:

$$W_{13} = \int_1^3 PdV \approx \left(\frac{P_1 + P_2}{2}\right) m(v_2 - v_1) + \left(\frac{P_2 + P_3}{2}\right) m(v_3 - v_2)$$

$$= \frac{2000 + 1555}{2} 1(0.08313 - 0.10571) + \frac{1555 + 857}{2} 1(0.07543 - 0.08313)$$

$= \mathbf{-49.4\ kJ}$

From the energy equation we get the heat transfer as:

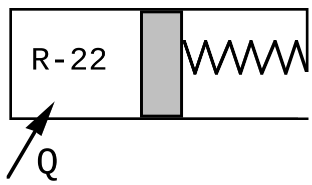
${}_1Q_3 = m(u_3 - u_1) + {}_1W_3 = 1x\ (802.7 - 1630.7) - 49.4 =$ **-877.4 kJ**

5.50 A cylinder fitted with a frictionless piston that is restrained by a linear spring contains R-22 at 20°C, quality 60% with a volume of 8 L, shown in Fig. P5.50. The piston cross-sectional area is 0.04 m^2, and the spring constant is 500 kN/m. A total of 62 kJ of heat is now added to the R-22. Verify that the final pressure is around 1600 kPa and find the final temperature of the R-22.

Solution:

C.V. R-22. This is a control mass.

Continuity: m = constant, Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$



State 1: 20°C ; $x_1 = 0.6$; Table B.4.1 => $P_1 = 910$ kPa

$v_1 = 0.000824 - 0.6 \times 0.02518 = 0.01593 \text{ m}^3/\text{kg}$

$u_1 = 67.92 + 0.6 \times 164.92 = 166.87$ kJ/kg

$V_1 = 8$ L => $m = V_1/v_1 = 0.008/0.01593 = 0.502$ kg

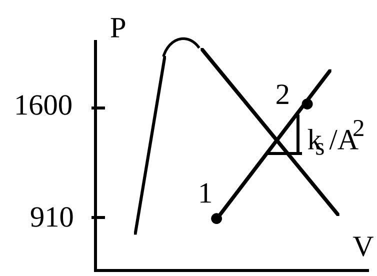
Process: P linear in V with $A_p = 0.04 \text{ m}^2$, $k_s = 500$ kN/m to match P in kPa as:

$$P_2 = P_1 + \frac{k_s}{A_p^2}(V_2 - V_1)$$

$$= 910 + \frac{500}{(0.04)^2}(mv_2 - 0.008)$$

$${}_1W_2 = \int Pdv = (1/2)\,(P_2 + P_1)\,(V_2 - V_1)$$

$$62 = {}_1Q_2 = m(u_2 - u_1) + {}_1W_2$$



Now we want to find the final P such that the process gives the stated Q of 62 kJ. Assume $\mathbf{P_2 = 1600}$ **kPa** then the final state is

$$V_2 = 0.008 + \frac{1600 - 910}{500} \times 0.04^2 = 0.0102 \text{ m}^3$$

$$v_2 = 0.0102/0.502 = 0.02033$$

State 2: At P_2 , v_2 Table B.4.2 $\rightarrow \begin{cases} \mathbf{T_2 = 106.4°C} \quad h_2 = 318.1 \\ u_2 = h_2 - P_2 v_2 = 285.5 \end{cases}$

$${}_1W_2 = \left(\frac{910 + 1600}{2}\right)(0.0102 - 0.008) = 2.76 \text{ kJ}$$

$${}_1Q_2 = 0.502 \times (285.5 - 166.87) + 2.76 = 62.3 \text{ kJ} = 62 \quad \text{OK}$$

If we had tried P = 1500 kPa, we would find T = 81°C and ${}_1Q_2$ = 53.2 kJ

5.51 A 1-L capsule of water at 700 kPa, 150°C is placed in a larger insulated and otherwise evacuated vessel. The capsule breaks and its contents fill the entire volume. If the final pressure should not exceed 125 kPa, what should the vessel volume be?

C.V. Larger vessel.

Continuity: $m_2 = m_1 = m = V/v_1 = 0.916$ kg

Process: expansion with ${}_1Q_2 = \emptyset$, ${}_1W_2 = \emptyset$

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = \emptyset \;\Rightarrow\; u_2 = u_1$

State 1: $v_1 \cong v_f = 0.001091$ m^3/kg; $u_1 \cong u_f = 631.66$ kJ/kg

State 2: P_2 , $u_2 \;\Rightarrow\; x_2 = (631.66 – 444.16)/2069.3 = 0.09061$

$v_2 = 0.001048 + 0.09061 \times 1.37385 = 0.1255$ m^3/kg

$V_2 = mv_2 = 0.916 \text{ x } 0.1255 = \mathbf{0.115\ m^3} =$ **115 L**

5.52 A cylinder with a frictionless piston contains steam at 2 MPa, 500°C with a volume of 5 L, shown in Fig. P5.52. The external piston force is proportional to cylinder volume cubed. Heat is transferred out of the cylinder, reducing the volume and thus the force until the cylinder pressure has dropped to 500 kPa. Find the work and heat transfer for this process.

C.V. Water,

Continuity $m_2 = m_1 = m$; Energy: $m(u_2 -u_1) = {}_1Q_2 - {}_1W_2$

Process: $F = P•A \sim V^3 \;\Rightarrow\; P \sim V^3$; Polytropic process with $n = -3$.

$$\frac{P_2}{P_1} = \left(\frac{V_2}{V_1}\right)^3 \;\Rightarrow\; V_2 = V_1\left(\frac{P_2}{P_1}\right)^{1/3} = 0.005\left(\frac{500}{2000}\right)^{1/3} = 0.00315 \text{ m}^3 = 3.15 \text{ L}$$

State 1: Table B.1.3 $v_1 = 0.17568$ m^3/kg , $u_1 = 3116.2$ kJ/kg

State 2: P_2 , $v_2 = v_1 \text{ x } V_2 / V_1 = 0.17568 \text{ x } \frac{3.15}{5} = 0.11068$ m^3/kg

$x_2 = (0.11068-0.001093)/0.3738 = 0.293$,

$u_2 = 639.66 + 0.293 \text{ x } 1921.57 = 1203$ kJ/kg

$${}_1W_2 = \int PdV = \int C•V^3 dV = \frac{1}{4}C\left(V_2{}^4 - V_1{}^4\right) = \frac{1}{4}(P_2V_2 - P_1V_1)$$

$$= \frac{1}{4}(500 \text{ x } 0.00315 - 2000 \text{ x } 0.005) = \mathbf{-2.106\ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = \frac{0.005}{0.17568}(1203 - 3116.2) - 2.106 = \mathbf{-56.56\ kJ}$$

5.53 Superheated refrigerant R-134a at 20°C, 0.5 MPa is cooled in a piston/cylinder arrangement at constant temperature to a final two-phase state with quality of 50%. The refrigerant mass is 5 kg, and during this process 500 kJ of heat is removed. Find the initial and final volumes and the necessary work.

C.V. R-134a, this is a control mass.

Continuity: $m_2 = m_1 = m$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = -500 - {}_1W_2$

State 1: T_1 , P_1 Table B.5.2, $v_1 = 0.04226$ m^3/kg => $V_1 = mv_1 =$ **0.211 m^3**

$u_1 = h_1 - P_1v_1 = 411.65 - 500 \times 0.04226 = 390.52$ kJ/kg

State 2: T_2 , x_2 $\Rightarrow$ $u_2 = 227.03 + 0.5 \times 162.16 = 308.11$ kJ/kg,

$v_2 = 0.000817 + 0.5 \times 0.03524 = 0.018437$ m^3/kg => $V_2 = mv_2 =$ **0.0922 m^3**

${}_1W_2 = -500 - m(u_2 - u_1) = -500 - 5 \text{ x } (308.11 - 390.52) =$ **-87.9 kJ**

5.54 Calculate the heat transfer for the process described in Problem 4.20.
Consider a piston cylinder with 0.5 kg of R-134a as saturated vapor at -10°C. It is now compressed to a pressure of 500 kPa in a polytropic process with n = 1.5. Find the final volume and temperature, and determine the work done during the process.
Solution:

Take CV as the R-134a which is a control mass

Continuity: $m_2 = m_1 = m$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: $Pv^{1.5}$ = constant. Polytropic process with n = 1.5

1: (T, x) P = Psat = 201.7 kPa from Table B.5.1

$v_1 = 0.09921$ m^3/kg, $u_1 = 372.27$ kJ/kg

2: (P, process) $v_2 = v_1 (P_1/P_2)^{(1/1.5)} = 0.09921 \times (201.7/500)^{0.667} = 0.05416$

=> Table B.5.2 superheated vapor, T_2 = 79°C,

$u_2 = h_2 - P_2v_2 = 467.98 - 500 \times 0.05416 = 440.9$ kJ/kg

Process gives $P = C\, v^{(-1.5)}$, which is integrated for the work term, Eq.(4.4)

${}_1W_2 = \int P\, dV = m(P_2v_2 - P_1v_1)/(1-1.5)$

$= -2\times0.5\times (500\times0.05416 - 201.7\times0.09921) =$ **-7.07 kJ**

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.5(440.9 - 372.27) + (-7.07) =$ **27.25 kJ**

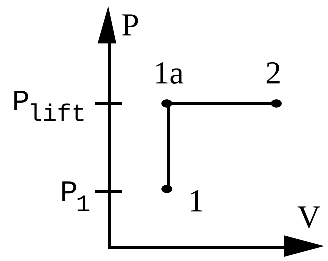
5.55 Calculate the heat transfer for the process described in Problem 4.26.
A piston cylinder setup similar to Problem 4.24 contains 0.1 kg saturated liquid and vapor water at 100 kPa with quality 25%. The mass of the piston is such that a pressure of 500 kPa will float it. The water is heated to 300°C. Find the final pressure, volume and the work, ${}_1W_2$.
Solution:

Take CV as the water: $m_2 = m_1 = m$

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: v = constant until $P = P_{lift}$

To locate state 1: Table B.1.2



$v_1 = 0.001043 + 0.25 \times 1.69296 = 0.42428\ m^3/kg$

$u_1 = 417.33 + 0.25 \times 2088.7 = 939.5\ kJ/kg$

1a: $v_{1a} = v_1 = 0.42428 > v_g$ at 500 kPa so state 1a is sup.vapor $T_{1a} = 200°C$

State 2 is 300°C so heating continues after state 1a to 2 at constant P =>

2: T_2, $P_2 = P_{lift}$ => Tbl B.1.3 $v_2 = 0.52256\ m^3/kg$; $u_2 = 2802.9\ kJ/kg$

$${}_1W_2 = P_{lift}\ m(v_2 - v_1) = 500 \times 0.1\ (0.5226 - 0.4243) = 4.91\ kJ$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.1(2802.9 - 939.5) + 4.91 = \mathbf{191.25\ kJ}$$

5.56 A piston/cylinder, shown in Fig. P5.56, contains R-12 at − 30°C, $x = 20\%$. The volume is 0.2 m^3. It is known that $V_{stop} = 0.4\ m^3$, and if the piston sits at the bottom, the spring force balances the other loads on the piston. It is now heated up to 20°C. Find the mass of the fluid and show the *P–v* diagram. Find the work and heat transfer.
Solution:

C.V. R-12, this is a control mass. Properties in Table B.3

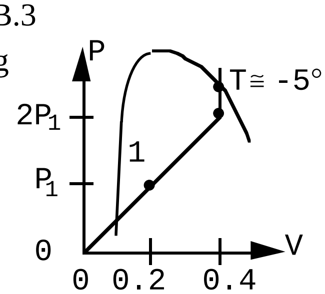
State 1: $v_1 = 0.000672 + 0.2*0.1587 = 0.0324\ m^3/kg$

$u_1 = 8.79 + 0.2 \times 149.4 = 38.67\ kJ/kg$

Continuity Eq.: $m_2 = m_1 = V_1/v_1 = \mathbf{6.17\ kg,}$

Energy: $E_2 - E_1 = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

System: on line $V \le V_{stop}$; $P_{stop} = 2P_1 = 200$ kPa



Since $T_2 > T_{stop} \Rightarrow v_2 = v_{stop} = 0.0648\ m^3/kg$

2: T_2 , v_2 $P_2 = 292.3$ kPa

$u_2 = h_2 - P_2v_2 = 181.9\ kJ/kg$

(P,v) $\Rightarrow T_{stop} \cong -17°C$
TWO-PHASE STATE

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_{stop})(V_{stop} - V_1) = \frac{1}{2}(100 + 200)0.2 = \mathbf{30\ kJ}$$

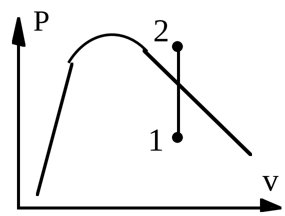
$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = \mathbf{913.5\ kJ}$$

5.57 Ammonia, NH_3, is contained in a sealed rigid tank at 0°C, x = 50% and is then heated to 100°C. Find the final state P_2, u_2 and the specific work and heat transfer.

Cont.: $m_2 = m_1$; Energy: $E_2 - E_1 = {}_1Q_2$; $({}_1W_2 = \emptyset)$

Process: $V_2 = V_1 \Rightarrow v_2 = v_1 = 0.001566 + 0.5 * 0.28783 = 0.14538$

Table B.2.2: v_2 & T_2 $\Rightarrow$ between 1000 kPa and 1200 kPa



$\Rightarrow P_2 =$ **1187 kPa**

x_2 = **undef**; $h_2 = 1658.4$ kJ/kg

$u_2 = 1658.4 - 1187 \text{ x} 0.14538 = 1485.83$ kJ/kg

$u_1 = 179.69 + 0.5 \times 1138.3 = 748.84$ kJ/kg

${}_1w_2 = \mathbf{0}$; ${}_1q_2 = u_2 - u_1 = 1485.83 - 748.84 =$ **737 kJ/kg**

5.58 A house is being designed to use a thick concrete floor mass as thermal storage material for solar energy heating. The concrete is 30 cm thick and the area exposed to the sun during the day time is 4 m × 6 m. It is expected that this mass will undergo an average temperature rise of about 3°C during the day. How much energy will be available for heating during the nighttime hours?

C.V. The mass of concrete.

Concrete V = 4 x 6 x 0.3 = 7.2 m^3 ; m = ρV = 2200x 7.2 = 15 840 kg

ΔU = m C ΔT = 15840 x 0.88 x 3 = 41818 kJ = **41.82 MJ**

5.59 A car with mass 1275 kg drives at 60 km/h when the brakes are applied quickly to decrease its speed to 20 km/h. Assume the brake pads are 0.5 kg mass with heat capacity of 1.1 kJ/kg K and the brake discs/drums are 4.0 kg steel where both masses are heated uniformly. Find the temperature increase in the brake assembly.

C.V. Car. Car looses kinetic energy and brake system gains internal u.

No heat transfer (short time) and no work term.

$$m = \text{constant}; \qquad E_2 - E_1 = 0 - 0 = m_{car}\frac{1}{2}(V_2^2 - V_1^2) + m_{brake}(u_2 - u_1)$$

The brake system mass is two different kinds so split it, also use C_v since we do not have a u table for steel or brake pad material.

$$m_{steel}\, C_v\, \Delta T + m_{pad}\, C_v\, \Delta T = m_{car}\, 0.5\, (60^2 - 20^2)\, (1000/3600)^2$$

$$(4 \times 0.46 + 0.5 \times 1.1)\, \Delta T = 1275 \times 0.5 \times 3200 \times 0.07716 = 157406 \text{ J} = 157.4 \text{ kJ}$$

$$\Rightarrow \Delta T = \mathbf{65.9\ °C}$$

5.60 A copper block of volume 1 L is heat treated at 500°C and now cooled in a 200-L oil bath initially at 20°C, shown in Fig. P5.60. Assuming no heat transfer with the surroundings, what is the final temperature?

Solution:

C.V. Copper block and the oil bath.

$m_{met} = V\rho = 0.001x8300 = 8.3kg, \quad m_{oil} = V\rho = 0.2x910 = 182kg$

$m_{met}(u_2 - u_1)_{met} + m_{oil}(u_2 - u_1)_{oil} = {}_1Q_2 - {}_1W_2 = 0$

solid and liquid: $\Delta u \cong C_V \Delta T$

$m_{met}C_{Vmet}(T_2 - T_{1,met}) + m_{oil}C_{Voil}(T_2 - T_{1,oil}) = 0$

$8.3 \text{ x } 0.42(T_2 - 500) + 182 \text{ x } 1.8 (T_2 - 20) = 0$

$331.09 \; T_2 – 1743 – 6552 = 0$

$\Rightarrow \; T_2 = \mathbf{25\ °C}$

5.61 Saturated, x = 1%, water at 25°C is contained in a hollow spherical aluminum vessel with inside diameter of 0.5 m and a 1-cm thick wall. The vessel is heated until the water inside is saturated vapor. Considering the vessel and water together as a control mass, calculate the heat transfer for the process.

C.V. Vessel and water. This is a control mass of constant volume.

$m_2 = m_1 ; \qquad U_2 - U_1 = {}_1Q_2 - {}_1W_2 = {}_1Q_2$

State 1: $v_1 = 0.001003 + 0.01 \text{ x } 43.359 = 0.4346 \text{ m}^3\text{/kg}$

$u_1 = 104.88 + 0.01 \text{ x } 2304.9 = 127.9 \text{ kJ/kg}$

State 2: $x_2 = 1$ and constant volume so $\quad v_2 = v_1 = V/m$

$v_{g\ T2} = v_1 = 0.4346 \;\Rightarrow\; T_2 = 146.1°C; \quad u_2 = u_{G2} = 2555.9$

$V_{INSIDE} = \frac{\pi}{6}(0.5)^3 = 0.06545 \text{ m}^3 \; ; \; m_{H_2O} = \frac{0.06545}{0.4346} = 0.1506 \text{ kg}$

$V_{Al} = \frac{\pi}{6}((0.52)^3 - (0.5)^3) = 0.00817 \text{ m}^3$

$m_{Al} = \rho_{Al}V_{Al} = 2700 \text{ x } 0.00817 = 22.065 \text{ kg}$

${}_1Q_2 = U_2 - U_1 = m_{H_2O}(u_2 - u_1)_{H_2O} + m_{Al}C_{V\ Al}(T_2 - T_1)$

$= 0.1506(2555.9 - 127.9) + 22.065 \text{ x } 0.9(146.1 - 25)$

$= \mathbf{2770.6\ kJ}$

5.62 An ideal gas is heated from 500 to 1500 K. Find the change in enthalpy using constant specific heat from Table A.5 (room temperature value) and discuss the accuracy of the result if the gas is

a. Argon b. Oxygen c. Carbon dioxide

Solution:

$T_1 = 500$ K, $T_2 = 1500$ K, $\Delta h = C_{P0}(T_2\text{-}T_1)$

a) Ar : $\Delta h = 0.520(1500\text{-}500) = 520$ kJ/kg

Monatomic inert gas very good approximation.

b) O_2 : $\Delta h = 0.922(1500\text{-}500) = 922$ kJ/kg

Diatomic gas approximation is OK with some error.

c) CO_2: $\Delta h = 0.842(1500\text{-}500) = 842$ kJ/kg

Polyatomic gas heat capacity changes, see figure 5.11

5.63 A rigid insulated tank is separated into two rooms by a stiff plate. Room A of 0.5 m^3 contains air at 250 kPa, 300 K and room B of 1 m^3 has air at 150 kPa, 1000 K. The plate is removed and the air comes to a uniform state without any heat transfer. Find the final pressure and temperature.

C.V. Total tank. Control mass of constant volume.

Mass and volume: $m_2 = m_A + m_B$; $V = V_A + V_B = 1.5 \text{ m}^3$

Energy Eq.: $m_2 u_2 - m_A u_{A1} - m_B u_{B1} = Q - W = 0$

Ideal gas at 1: $m_A = P_{A1}V_A/RT_{A1} = 250 \times 0.5/(0.287 \times 300) = 1.452$ kg

$u_{A1} = 214.364$ kJ/kg from Table A.7

Ideal gas at 2: $m_B = P_{B1}V_B/RT_{B1} = 150 \times 1/(0.287 \times 1000) = 0.523$ kg

$u_{B1} = 759.189$ kJ/kg from Table A.7

$m_2 = m_A + m_B = 1.975$ kg

$u_2 = (m_A u_{A1} + m_B u_{B1})/m_2 = (1.452 \times 214.364 + 0.523 \times 759.189)/1.975$

$= 358.64$ kJ/kg => Table A.7 $\mathbf{T_2 = 498.4\ K}$

$P_2 = m_2 RT_2 /V = 1.975 \times 0.287 \times 498.4/1.5 =$ **188.3 kPa**

5.64 An insulated cylinder is divided into two parts of 1 m^3 each by an initially locked piston, as shown in Fig. P5.64. Side A has air at 200 kPa, 300 K, and side B has air at 1.0 MPa, 1000 K. The piston is now unlocked so it is free to move, and it conducts heat so the air comes to a uniform temperature $T_A = T_B$. Find the mass in both A and B, and the final *T* and *P*.

C.V. A + B   Force balance on piston: $P_A A = P_B A$

So the final state in A and B is the same.

State 1A: Table A.7 $u_{A1} = 214.364$ kJ/kg,

$$m_A = P_{A1}V_{A1}/RT_{A1} = 200 \times 1/(0.287 \times 300) = \mathbf{2.323\ kg}$$

State 1B: Table A.7 $u_{B1} = 759.189$ kJ/kg,

$$m_B = P_{B1}V_{B1}/RT_{B1} = 1000 \times 1/(0.287 \times 1000) = \mathbf{3.484\ kg}$$

For chosen C.V. ${}_1Q_2 = 0$, ${}_1W_2 = 0$

$m_A(u_2 - u_1)_A + m_B(u_2 - u_1)_B = 0$

$(m_A + m_B)u_2 = m_A u_{A1} + m_B u_{B1}$

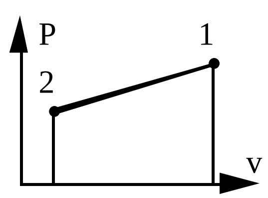
$= 2.323 \times 214.364 + 3.484 \times 759.189 = 3143$ kJ

$u_2 = 3143/(3.484 + 2.323) = 541.24$ kJ/kg $\Rightarrow$ $\mathbf{T_2 = 736\ K}$

$P = (m_A + m_B)RT_2/V_{tot} = 5.807 \times 0.287 \times 736 / 2 = \mathbf{613\ kPa}$

5.65 A cylinder with a piston restrained by a linear spring contains 2 kg of carbon dioxide at 500 kPa, 400°C. It is cooled to 40°C, at which point the pressure is 300 kPa. Calculate the heat transfer for the process.

Solution:



Linear spring gives

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$$

Equation of state: PV = mRT

State 1: $V_1 = mRT_1/P_1 = 2 \times 0.18892 \times 673.15 /500 = 0.5087\ m^3$

State 2: $V_2 = mRT_2/P_2 = 2 \times 0.18892 \times 313.15 /300 = 0.3944\ m^3$

${}_1W_2 = \frac{1}{2}(500 + 300)(0.3944 - 0.5087) = -45.72$ kJ

From Figure 5.11: $C_p(T_{avg}) = 45/44 = 1.023 \Rightarrow C_v = 0.83 = C_p - R$

For comparison the value from Table A.5 at 300 K is $C_v = 0.653$ kJ/kg K

${}_1Q_2 = mC_v(T_2 - T_1) + {}_1W_2 = 2 \times 0.83(40 - 400) - 45.72 = \mathbf{-643.3\ kJ}$

5.66 A piston/cylinder in a car contains 0.2 L of air at 90 kPa, 20°C, shown in Fig. P5.66. The air is compressed in a quasi-equilibrium polytropic process with polytropic exponent *n* = 1.25 to a final volume six times smaller. Determine the final pressure, temperature, and the heat transfer for the process.

Solution:

C.V. Air. This is a control mass going through a polytropic process.

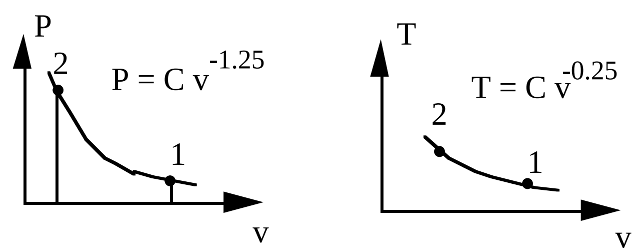
Continuty: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: $Pv^n = \text{const.}$

$$P_1v_1^n = P_2v_2^n \Rightarrow P_2 = P_1(v_1/v_2)^n = 90 \times 6^{1.25} = \mathbf{845.15\ kPa}$$

Substance ideal gas: $Pv = RT$

$$T_2 = T_1(P_2v_2/P_1v_1) = 293.15(845.15/90 \times 6) = \mathbf{458.8\ K}$$



$$m = \frac{PV}{RT} = \frac{90 \times 0.2 \times 10^{-3}}{0.287 \times 293.15} = 2.14 \times 10^{-4} \text{ kg}$$

$${}_1w_2 = \int Pdv = \frac{1}{1 - n}(P_2v_2 - P_1v_1) = \frac{R}{1 - n}(T_2 - T_1)$$

$$= \frac{0.287}{1 - 1.25}(458.8 - 293.15) = -190.17 \text{ kJ/kg}$$

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = 329.4 - 208.03 - 190.17 = -68.8 \text{ kJ/kg}$$

$${}_1Q_2 = m\ {}_1q_2 = \mathbf{-0.0147\ kJ} \quad \text{(i.e a heat loss)}$$

5.67 Water at 20°C, 100 kPa, is brought to 200 kPa, 1500°C. Find the change in the specific internal energy, using the water table and the ideal gas water table in combination.

Solution:

State 1: Table B.1.1 $u_1 \cong u_f = 83.95$ kJ/kg

State 2: Highest T in Table B.1.3 is 1300°C

Using a Δu from the ideal gas tables, A.8, we get

$\bar{h}(1500°C) - \bar{h}(1300°C) = 61367.7 - 51629.5 = 9738.2$ kJ/kmol

$u_{1500} - u_{1300} = \Delta\bar{h}/M - R(1500 - 1300) = 540.56 - 92.3 = 448.26$ kJ/kg

Since the ideal gas change is at low P we use 1300°C, lowest P available 10 kPa from steam tables, B.1.3, $u_x = 4683.7$ kJ/kg as the reference.

$$u_2 - u_1 = (u_2 - u_x)_{ID.G.} + (u_x - u_1)$$

$$= 448.26 + 4683.7 - 83.95 = \mathbf{5048\ kJ/kg}$$

5.68 For an application the change in enthalpy of carbon dioxide from 30 to 1500°C at 100 kPa is needed. Consider the following methods and indicate the most accurate one.

a. Constant specific heat, value from Table A.5.

b. Constant specific heat, value at average temperature from the equation in Table A.6.

c. Variable specific heat, integrating the equation in Table A.6.

d. Enthalpy from ideal gas tables in Table A.8.

Solution:

a) $\Delta h = C_p\Delta T = 0.842\ (1500 - 30) = \mathbf{1237.7\ kJ/kg}$

b) $T_{ave} = 1038.2$ K ; $\theta = T/100 = 10.382$ Table A.6

$\bar{C}_p = 54.64 \quad \Rightarrow \quad C_p = \bar{C}_p/M = 1.2415$

$\Delta h = C_{p,ave}\Delta T = 1.2415 \text{ x } 1470 = \mathbf{1825\ kJ/kg}$

c) For the entry to Table A.6: $\theta_2 = 17.7315$; $\theta_1 = 3.0315$

$$\Delta h = \int C_p dT = \frac{100}{M}\int \bar{C}_p d\theta$$

$$= \frac{100}{44.01}\left[-3.7357(\theta_2 - \theta_1) + \frac{2}{3} \text{ x } 30.529(\theta_2^{1.5} - \theta_1^{1.5})\right.$$

$$\left. - 4.1034 \text{ x } \frac{1}{2}(\theta_2^2 - \theta_1^2) + 0.024198 \text{ x } \frac{1}{3}(\theta_2^3 - \theta_1^3)\right] = \mathbf{1762.76\ kJ/kg}$$

d) $\Delta h = (77833 - 189)/44.01 = \mathbf{1764.3\ kJ/kg}$

The result in d) is best, very similar to c). For large ΔT or small ΔT at high T_{ave} a) is very poor.

5.69 Air in a piston/cylinder at 200 kPa, 600 K, is expanded in a constant-pressure process to twice the initial volume (state 2), shown in Fig. P5.69. The piston is then locked with a pin and heat is transferred to a final temperature of 600 K. Find *P*, *T*, and *h* for states 2 and 3, and find the work and heat transfer in both processes.

C.V. Air. Control mass $m_2 = m_3 = m_1$

1 => 2: $u_2 - u_1 = {}_1q_2 - {}_1w_2$; ${}_1w_2 = \int P\,dv = P_1(v_2 - v_1) = R(T_2 - T_1)$

Ideal gas $Pv = RT \Rightarrow T_2 = T_1v_2/v_1 = 2T_1 =$ **1200 K**

$P_2 = P_1 = 200$ kPa, ${}_1w_2 = RT_1 =$ **172.2 kJ/kg**

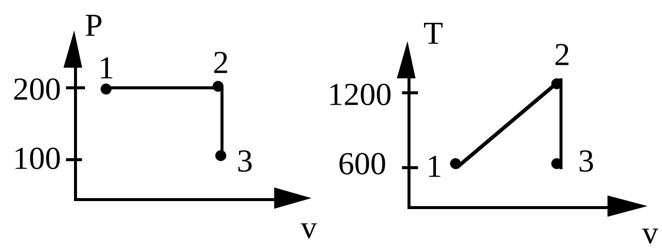
Table A.7 **h_2 = 1277.8 kJ/kg,** **$h_3 = h_1$ = 607.3 kJ/kg**

${}_1q_2 = u_2 - u_1 + {}_1w_2 = h_2 - h_1 = 1277.8 - 607.3 =$ **670.5 kJ/kg**

2→3: $v_3 = v_2 = 2v_1 \Rightarrow$ **${}_2w_3 = 0$,**

$P_3 = P_2T_3/T_2 = P_1T_1/2T_1 = P_1/2 =$ **100 kPa**

${}_2q_3 = u_3 - u_2 = 435.1 - 933.4 =$ **-498.3 kJ/kg**



5.70 An insulated floating piston divides a cylinder into two volumes each of 1 m^3, as shown in Fig. P5.70. One contains water at 100°C and the other air at –3°C and both pressures are 200 kPa. A line with a safety valve that opens at 400 kPa is attached to the water side of the cylinder. Assume no heat transfer to the water and that the water is incompressible. Show possible air states in a *P–v* diagram, and find the air temperature when the safety valve opens. How much heat transfer is needed to bring the air to 1300 K?

Solution:

C.V. air: CONT: $m_3 = m_2 = m_1$; ENERGY: $m_{air}(u_3 - u_1) = {}_1Q_3 - {}_1W_3$

1: (T,P,V) Ideal gas Table A.5 and A.7

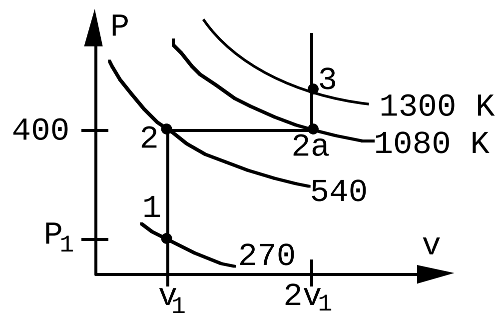
$m_{air} = P_1V_1/RT_1$

$= 200*1/(0.287*270.15)$

$= 2.578$ kg

2: $P_2 = 400$ kPa, $v_2 = v_1$

=> $T_2 = T_1P_2/P_1 = 2T_1 = 540.3$ K



C.V. H_2O: It is compressed liquid

2: no H_2O out $\Rightarrow$ no change in v_{H_2O}

=> no work $T_2 = T_1$ no Q

3: to fix it find 2a: $T_{2a} = T_1P_{2a}V_{2a}/P_1V_1 = 4T_1 = 1080$ K $< T_3$ so $V_3 = V_{2a}$

$1 \rightarrow 3$ for air: ${}_1W_3 = \int PdV = P_2(V_3 - V_1) = 400(2 - 1) = 400$ kJ

${}_1Q_3 = m_{air}(u_3 - u_1) + {}_1W_3 = 2.578\ (1022.75 - 192.9) + 400 =$ **2539 kJ**

5.71 Two containers are filled with air, one a rigid tank A, and the other a piston/cylinder B that is connected to A by a line and valve, as shown in Fig. P5.71. The initial conditions are: m_A = 2 kg, T_A = 600 K, P_A = 500 kPa and V_B = 0.5 m^3, T_B = 27°C, P_B = 200 kPa. The piston in B is loaded with the outside atmosphere and the piston mass in the standard gravitational field. The valve is now opened, and the air comes to a uniform condition in both volumes. Assuming no heat transfer, find the initial mass in B, the volume of tank A, the final pressure and temperature and the work, $_1W_2$.

Cont.: $m_2 = m_1 = m_{A1} + m_{B1}$

Energy: $m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = -_1W_2$; $\quad _1W_2 = P_{B1}(V_2 - V_1)$

System: $P_B = \text{const} = P_{B1} = P_2$; $\quad$ Substance: $PV = mRT$

$m_{B1} = P_{B1}V_{B1}/RT_{B1} =$ **1.161 kg** ; $\quad V_A = m_{A1}RT_{A1}/P_{A1} =$ **0.6888 m^3**

$P_2 = P_{B1} =$ **200 kPa** ; $\quad$ A.7: $u_{A1} = 434.8$, $u_{B1} = 214.09$ kJ/kg

$m_2u_2 + P_2V_2 = m_{A1}u_{A1} + m_{B1}u_{B1} + P_{B1}V_1 = m_2h_2 = 1355.92$ kJ

$\Rightarrow h_2 = 428.95$ kJ/kg $\quad\Rightarrow\quad T_2 = 427.7$ K $\Rightarrow V_2 = m_{tot}RT_2/P_2 = 1.94$ m^3

$_1W_2 = 200 \times (1.94 - 1.1888) =$ **150.25 kJ**

5.72 A 250-L rigid tank contains methane gas at 500°C, 600 kPa. The tank is cooled to 300 K.

a. Find the final pressure and the heat transfer for the process.

b. What is the percent error in the heat transfer if the specific heat is assumed constant at the room temperature value?

Solution:

a) Assume ideal gas, $P_2 = P_1 \times (T_2 / T_1) = 600 \times 300 / 773.15 =$ **232.8 kPa**

$$m = P_1V/RT_1 = \frac{600 \times 0.25}{0.51835 \times 773.2} = 0.374 \text{ kg}$$

Equation from Table A.6 valid down to T = 300 K

$$u_2 - u_1 = \frac{1}{M}\int_{T1}^{T2} (\bar{C}_{P0} - \bar{R})dT = \frac{100}{16.04}\Big[-681.184\theta + \frac{439.74}{1.25}\theta^{1.25} - \frac{24.875}{1.75}\theta^{1.75} + \frac{323.88}{0.5}\theta^{0.5}\Big]_{7.732}^{3.0} = -1186.3$$

$_1Q_2 = m(u_2 - u_1) = 0.374(-1186.3) =$ **-444 kJ**

b) Using room temp. C_{V0},

$_1Q_2 = 0.374 \times 1.7354\ (300 - 773.2) =$ **-307.1 kJ**

which is in error by **30.8 %**

5.73 A piston/cylinder arrangement, shown in Fig. P5.73, contains 10 g of air at 250 kPa, 300°C. The 75-kg piston has a diameter of 0.1 m and initially pushes against the stops. The atmosphere is at 100 kPa and 20°C. The cylinder now cools to 20°C as heat is transferred to the ambient. Calculate the heat transfer.

Determine if piston will drop. So a force balance to float the piston gives:

$$P_{float} = P_0 + \frac{m_p g}{A} = 100 + \frac{75 \text{ x } 9.80665}{\pi \text{ x } 0.1^2 \text{ x } 0.25 \text{ x } 1000} = 193.6 \text{ kPa}$$

If air is cooled to T_2 at constant volume

$P_2 = P_1T_2/T_1 = 250 \text{ x } 293.15/573.15 = 127.9 \text{ kPa} < P_{float}$

State 2: T_2, $P_2 = P_{float}$

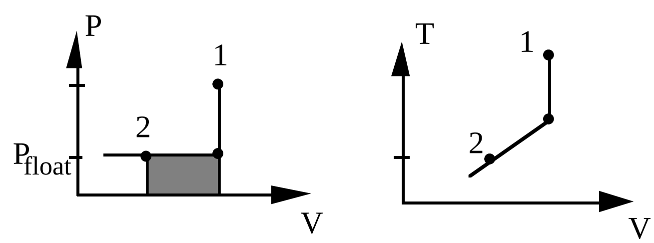
State 1: $V_1 = mRT_1/ P_1 = 0.010 \text{ x } 0.287 \text{ x } 573.15 / 250 = 0.00658 \text{ m}^3$

$$\text{Ideal gas} \Rightarrow V_2 = \frac{V_1T_2P_1}{P_2T_1} = \frac{0.00658 \text{ x } 293.15 \text{ x } 250}{193.65 \text{ x } 573.15} = 0.00434 \text{ m}^3$$

${}_1W_2 = \int P\, dV = P_{float}(V_2 - V_1) = 193.65(0.00434 – 0.00658) = -0.434 \text{ kJ}$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 \cong mC_V(T_2 - T_1) + {}_1W_2$

$= 0.1 \text{ x } 0.717 \text{ x } (20 - 300) - 0.434 = \mathbf{-2.44\ kJ}$



5.74 Oxygen at 300 kPa, 100°C is in a piston/cylinder arrangement with a volume of 0.1 m^3. It is now compressed in a polytropic process with exponent, n = 1.2, to a final temperature of 200°C. Calculate the heat transfer for the process.

Continuty: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: T_1 , P_1 & ideal gas, small change in T, so use Table A.5

$$\Rightarrow m = \frac{P_1V_1}{RT_1} = \frac{300 \text{ x } 0.1 \text{ m}^3}{0.25983 \text{ x } 373.15} = 0.3094 \text{ kg}$$

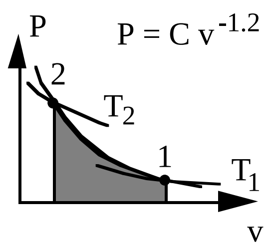
Process: PV^n = constant

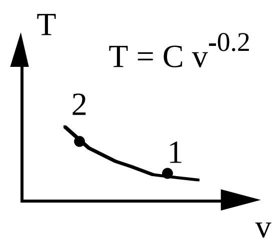
$${}_1W_2 = \frac{1}{1\text{-n}}(P_2V_2 - P_1V_1) = \frac{mR}{1\text{-n}}(T_2 - T_1) = \frac{0.3094 \text{ x } 0.25983}{1 - 1.2}(200 - 100)$$

$$= -40.196 \text{ kJ}$$

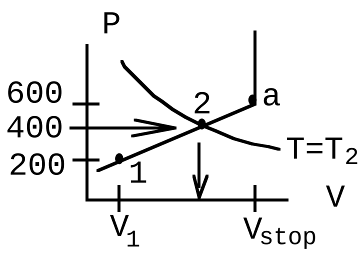
$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 \cong mC_v(T_2 - T_1) + {}_1W_2$$

$$= 0.3094 \text{ x } 0.662\ (200 - 100) - 40.196 = \mathbf{-19.72\ kJ}$$





5.75 A piston/cylinder contains 2 kg of air at 27°C, 200 kPa, shown in Fig. P5.75. The piston is loaded with a linear spring, mass and the atmosphere. Stops are mounted so that $V_{stop} = 3\ m^3$, at which point $P = 600$ kPa is required to balance the piston forces. The air is now heated to a final pressure of 400 kPa. Find the final temperature, volume and the work and heat transfer. Find the work done on the spring.



From the physical setup the balance of forces on the piston gives P vs. V linear from 1 to a, see figure.

To find state 2: From P_2 to line to V_2 so we need V_1 to fix the line location.

$V_1 = mRT_1/P_1 = 2 \times 0.287 \times 300.15/200 = 0.8614\ m^3$

$V_2 = V_1 + [\ (P_2 - P_1)/(P_a - P_1)]\ x\ (V_a - V_1)$

$= 0.8614 + (400 - 200)\ x\ (3 – 0.8614)/(600 – 200) = 1.9307\ m^3$

$T_2 = P_2V_2/mR = 400\ x1.9307/(2\ x0.287) = 1345.4$ K

$_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(200 + 400)(1.9307 - 0.8614)$

= **320.79 kJ**

Since T_2 is very large we do not use constant C_V, so energy eq. and Table A.7

$_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2\ x\ (1063.8 – 214.36) + 320.79 =$ **2019.7 kJ**

$W_{spring} = {}_1W_2 - W_{atm} = {}_1W_2 - P_0(V_2 - V_1)$

$= 320.79 – 101(1.9307 – 0.8614) =$ **212.8 kJ**

5.76 A piston/cylinder contains 0.001 m^3 air at 300 K, 150 kPa. The air is now compressed in a process in which $P\,V^{1.25} = C$ to a final pressure of 600 kPa. Find the work performed by the air and the heat transfer.

Solution:

C.V. Air. This is a control mass, values from Table A.5 are used.

Continuty: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process : $PV^{1.25} = \text{const.}$

State 2: $V_2 = V_1\,(P_1/P_2)^{1.25} = 0.00033\ m^3$

$$T_2 = T_1\,P_2V_2/(P_1V_1) = 300\frac{600 \times 0.00033}{150 \times 0.001} = 395.85\text{ K}$$

$${}_1W_2 = \frac{1}{n\text{-}1}(P_2\,V_2 - P_1V_1) = \frac{1}{n\text{-}1}(600 \times 0.00033 - 150 \times 0.001) = -\,0.192\text{ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = \frac{P_1V_1}{RT_1}C_v\,(T_2 - T_1) + {}_1W_2$$

$$= 0.001742 \times 0.717 \times 95.85 - 0.192 = \mathbf{-\,0.072\ kJ}$$

5.77 An air pistol contains compressed air in a small cylinder, shown in Fig. P5.77. Assume that the volume is 1 cm^3, pressure is 1 MPa, and the temperature is 27°C when armed. A bullet, m = 15 g, acts as a piston initially held by a pin (trigger); when released, the air expands in an isothermal process (T = constant). If the air pressure is 0.1 MPa in the cylinder as the bullet leaves the gun, find

a. The final volume and the mass of air.

b. The work done by the air and work done on the atmosphere.

c. The work to the bullet and the bullet exit velocity.

Solution:

C.V. Air.

Air ideal gas: $m_{air} = P_1V_1/RT_1 = 1000 \times 10^{-6}/(0.287 \times 300) = \mathbf{1.17 \times 10^{-5}\ kg}$

Process: $PV = \text{const} = P_1V_1 = P_2V_2 \Rightarrow V_2 = V_1P_1/P_2 = \mathbf{10\ cm^3}$

$${}_1W_2 = \int PdV = \int \frac{P_1V_1}{V}dV = P_1V_1 \ln(V_2/V_1) = \mathbf{2.32\ J}$$

$${}_1W_{2,ATM} = P_0(V_2 - V_1) = 101 \times (10\text{-}1) \times 10^{-6}\text{ kJ} = \mathbf{0.909\ J}$$

$$W_{bullet} = {}_1W_2 - {}_1W_{2,ATM} = 1.411\text{ J} = \frac{1}{2}m_{bullet}(V_{exit})^2$$

$$V_{exit} = (2W_{bullet}/m_B)^{1/2} = (2 \times 1.411/0.015)^{1/2} = \mathbf{13.72\ m/s}$$

5.78 A spherical elastic balloon contains nitrogen (N_2) at 20^{o}C, 500 kPa. The initial volume is 0.5 m^3. The balloon material is such that the pressure inside is proportional to the balloon diameter. Heat is now transferred to the balloon until its volume reaches 1.0 m^3 , at which point the process stops.
a) Can the nitrogen be assumed to behave as an ideal gas throughout this process?
b) Calculate the heat transferred to the nitrogen.

Solution:

C.V. Nitrogen, which is a control mass.

Continuty: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: $P \propto D \propto V^{1/3}$ => $PV^{-1/3}$ = constant. Polytropic process n = -1/3.

State 1: 20^{o}C = 293.2 K, 500 kPa, Table A.2: T_C = 126.2 K, P_C = 3.39 MPa

$T >> T_C$ and $P << P_C$ => Ideal Gas OK, gas constant from Table A.5.

$V_1 = 0.5\ m^3$ => $m = P_1V_1/RT_1 = 500 \times 0.5/(0.2968 \times 293.15) = 2.873$ kg

Assume also Ideal gas for state 2. Then find T and check.

Process => $P_2 = P_1 [\ V_2/\ V_1]^{1/3} = 500\ [1.0 / 0.5]^{1/3} = 630$ kPa

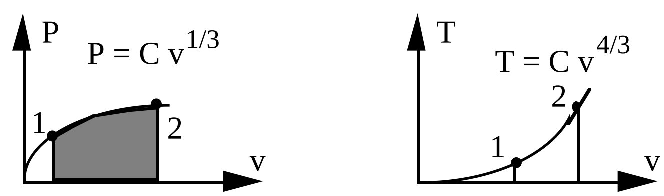
From ideal gas law: $$T_2 = T_1 \frac{P_2\ V_2}{P_1\ V_1} = 293.15 \times \frac{630 \times 1.0}{500 \times 0.5} = 738.7\ K$$

State 2: since $T_2 >> T_C$ and $P_2 << P_C$ => **Also Ideal Gas.**

$${}_1W_2 = \int_1^2 P\ dV = \frac{P_2\ V_2 - P_1\ V_1}{1- n} = \frac{630 \times 1.0 - 500 \times 0.5}{1 - (-1/3)} = 285\ kJ$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m\ C_{Vo}\ (T_2 - T_1) + {}_1W_2$$

$= 2.873 \times 0.745\ (738.7 - 293.2) + 285 =$ **1238.6 kJ**



5.79 A 10-m high cylinder, cross-sectional area 0.1 m^2, has a massless piston at the bottom with water at 20°C on top of it, shown in Fig. P5.79. Air at 300 K, volume 0.3 m^3, under the piston is heated so that the piston moves up, spilling the water out over the side. Find the total heat transfer to the air when all the water has been pushed out.

Solution:

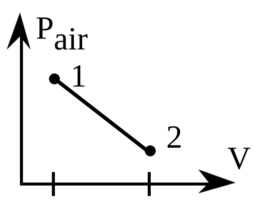
The water on top is compressed liquid and has volume and mass

$$V_{H_2O} = V_{tot} - V_{air} = 10 \times 0.1 - 0.3 = 0.7 \text{ m}^3$$

$$m_{H_2O} = V_{H_2O}/v_f = 0.7 / 0.001002 = 698.6 \text{ kg}$$

The initial air pressure is then

$$P_1 = P_0 + m_{H_2O}g/A = 101.325 + \frac{698.6 \times 9.807}{0.1 \times 1000} = \mathbf{169.84\ kPa}$$



and then $m_{air} = PV/RT = \frac{169.84 \times 0.3}{0.287 \times 300} = 0.592$ kg

State 2: No liquid water over the piston so

$P_2 = P_0 + \emptyset = 101.325$ kPa, $V_2 = 10 \times 0.1 = 1 \text{ m}^3$

State 2: P_2, V_2 $\Rightarrow$ $T_2 = \frac{T_1 P_2 V_2}{P_1 V_1} = \frac{300 \times 101.325 \times 1}{169.84 \times 0.3} = 596.59$ K

The process line shows the work as an area

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(169.84 + 101.325)(1 - 0.3) = 94.91 \text{ kJ}$$

The energy equation solved for the heat transfer becomes

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 \cong mC_V(T_2 - T_1) + {}_1W_2$$

$$= 0.592 \times 0.717 \times (596.59 - 300) + 94.91 = \mathbf{220.7\ kJ}$$

Remark: we could have used u values from Table A.7:

$u_2 - u_1 = 432.5 - 214.36 = 218.14$ kJ/kg versus 212.5 kJ/kg with Cv.

5.80 A cylinder fitted with a frictionless piston contains carbon dioxide at 500 kPa, 400 K, at which point the volume is 50 L. The gas is now allowed to expand until the piston reaches a set of fixed stops at 150 L cylinder volume. This process is polytropic, with the polytropic exponent n equal to 1.20. Additional heat is now transferred to the gas, until the final temperature reaches 500 K. Determine

a) The final pressure inside the cylinder.

b) The work and heat transfer for the overall process.

Solution:

C.V. The mass of carbon dioxide. Constant mass has process 1 - 2 - 3.

Continuity: $m_3 = m_2 = m_1$; Energy: $m (u_3 - u_1) = {}_1Q_3 - {}_1W_3$

Process 1 - 2: Polytropic expansion PV^n = constant.

Process 2 - 3: Constant volume $V_3 = V_2 \;\; => \;\; {}_2W_3 = 0$

State 1: 400 K, 500 kPa, Ideal gas Table A.5, R = 0.1889

$$V_1 = 50 \text{ L} \quad => \quad m = P_1V_1/RT_1 = \frac{500 \text{ x } 0.05}{0.1889 \text{ x } 400} = 0.331 \text{ kg}$$

State 2: Polytropic expansion to stops at V_2 = 150 L

$$P_2 = P_1 \times (V_1/V_2)^n = 500 \times (50 / 150)^{1.2} = 133.8 \text{ kPa}$$

State 3: Add Q to T_3 = 500 K, constant volume $V_3 = V_2$

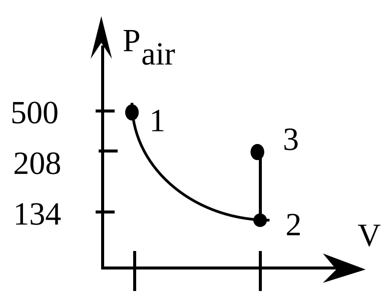
$$P_3 = P_1 \times \frac{V_1}{V_3} \times \frac{T_3}{T_1} = 500 \times \frac{50}{150} \times \frac{500}{400} = \mathbf{208.3 \text{ kPa}}$$

$${}_1W_3 = {}_1W_2 + {}_2W_3 = {}_1W_2 + 0 = \int P \, dV$$

$$= \frac{P_2 V_2 - P_1 V_1}{1 - n} = \frac{133.8 \text{ x } 0.15 - 500 \text{ x } 0.05}{1 - 1.2} = \mathbf{+24.7 \text{ kJ}}$$

$${}_1Q_3 = m(u_3 - u_1) + {}_1W_3 = m C_{Vo} (T_3 - T_1) + {}_1W_3$$

$$= 0.331 \text{ x } 0.653 (500 - 400) + 24.7 = 21.6 + 24.7 = \mathbf{+46.3 \text{ kJ}}$$



5.81 A cylinder fitted with a frictionless piston contains R-134a at 40°C, 80% quality, at which point the volume is 10 L. The external force on the piston is now varied in such a manner that the R-134a slowly expands in a polytropic process to 400 kPa, 20°C. Calculate the work and the heat transfer for this process.

C.V. The mass of R-134a.

Process: PV^n = constant => $P_1V_1^n = P_2V_2^n$

State 1: (T, x) Table B.5.1 => $P_1 = P_g = 1017$ kPa

$v_1 = 0.000873 + 0.8 \times 0.019147 = 0.01619 \text{ m}^3/\text{kg}$

$u_1 = 255.65 + 0.8 \times 143.81 = 370.7$ kJ/kg

$m = V_1/v_1 = 0.010/0.01619 = 0.618$ kg

State 2: (P_2, T_2) Table B.5.2 $v_2 = 0.05436 \text{ m}^3/\text{kg}$, $h_2 = 414.0$ kJ/kg

$u_2 = h_2 - P_2v_2 = 414.0 - 400 \text{ x } 0.05436 = 392.3$ kJ/kg

$V_2 = mv_2 = 0.618 \text{ x } 0.05436 = 0.0336 \text{ m}^3 = 33.6$ L

$$\text{Process} \;\; => \;\; n = \ln \frac{P_1}{P_2} / \ln \frac{V_2}{V_1} = \ln\frac{1017}{400} / \ln\frac{33.6}{10} = \frac{0.93315}{1.21194} = 0.77$$

$${}_1W_2 = \int P\,dV = \frac{P_2 V_2 - P_1 V_1}{1-n} = \frac{400 \text{ x } 0.0336 - 1017 \text{ x } 0.010}{1 - 077} = +\mathbf{14.2\ kJ}$$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.618\ (392.3 - 370.6) + 14.2 = 13.4 + 14.2 =$ **27.6 kJ**

5.82 A piston/cylinder contains argon gas at 140 kPa, 10°C, and the volume is 100 L. The gas is compressed in a polytropic process to 700 kPa, 280°C. Calculate the heat transfer during the process.

Find the final volume, then knowing P_1, V_1, P_2, V_2 the polytropic exponent can be determined. Argon is an ideal monatomic gas (Cv is constant).

$$V_2 = V_1 \text{ x } \frac{P_1}{P_2}\frac{T_2}{T_1} = 0.1 \text{ x } \frac{140}{700}\frac{553.15}{283.15} = \mathbf{0.0391\ m^3}$$

$$P_1V_1^n = P_2V_2^n \quad \Rightarrow \quad n = \ln(P_2/P_1)/\ln(V_1/V_2) = \frac{1.6094}{0.939} = 1.714$$

$${}_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{700\text{x}0.0391 - 140\text{x}0.1}{1 - 1.714} = \mathbf{-18.73\ kJ}$$

$m = P_1V_1/RT_1 = 140 \text{ x } 0.1/(0.20813 \text{ x } 283.15) =$ **0.2376 kg**

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = mC_v(T_2 - T_1) + {}_1W_2$

$= 0.2376 \text{ x } 0.3122\ (280 - 10) - 18.73 =$ **1.3 kJ**

5.83 Water at 150°C, quality 50% is contained in a cylinder/piston arrangement with initial volume 0.05 m^3. The loading of the piston is such that the inside pressure is linear with the square root of volume as $P = 100 + CV^{0.5}$ kPa. Now heat is transferred to the cylinder to a final pressure of 600 kPa. Find the heat transfer in the process.

Continuty: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: $v_1 = 0.1969$, $u_1 = 1595.6$ kJ/kg $\Rightarrow$ $m = V/v_1 = 0.254$ kg

Process equation $\Rightarrow$ $P_1 - 100 = CV_1^{1/2}$ so

$$(V_2/V_1)^{1/2} = (P_2 - 100)/(P_1 - 100)$$

$$V_2 = V_1 \text{ x} \left[\frac{P_2 - 100}{P_1 - 100}\right]^2 = 0.05 \text{ x} \left[\frac{500}{475.8 - 100}\right]^2 = 0.0885$$

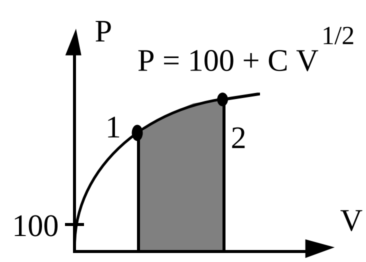
$${}_1W_2 = \int PdV = \int (100 + CV^{1/2})dV = 100\text{x}(V_2 - V_1) + \frac{2}{3}C(V_2^{1.5} - V_1^{1.5})$$

$$= 100(V_2 - V_1)(1 - 2/3) + (2/3)(P_2V_2 - P_1V_1)$$

${}_1W_2 = 100\ (0.0885\text{-}0.05)/3 + 2\ (600 \text{ x } 0.0885\text{-}475.8 \text{ x } 0.05)/3 = 20.82$ kJ

State 2: P_2, $v_2 = V_2/m = 0.3484$ $\Rightarrow$ $u_2 = 2631.9$ kJ/kg, $T_2 \cong 196°C$

${}_1Q_2 = 0.254 \text{ x } (2631.9 - 1595.6) + 20.82 =$ **284 kJ**



5.84 A piston/cylinder has 1 kg propane gas at 700 kPa, 40°C. The piston cross-sectional area is 0.5 m^2, and the total external force restraining the piston is directly proportional to the cylinder volume squared. Heat is transferred to the propane until its temperature reaches 700°C. Determine the final pressure inside the cylinder, the work done by the propane, and the heat transfer during the process.

Process: $P = P_{ext} = CV^2 \;\Rightarrow\; PV^{-2} = \text{const}, \;\; n = -2$

Ideal gas: $PV = mRT$, and process yields

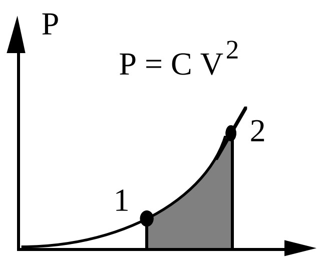
$$P_2 = P_1(T_2/T_1)^{\frac{n}{n-1}} = 700 \left(\frac{700+273.15}{40+273.15}\right)^{2/3} = \mathbf{1490.7\ kPa}$$

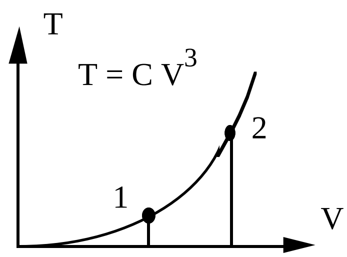
$$_1W_2 = \int_1^2 PdV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{mR(T_2 - T_1)}{1 - n}$$

$$= \frac{1 \times 0.18855 \times (700 - 40)}{1 - (-2)} = \mathbf{41.48\ kJ}$$

$$_1Q_2 = m(u_2 - u_1) + {_1W_2} = mC_V(T_2 - T_1) + {_1W_2}$$

$$= 1 \text{ x } 1.490 \text{ x } (700 - 40) + 41.48 = \mathbf{1024.9\ kJ}$$





5.85 A closed cylinder is divided into two rooms by a frictionless piston held in place by a pin, as shown in Fig. P5.85. Room A has 10 L air at 100 kPa, 30°C, and room B has 300 L saturated water vapor at 30°C. The pin is pulled, releasing the piston, and both rooms come to equilibrium at 30°C and as the water is compressed it becomes two-phase. Considering a control mass of the air and water, determine the work done by the system and the heat transfer to the cylinder.

$P_2 = P_{G\ H_2O \text{ at } 30°C} = P_{A2} = P_{B2} = 4.246$ kPa

Air, I.G.: $P_{A1}V_{A1} = m_A R_A T = P_{A2}V_{A2} = P_{G\ H_2O \text{ at } 30°C}V_{A2}$

$$\rightarrow V_{A2} = \frac{100 \times 0.01}{4.246} \text{ m}^3 = 0.2355 \text{ m}^3$$

$V_{B2} = V_{A1} + V_{B1} - V_{A2} = 0.30 + 0.01 - 0.2355 = 0.0745 \text{ m}^3$

$$m_B = \frac{V_{B1}}{v_{B1}} = \frac{0.3}{32.89} = 9.121\text{x}10^{-3} \text{ kg} \Rightarrow v_{B2} = 8.166 \text{ m}^3/\text{kg}$$

$8.166 = 0.001004 + x_{B2} \times (32.89 - 0.001) \Rightarrow x_{B2} = 0.2483$

System A+B: $W = 0$; $\Delta U_A = 0$ (IG & $\Delta T = 0$)

$u_{B2} = 125.78 + 0.2483 \times 2290.8 = 694.5$, $u_{B1} = 2416.6$ kJ/kg

${}_1Q_2 = 9.121\text{x}10^{-3}(694.5 - 2416.6) = \mathbf{-15.7\ kJ}$

5.86 A small elevator is being designed for a construction site. It is expected to carry four 75-kg workers to the top of a 100-m tall building in less than 2 min. The elevator cage will have a counterweight to balance its mass. What is the smallest size (power) electric motor that can drive this unit?

$m = 4 \times 75 = 300$ kg ; $\Delta Z = 100$ m ; $\Delta t = 2$ minutes

$$-\dot{W} = \Delta\dot{PE} = mg\frac{\Delta Z}{\Delta t} = \frac{300 \times 9.807 \times 100}{1000 \times 2 \times 60} = \mathbf{2.45\ kW}$$

5.87 The rate of heat transfer to the surroundings from a person at rest is about 400 kJ/h. Suppose that the ventilation system fails in an auditorium containing 100 people. Assume the energy goes into the air of volume 1500 m^3 initially at 300 K and 101 kPa. Find the rate (degrees per minute) of the air temperature change.

$\dot{Q} = n\,Q = 100 \times 400 = \mathbf{40000\ kJ/h} = \mathbf{666.7\ kJ/min}$

$$\frac{dE_{air}}{dt} = \dot{Q} = m_{air}C_v\frac{dT_{air}}{dt}$$

$m_{air} = PV/RT = 101 \times 1500 / 0.287 \times 300 = 1759.6$ kg

$$\frac{dT_{air}}{dt} = \dot{Q}/mC_v = 666.7 / (1759.6 \times 0.717) = \mathbf{0.53\ °C/min}$$

5.88 Consider the 100-L Dewar (a rigid double-walled vessel for storing cryogenic liquids) shown in Fig. P5.88. The Dewar contains nitrogen at 1 atm, 90% liquid and 10% vapor by volume. The insulation holds heat transfer into the Dewar from the ambient to a very low rate, 5 J/s. The vent valve is accidentally closed so that the pressure inside slowly rises. How long time will it take to reach a pressure of 500 kPa?

State 1: $T_1 = 77.3$ K, $V_{liq1} = 0.9$ V, $V_{vap1} = 0.1$ V,

Table B.6.1: $v_{1f} = 0.00124\ m^3/kg$, $v_{1g} = 0.21639\ m^3/kg$,

$$m_{liq1} = \frac{0.9 \text{ x } 0.1}{0.00124} = 72.5806 \text{ kg}; \quad m_{vap1} = \frac{0.1 \text{ x } 0.1}{0.21639} = 0.0462 \text{ kg}$$

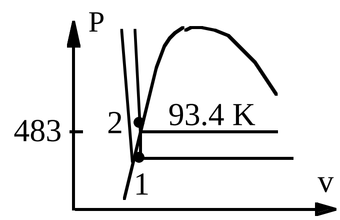
$m_{tot} = m_{liq1} + m_{vap1} = 72.6268$ kg; $x_1 = 0.0462 / 72.6268 = 0.000636$

$u_1 = -122.27 + 0.000636x177.04 = -122.16$ kJ/kg

$v_1 = 0.1/ 72.6268 = 0.001377\ m^3/kg$

Process: $v_2 = v_1 \cong v_f$ at $T \cong 93.4$ K,

Table B.6.1 $\Rightarrow$ $P_g = 483$ kPa



State 2: $P_2 = 500$ kPa, Compressed liquid at 93.4 K (use sat. liq.). Once in the liquid region then v is not strong function of P.

$u_2 = -88.108 - 500 \text{ x } 0.001377 = -88.797$

${}_1Q_2 = 72.6268 \text{ x}(-88.797 - 122.16) = 2423$ kJ

$\Delta t = {}_1Q_2/\dot{Q} = 2423/(0.005 \text{ x } 3600) =$ **134.6 h**

5.89 A computer in a closed room of volume 200 m^3 dissipates energy at a rate of 10 kW. The room has 50 kg wood, 25 kg steel and air, with all material at 300 K, 100 kPa. Assuming all the mass heats up uniformly how long time will it take to increase the temperature 10°C?

C.V. Air, wood and steel. $m_2 = m_1$; $U_2 - U_1 = {}_1Q_2 = \dot{Q}\Delta t$

The total volume is nearly all air, but we can find volume of the solids.

$V_{wood} = m/\rho = 50/510 = 0.098\ m^3$; $V_{steel} = 25/7820 = 0.003\ m^3$

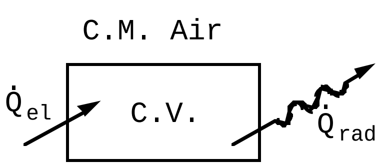
$V_{air} = 200 - 0.098 - 0.003 = 199.899\ m^3$

$m_{air} = PV/RT = 101.325 \times 199.899/(0.287 \times 300) = 235.25$ kg

We do not have a u table for steel or wood so use heat capacity.

$$\Delta U = [m_{air}\, C_v + m_{wood}\, C_v + m_{steel}\, C_v\,]\Delta T$$
$$= (235.25 \times 0.717 + 50 \times 1.38 + 25 \times 0.46)\ 10$$
$$= 1686.7 + 690 + 115 = 2492 \text{ kJ} = \dot{Q} \times \Delta t = 10{*}\Delta t$$
$$=> \quad \Delta t = 2492/10 = 249.2 \text{ sec} = 4.2 \text{ minutes}$$

5.90 The heaters in a spacecraft suddenly fail. Heat is lost by radiation at the rate of 100 kJ/h, and the electric instruments generate 75 kJ/h. Initially, the air is at 100 kPa, 25°C with a volume of 10 m^3. How long will it take to reach an air temperature of −20°C?



Continuity Eq: $\dfrac{dM}{dt} = 0$ $\qquad \dot{W} = 0$

$\dot{KE} = 0$

Energy Eq: $\dfrac{dE}{dt} = \dot{Q}_{el} - \dot{Q}_{rad}$ $\qquad \dot{PE} = 0$

$$\dot{E} = \dot{U} = \dot{Q}_{el} - \dot{Q}_{rad} = \dot{Q}_{net} \;\Rightarrow\; U_2 - U_1 = m(u_2 - u_1) = \dot{Q}_{net}(t_2 - t_1)$$

Ideal gas: $m = P_1V_1/RT_1 = 100 \text{x} 10 / (0.287 \text{x} 298.15) = 11.688$ kg

$$u_2 - u_1 = C_{v0}(T_2 - T_1) = 0.717\ (-20 - 25) = -32.26 \text{ kJ/kg}$$

$$t_2 - t_1 = mC_{v0}(T_2 - T_1)/\dot{Q}_{net} = 11.688 \times (-32.26)/(-25) = \mathbf{15.08\ h}$$

Advanced Problems

5.91 A cylinder fitted with a piston restrained by a linear spring has a cross-sectional area of 0.05 m^2 and initial volume of 20 L, shown in Fig. P5.91. The cylinder contains ammonia at 1 MPa, 60°C. The spring constant is 150 kN/m. Heat is rejected from the system, and the piston moves until 6.25 kJ of work has been done on the ammonia.

a. Find the final temperature of the ammonia.

b. Calculate the heat transfer for the process.

C.V. Ammonia. This is a control mass.

State 1: Table B.2.2 $v_1 = 0.15106$, $m = V_1/v_1 = 0.020/0.15106 = 0.1324$ kg

$u_1 = 1563.1 - 1000*0.15106 = 1412.1$ kJ/kg ; $A_P = 0.05\ m^2$

Process: $P = P_1 + [k_s/A_P^2](V - V_1)$; P is linear in V.

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(P_1 + P_2)(P_2 - P_1)\ [A_P^2 / k_s]$$

$$= [A_P^2 / 2k_s]\ (P_2^2 - P_1^2) = -6.25 \text{ kJ}$$

$$= [0.05^2/(2 \times 150)] \times (P_2^2 - 1000^2) \;\Rightarrow\; P_2 = 500 \text{ kPa}$$

From the process equation we find the specific volume

$$v_2 = v_1 + [A_P^2 / mk_s]\ (P_2 - P_1)$$

$$= 0.15106 + \frac{0.05^2}{0.1324 \times 150}(500 - 1000) = 0.08812$$

State 2: P_2 , v_2 $\Rightarrow$ Two-phase, $T \sim 4°C$ ($P_{sat} = 497.35$), $x_2 = 0.3461$

$u_2 = 198.52 + 0.3461 \times 1122.7 = 587.1$ kJ/kg

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.1324 \times (587.1 - 1412.1) - 6.25 =$ **-115.5 kJ**

5.92 A cylinder fitted with a piston contains 2 kg of R-12 at 10°C, 90% quality. The system undergoes a quasi-equilibrium polytropic expansion to 100 kPa, during which the system receives a heat transfer of 52.5 kJ. What is the final temperature of the R-12?

C.V. R-12.

Continuty: $m_2 = m_1$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: Table B.3.1, $v_1 = 0.000733 + 0.9 \text{ x } 0.04018 = 0.036895$

$u_1 = 45.06 + 0.9\text{x } 129.36 = 161.48 \text{ kJ/kg}$

Process: $PV^n = \text{const} \rightarrow {}_1W_2 = \int_1^2 PdV = m \frac{P_2v_2\text{-}P_1v_1}{1\text{-}n}$

$${}_1Q_2 = 52.5 = m(u_2\text{-}u_1) + m \frac{P_2v_2\text{-}P_1v_1}{1\text{-}n} \quad \text{and} \quad P_2v_2{}^n = P_1v_1{}^n$$

State 2: 100 kPa and on process line to given ${}_1Q_2$. Then u_2 = function(T_2) and

v_2 = function(T_2) => 2 equations in T_2 & n: solve by trial and error

Assume $T_2 = -20\ ^oC \rightarrow$ v = 0.1677, u = 179.99-100*0.1677 = 163.22

$$100\text{x}0.1677^n = 423.3\text{x}0.036\,895^n \rightarrow n = 0.953$$

$${}_1Q_2 = 2(163.22 - 161.48) + 2\text{x}\frac{100\text{x}0.1677\text{-}423.3\text{x}0.036895}{1\text{-}0.953}$$

$= 3.48 + 49.04 = 52.52$ kJ **OK**

$T_2 =$ **-20^oC**

5.93 A spherical balloon initially 150 mm in diameter and containing R-12 at 100 kPa is connected to a 30-L uninsulated, rigid tank containing R-12 at 500 kPa. Everything is at the ambient temperature of 20°C. A valve connecting the tank and balloon is opened slightly and remains so until the pressures equalize. During this process heat is exchanged so the temperature remains constant at 20°C and the pressure inside the balloon is proportional to the diameter at any time. Calculate the final pressure and the work and heat transfer during the process.

C.V.: balloon A + tank B

State A1: Table B.3.2; v_{A1} = 0.19728, u = 203.85 -100*0.19728 = 184.12 kJ/kg

$V_{A1} = \frac{\pi}{6}(0.15)^3 = 0.001\ 767\ m^3$; $m_{A1} = 0.001767/0.19728 = 0.009$ kg

State B1: v = 0.03482 + (20-15.6)*(0.03746-0.03482)/(30-15.6) = 0.03563

same interpolation: $u_{B1} = 197.06 - 500x0.03563 = 179.25$ kJ/kg

$m_{B1} = 0.03/0.03563 = 0.842$ kg ; $m_2 = m_{A1} + m_{B1} = 0.851$ kg

Process: $V_{A2} = V_{A1}(\frac{P_2}{P_{A1}})^3 = 0.001\ 767(\frac{P_2}{0.1})^3$

Assume P_2 = 262 kPa Table B.3: $v_2 = 0.07298\ m^3/kg$

u_2 = 201.222 - 262x0.07298 = 182.0

$V_{A2} = 0.001\ 767(\frac{0.262}{0.1})^3 = 0.03178\ m^3$

$m_2 = \frac{.03178+.03}{0.072982} = 0.847 \approx 0.851$ kg $\Rightarrow P_2 =$ **0.262 MPa**

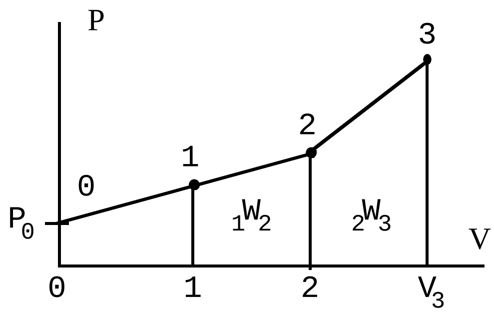
$_1W_2 = \int_1^2 PdV = \frac{P_2V_{A2}-P_1V_{A1}}{1-(-1/3)}$ = (262x0.031 78-100x0.001767)/(4/3) = **6.11** kJ

$_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} + {_1W_2}$

= 0.851x182.0 - 0.009x184.12 - 0.842x179.112 + 6.11 = **8.52 kJ**

5.94 Calculate the heat transfer for the process described in Problem 4.44.
Two springs with same spring constant are installed in a massless piston/cylinder with the outside air at 100 kPa. If the piston is at the bottom, both springs are relaxed and the second spring comes in contact with the piston at $V = 2\ m^3$. The cylinder (Fig. P4.44) contains ammonia initially at −2°C, $x = 0.13$, $V = 1\ m^3$, which is then heated until the pressure finally reaches 1200 kPa. At what pressure will the piston touch the second spring? Find the final temperature and the total work done by the ammonia.

Solution :



State 1: P = 399.7 kPa Table B.2.1

v = 0.00156 + 0.13 x 0.3106 = 0.0419

u = 170.52 + 0.13 x 1145.78 = 319.47

m = V/v = 1/0.0419 = 23.866 kg

At bottom state 0: $0\ m^3$, 100 kPa

State 2: V = 2 m^3 and on line 0-1-2

Final state 3: 1200 kPa, on line segment 2.

Slope of line 0-1-2: $\Delta P/\Delta V = (P_1 - P_0)/\Delta V = (399.7-100)/1 = 299.7\ \text{kPa}/m^3$

$$P_2 = P_1 + (V_2 - V_1)\Delta P/\Delta V = 399.7 + (2-1) \times 299.7 = \mathbf{699.4\ kPa}$$

State 3: Last line segment has twice the slope.

$$P_3 = P_2 + (V_3 - V_2)2\Delta P/\Delta V \quad \Rightarrow \quad V_3 = V_2 + (P_3 - P_2)/(2\Delta P/\Delta V)$$

$$V_3 = 2 + (1200-699.4)/599.4 = 2.835\ m^3$$

$$v_3 = v_1V_3/V_1 = 0.0419 \times 2.835/1 = 0.1188\ m^3/kg \quad \Rightarrow \quad T = \mathbf{51°C}$$

$$u_3 = h_3 - P_3v_3 = 1527.92 - 1200 \times 0.1188 = 1385\ kJ/kg$$

$$_1W_3 = {_1W_2} + {_2W_3} = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) + \frac{1}{2}(P_3 + P_2)(V_3 - V_2)$$

$$= 549.6 + 793.0 = \mathbf{1342.6\ kJ}$$

$$_1Q_3 = m(u_3-u_1) + {_1W_3} = 23.866 \times (1385 - 319.47) + 1342.6 = \mathbf{26773\ kJ}$$

5.95 Calculate the heat transfer for the process described in Problem 4.46.

From the solution to problem 4.46, we have state 1 is

saturated liquid @ 50 kPa. The work was found as 346.6 kJ.

$$u_1 = u_f = 340.44\ kJ/kg, \quad P_{lift} = P_2 = 1500\ kPa$$

$$u_2 = u_g(P_2) = 2594.5\ kJ/kg$$

$$_1Q_2 = m(u_2 - u_1) + {_1W_2} = 2 \times (2594.5 - 340.44) + 346.6$$

$$= \mathbf{4854.7\ kJ}$$

5.96 A cylinder fitted with a frictionless piston contains R-134a at 10°C, quality of 50%, and initial volume of 100 L. The external force on the piston now varies in such a manner that the piston moves, increasing the volume. It is noted that the temperature is 25°C when the last drop of liquid R-134a evaporates. The process continues to a final state of 40°C, 600 kPa. Assume the pressure is piecewise linear in volme and determine the final volume in the cylinder and the work and heat transfer for the overall process.

a) The final volume in the cylinder.

b) The work and heat transfer for the overall process.

Solution:

C.V. The mass of R-134a, which goes through process 1 - 2- 3.

Conservation of mass: $m_2 = m_1 = m$;

State 1: Table B.5.1 (10°C, $x_1 = 0.50$) $P = P_{g\ 10C} = 415.8$ kPa

$v_1 = 0.000794 + 0.5(0.04866) = 0.02512\ m^3/kg$

$u_1 = 213.25 + 0.5 \times 170.42 = 298.46$ kJ/kg

$V_1 = 0.1\ m^3 \quad => \quad m = V_1/v_1 = 0.1/0.02512 = 3.981$ kg

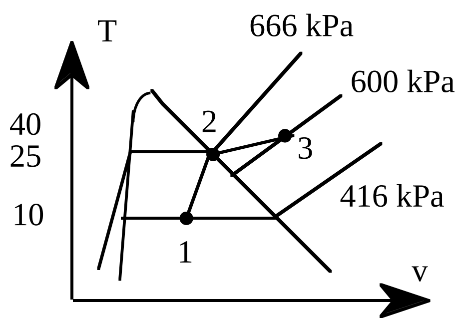
State 2: 25°C, $x_2 = 1.0$: $P = P_{g\ 25C} = 666.3$ kPa

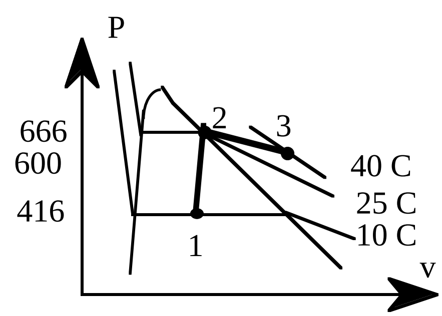
$v_2 = v_{g\ 25C} = 0.03098\ m^3/kg \quad => \quad V_2 = mv_2 = 0.1233\ m^3$

State 3: Table B.5.2 (40°C, 600kPa)

$v_3 = 0.03796\ m^3/kg => \quad V_3 = mv_3 = 0.1511\ m^3$

$u_3 = h_3 - P_3v_3 = 428.88 - 600*0.03796 = 406.11$ kJ/kg





b) $_1W_3 = \int_1^3 P\,dV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) + \frac{1}{2}(P_2 + P_3)(V_3 - V_2) =$

$$= \frac{415.8 + 666.3}{2}(0.1233 - 0.1) + \frac{666.3 - 600}{2}(0.1511 - 0.1233)$$

$= 12.6 + 17.6 =$ **30.2 kJ**

$_1Q_3 = m(u_3 - u_1) + {_1W_3} = 3.981\ (406.11 - 298.46) + 30.2 = 428.4 + 30.2$

$=$ **458.6 kJ**

5.97 A rigid 1-m^3 tank contains butane at 500 K, 100 kPa. The tank is now heated to 1500 K.
a) Is it reasonable to use the specific heat value from Table A.10 to calculate the heat transfer in this process?
b) Calculate the work and the heat transfer for this process.
Solution:

C.V. The amount of butane. This is a control mass of constant volume.

Mass: $m_2 = m_1 = m$; Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = {}_1Q_2$

Process: V = constant. => ${}_1W_2 = 0$. used in energy equation.

a) C_{po} and C_{vo} in Table A.5 are at 300 K. C_4H_{10} is polyatomic so the specific heat is a strong funciton of temperature.

At T_{AVG} = 1000 K Table A.6 $\theta = T/100 = 10$.

$C_{Po} = [3.954 + 37.12\ (10) - 1.833\ (10^2\ ) + 0.03498\ (10^3)\ ]/58.124$

$= 226.834/58.124 = 3.903$ kJ/kg K

$C_{Vo} = C_{Po} - R = 3.903 - 0.143 = 3.76$ kJ/kg

Compare to Table A.5: $C_{Po} = 1.716$; $C_{Vo} = 1.5734$ **Very poor values**

To find the total heat transfer we need the mass, use ideal gas law:

$$m = P_1V/RT_1 = 100 \times 1/(0.143 \times 500) = 1.399 \text{ kg}$$

${}_1Q_2 = m(u_2 - u_1) = m\ C_{Vo}\ (T_2 - T_1) = 1.399 \times 3.76\ (1500 - 500) =$ **5260 kJ**

5.98 A cylinder fitted with a frictionless piston contains 0.2 kg of saturated (both liquid and vapor present) R-12 at -20°C. The external force on the piston is such that the pressure inside the cylinder is related to the volume by the expression:

$$P = -47.5 + 4.0 \times V^{1.5} \quad , \text{ kPa and L}$$

Heat is now transferred to the cylinder until the pressure inside reaches 250 kPa. Calculate the work and heat transfer.

Solution:

C.V. The 0.2 kg of R-12, which is a control mass.

Process: $P = -47.5 + 4.0 \times V^{3/2}$ with P in kPa and V in L.

State 1: Table B.3.1 at -20°C: $P = P_g = 150.9$ kPa.

$$V_1 = [(P_1 + 47.5)/4.0]^{2/3} = (49.6)^{2/3} = 13.5 \text{ L}$$

$$v_1 = \frac{V}{m} = \frac{0.0135}{0.2} = 0.0675 \text{ m}^3\text{/kg} \quad \Rightarrow \quad x = \frac{0.0675 - 0.000685}{0.10862} = 0.6178$$

$$u_1 = 17.71 + 0.6178 * 144.59 = 107.04 \text{ kJ/kg}$$

State 2: 250 kPa and on process line => we can find V and then v.

$$V_2 = [(P_2 + 47.5)/4.0]^{2/3} = (74.375)^{2/3} = 17.685 \text{ L}$$

$$v_2 = 0.017685/0.2 = 0.08843 \text{ m}^3\text{/kg}$$

Table B.3.2 At P_2, v_2: $T_2 \cong 60$°C, $u_2 = 228.65 - 250 * 0.08843 = 206.5$ kJ/kg

$$_1W_2 = \int_1^2 P\,dV = \left[-47.5\,(V_2 - V_1) + \frac{4}{2.5}(V_2^{2.5} - V_1^{2.5})\right]$$

$$= \left[-47.5\,(17.685 - 13.5) + \frac{4}{2.5}(17.685^{2.5} - 13.5^{2.5})\right]/1000 = \mathbf{0.835\ kJ}$$

$$_1Q_2 = m(u_2 - u_1) + {_1W_2} = 0.2\,(206.5 - 107.04) + 0.835 = \mathbf{20.73\ kJ}$$

5.99 A certain elastic balloon will support an internal pressure equal to P_o = 100 kPa until the balloon becomes spherical at a diameter of D_o = 1 m, beyond which

$$P = P_o + C(1-x^6)x \; ; \quad x = D_o/D$$

because of the offsetting effects of balloon curvature and elasticity. This balloon contains helium gas at 250 K, 100 kPa, with a 0.4 m^3 volume. The balloon is heated until the volume reaches 2 m^3. During the process the maximum pressure inside the balloon is 200 kPa.

a. What is the temperature inside the balloon when pressure is maximum?

b. What are the final pressure and temperature inside the balloon?

c. Determine the work and heat transfer for the overall process.

Balloon becomes spherical at $V_0 = (\pi/6) \times (1)^3 = 0.5236 \text{ m}^3$ and the initial mass is

$$m = \frac{P_1V_1}{RT_1} = \frac{100 \times 0.4}{2.07703 \times 250} = 0.077 \text{ kg}$$

a) $$\frac{dP}{dD^*} = C[-D^{*\,-2}_{max} + 7D^{*\,-8}_{max}] = 0 \;\; \text{at } P_{max}$$

$$\text{or } -D^{*\,6}_{max} + 7 = 0 \;, \quad D_{max} = D^*_{max} = 7^{1/6} = 1.38309$$

$$V_{max} = (\pi/6)\, D_{max}^{\;3} = 1.3853 \text{ m}^3, \quad P_{max} = 200 \text{ kPa}$$

$$T_{max} = T_1 \times \frac{P_{max}}{P_1} \times \frac{V_{max}}{V_1} = 250 \times \frac{200}{100} \times \frac{1.3853}{0.4} = \mathbf{1731.6\ K}$$

b) $$200 = 100 + C(1.38309^{-1} - 1.38309^{-7}) \;, \quad => \quad C = 161.36$$

$$V_2 = 2.0 \text{ m}^3 = (\pi/6)\; D_2^{\;3} \quad \rightarrow \quad D_2 = 1.5632 \text{ m}$$

$$P_2 = 100 + 161.36(1.5632^{-1} - 1.5632^{-7}) = \mathbf{196\ kPa}$$

$$T_2 = T_1 \times \frac{P_2}{P_1} \times \frac{V_2}{V_1} = 250 \times \frac{196}{100} \times \frac{2.0}{0.4} = \mathbf{2450\ K}$$

c) $${}_1W_2 = \int_1^2 PdV = P_0(V_0 - V_1) + \int_{V_0}^{V_2} PdV$$

$$= P_0(V_0 - V_1) + P_0(V_2 - V_0) + \int_{V_0}^{V_2} C(D^{*\,-1} - D^{*\,-7})dV$$

$$V = \frac{\pi}{6}D^3, \quad dV = \frac{3\pi}{6}D^2dD = \frac{3\pi}{6}D_o^{\,3}D^{*\,2}dD^*$$

$${}_1W_2 = P_0(V_2 - V_1) + 3CV_0\left[\frac{D^{*\,2}}{2} + \frac{D^{*\,-4}}{4}\right]_{D^*=1}^{D^*=1.563\,19}$$

$$= 100(2 - 0.4) + 3 \times 161.36 \times 0.5236[1.26365 - 0.75] = \mathbf{290.2\ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.077 \times 3.1156(2450 - 250) + 290.2$$

$$= 527.8 + 290.2 = \mathbf{818\ kJ}$$

5.100 A frictionless, thermally conducting piston separates the air and water in the cylinder shown in Fig. P5.100. The initial volumes of A and B are each 500 L, and the initial pressure on each side is 700 kPa. The volume of the liquid in B is 2% of the volume of B at this state. Heat is transferred to both A and B until all the liquid in B evaporates. Notice that $P_A = P_B$ and $T_A = T_B = T_{sat}$ through the process and iterate to find final pressure and then determine the heat transfer.

a) System: Air(A) + H_2O(B)

$$m_B = m_{LIQB1} + m_{VAPB1} = \frac{0.02 \text{x} 0.5}{0.001108} + \frac{0.98 \text{x} 0.5}{0.2729} = 10.821 \text{ kg}$$

$$m_A = \frac{P_1 V_{A1}}{R_A T_{A1}} = \frac{700 \text{ x } 0.5}{0.287 \text{ x } 438.2} = 2.783 \text{ kg}$$

$$\text{At all times: } \begin{cases} T_A = T_B = T_{SAT} & P_A = P_B \\ V_A + V_B = 1 \text{ m}^3 \end{cases}$$

$$\frac{m_A R_A T_{SAT}}{P_2} + m_B v_G = \frac{2.783 \text{ x } 0.287 \text{ x } T_{SAT}}{P_2} + 10.821 v_G = 1.0$$

Assume $P_2 = 2.57$ MPa $\Rightarrow T_{SAT} = 225.4°C$

$$\frac{2.783 \text{ x } 0.287 \text{ x } 498.6}{2570} + 10.821 \text{ x } 0.07812 \approx 1.0$$

$\Rightarrow P_2 = 2.57$ MPa

$$x_{B1} = \frac{m_{VAP\,B1}}{m_B} = \frac{1.796}{10.821} = 0.166; \quad u_{B1} = 696.4 + 0.166 \text{ x } 1876.1 = 1007.9$$

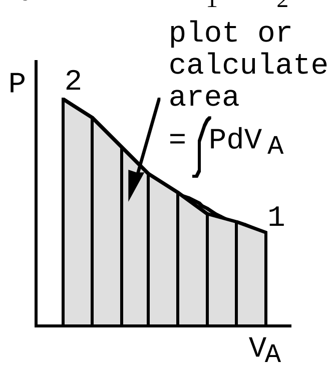
${}_1W_2 = 0$ for system A+B

$${}_1Q_2 = m_A(u_{A2} - u_{A1}) + m_B(u_{B2} - u_{B1})$$

$$= 2.783 \text{ x } 0.717(225.4 - 165) + 10.821(2603.2 - 1007.9) = \mathbf{17383 \text{ kJ}}$$

b) System: Air(A) only

At any P between P_1 & P_2, $T = T_{SAT}$ for H_2O



P(kPa)	T(K)	$V_A(m^3) = \frac{m_A R_A T}{P}$
700	438.2	0.50
900	448.6	0.3981
1200	461.2	0.3070
1500	471.5	0.2511
2000	485.6	0.1939
2570	498.6	0.1550

$$W_A = \int P dV_A = \mathbf{-441.6 \text{ kJ}}$$

$$Q_A = 2.783 \text{ x } 0.717(225.4 - 165) - 441.6 = \mathbf{-321.2 \text{ kJ}}$$

5.101 A closed, vertical cylinder is divided into two parts A and B by a thermally non-conducting frictionless piston. The upper part A contains air at ambient temperature, 20C, and the initial volume is 150 L. The lower part B contains R-134a at -15C, quality 20%, and initial volume of 50L. Heat is now transferred from a heat source to part B, causing the piston to move upward until the volume of B reaches 145L. Neglect the piston mass, such that the pressures in A and B are always equal and assume the temperature in A remains constant during the process.

a) What is the final pressure in A and the final temperature in B.

b) Calculate the work done by the R-134a during the process.

c) calculate the heat transfer to the R-134a during the process.

d) What is the heat transfer to (or from) the air in A?

Solution:

Consider first the pressure and the volumes

$P_{A1} = P_{B1} = P_g$ at -15C = 165 kPa from Table B.5.1

$V_{A1} = 0.150\ m^3$, $V_{B1} = 0.05\ m^3$, $V_{B2} = 0.145\ m^3$

$V_{A2} = 0.150 + 0.050 - 0.145 = 0.055\ m^3$

Since T_A is constant and air is an ideal gas we have

$P_{A1}V_{A1} = P_{A2}V_{A2} = mRT_A$ => $P_{A2} = 165 \times 0.150/0.055 =$ **450 kPa**

State B1: $v_{B1} = 0.000746 + 0.2 \times 0.11932 = 0.02461$

$u_{B1} = 180.1 + 0.2 \times 189.3 = 218.0$

$m = V_{B1}/v_{B1} = 0.05/0.02461 = 2.0317$ kg

$v_{B2} = V_{B2}/m = 0.145/2.0317 = 0.07137\ m^3/kg$

State B2: $P_{B2} = P_{A2} = 450$ kPa, v => $T_{B2} = 128.6$ C

$u_{B2} = h_{B2} - P_{B2}v_{B2} = 517.8 - 450*0.07137 = 485.7$ kJ/kg

As the piston moves the two work terms are related

$W_B = -W_A = - \int P_A\ dV_A = - P_{A1}V_{A1} \ln(V_{A2}/V_{A1})$

$= - 165 \times 0.150 \ln(0.055/0.15) =$ **24.8 kJ**

Notice: The approximation $W_B = 0.5(P_{B2}+P_{B1})(V_{B2}-V_{B1})$ gives an error of 18%

The energy equation for B becomes

$Q_B = m_B (u_{B2} - u_{B1}) + W_B = 2.0317(485.7 - 218) + 24.8 =$ **568.7 kJ**

The enrgy equation for A becomes

$Q_A = m_A(u_{A2} - u_{A1}) + W_A = 0 - 24.8 =$ **-24.8 kJ**

English Unit Problems

5.102E A hydraulic hoist raises a 3650 lbm car 6 ft in an auto repair shop. The hydraulic pump has a constant pressure of 100 lbf/in.^{2} on its piston. What is the increase in potential energy of the car and how much volume should the pump displace to deliver that amount of work?

Solution: C.V. Car.

No change in kinetic or internal energy of the car, neglect hoist mass.

$$E_2 - E_1 = PE_2 - PE_1 = mg\,(Z_2 - Z_1) = \frac{3650 \times 32.174 \times 6}{32.174} = 21900 \text{ lbf-ft}$$

The increase in potential energy is work into car from pump at constant P.

$$W = E_2 - E_1 = \int P\,dV = P\,\Delta V \qquad \Rightarrow$$

$$\Delta V = (E_2 - E_1) / P = 21900/(100 \text{ x } 144) = \mathbf{1.52\ ft^3}$$

5.103E A piston motion moves a 50 lbm hammerhead vertically down 3 ft from rest to a velocity of 150 ft/s in a stamping machine. What is the change in total energy of the hammerhead?

Solution: C.V. Hammerhead

The hammerhead does not change internal energy i.e. same P,T

$$E_2 - E_1 = m(u_2 - u_1) + m((1/2)V_2^{\ 2} - 0) + mg\,(h_2 - 0)$$

$$= [\ 50 \text{ x } (1/2) \text{ x} 150^2 + 50 \text{ x } 32.174 \text{ x } (-3)]/32.174$$

$$= [562500 - 4826]/32.174 = 17333 \text{ lbf-ft}$$

$$= 17333/778 = \mathbf{22.28\ Btu}$$

5.104E Find the missing properties and give the phase of the substance.

a. H_2O $u = 1000$ Btu/lbm, $T = 270$ F $h = ?$ $v = ?$ $x = ?$
b. H_2O $u = 450$ Btu/lbm, $P = 1500$ lbf/in.^{2} $T = ?$ $x = ?$ $v = ?$
c. R-22 $T = 30$ F, $P = 75$ lbf/in.^{2} $h = ?$ $x = ?$
d. R-134a $T = 140$ F, $h = 185$ Btu/lbm $v = ?$ $x = ?$
e. NH_3 $T = 170$ F, $P = 60$ lbf/in.^{2} $u = ?$ $v = ?$ $x = ?$

Solution:

a) Table C.8.1: $u_f < u < u_g$ => 2-phase mixture of liquid and vapor

$x = (u - u_f)/ u_{fg} = (1000 - 238.81)/854.14 =$ **0.8912**

$v = v_f + x\ v_{fg} = 0.01717 + 0.8912 \text{ x } 10.0483 =$ **8.972 ft^3/lbm**

$h = h_f + x\ h_{fg} = 238.95 + 0.8912 \text{ x } 931.95 =$ **1069.5 Btu/lbm**

$(= 1000 + 41.848 \text{ x } 8.972 \text{ x } 144/778)$

b) Table C.8.1: $u < u_f$ so compressed liquid B.1.3, x = **undefined**

T = **471.8 F**, v = **0.019689 ft^3/lbm**

c) Table B.3.1: P > Psat => x = **undef**, **compr. liquid**

Approximate as saturated liquid at same T, $h \cong h_f =$ **18.61 Btu/lbm**

d) Table C.11.1: h > hg => x = **undef**, **superheated vapor** C.11.2,

find it at given T between saturated 243.9 psi and 200 psi to match h:

$$v \cong 0.1836 + (0.2459 - 0.1836)\times\frac{185- 183.63}{186.82-183.63} = \mathbf{0.2104\ ft^3/lbm}$$

$$P \cong 243.93 + (200 - 243.93)\times\frac{185- 183.63}{186.82-183.63} = \mathbf{225\ lbf/in^2}$$

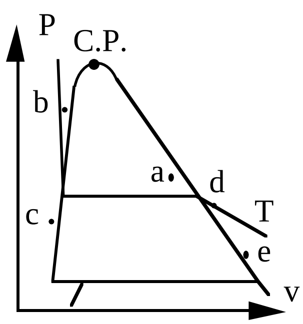
e) Table C.9.1: $P < P_{sat}$ $\Rightarrow$ x = **undef.** **superheated vapor** C.9.2,

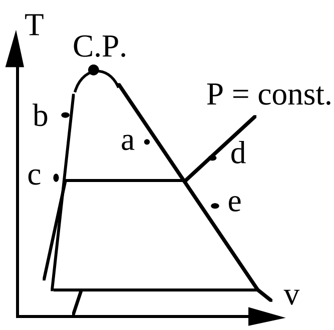
v = (6.3456 + 6.5694)/ 2 = **6.457 ft^3/lbm**

u = h-Pv = (1/2)(694.59 + 705.64) – 60 x 6.4575 x (144/778)

= 700.115 – 71.71 = **628.405 Btu/lbm**

States shown are placed relative to the two-phase region, not to each other.





5.105E Find the missing properties among (P, T, v, u, h) together with x, if applicable, and give the phase of the substance.

a. R-22 T = 50 F, u = 85 Btu/lbm
b. H_2O T = 600 F, h = 1322 Btu/lbm
c. R-22 P = 150 lbf/in.^{2}, h = 115.5 Btu/lbm
d. R-134a T = 100 F, u = 175 Btu/lbm
e. NH_3 T = 70 F, v = 2 ft^3/lbm

Solution:

a) Table C.10.1: $u < u_g$ => L+V mixture, P = **98.727 lbf/in^2**

$x = (85 - 24.04)/ 74.75 =$ **0.8155**

$v = 0.01282 + 0.8155\times0.5432 =$ **0.4558 ft^3/lbm**

$h = 24.27 + 0.8155\times84.68 =$ **93.33 Btu/lbm**

b) Table C.8.1: $h > h_g$ => superheated vapor follow 600 F in C.8.2

$P \cong$ **200 lbf/in^2** ; $v =$ **3.058 ft^3/lbm ;** $u =$ **1208.9 Btu/lbm**

c) Table C.10.1: $h > h_g$ => superheated vapor so in C.10.2

$T \cong$ **100 F** ; $v =$ **0.3953 ft^3/lbm**

$$u = h - Pv = 115.5 – 150 \times 0.3953 \times \frac{144}{778} = \mathbf{104.5\ Btu/lbm}$$

d) Table C.11.1: : $u > u_g$ => **sup. vap.,** calculate u at some P to end with

$P \approx$ **55 lbf/in^2** ; $v \approx$ **0.999 ft^3/lbm;** $h =$ **185.2 Btu/lbm**

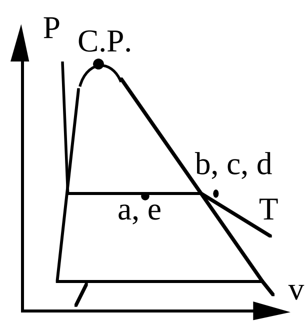
e) Table C.9.1: $v < v_g$ => L+V mixture, P = **128.8 lbf/in^2**

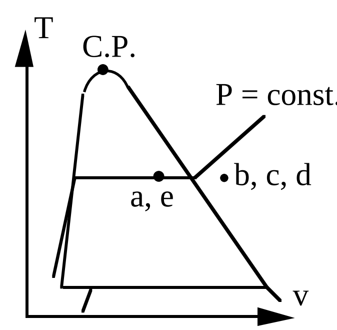
$x = (2 - 0.02631)/ 2.2835 =$ **0.864**

$h = 120.21 + 0.864\times507.89 =$ **559.05 Btu/lbm**

$u = 119.58 + 0.864\times453.44 =$ **511.4 Btu/lbm**

States shown are placed relative to the two-phase region, not to each other.





5.106E Water in a 6-ft^3 closed, rigid tank is at 200 F, 90% quality. The tank is then cooled to 20 F. Calculate the heat transfer during the process.

Solution:

C.V.: Water in tank. $m_2 = m_1$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: V = constant, $v_2 = v_1$, ${}_1W_2 = 0$

State 1: $v_1 = 0.01663 + 0.9 \times 33.6146 = 30.27$ ft^3/lbm

$u_1 = 168.03 + 0.9 \times 906.15 = 983.6$ Btu/lbm

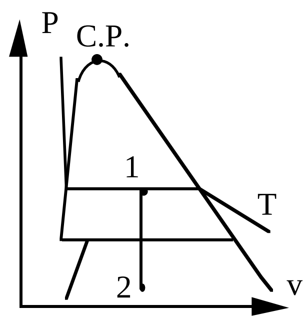
State 2: T_2, $v_2 = v_1$ $\Rightarrow$ mix of sat. solid + vap. Table C.8.4

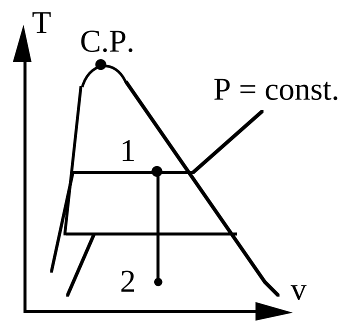
$v_2 = 30.27 = 0.01744 + x_2 \times 5655$ => $x_2 = 0.00535$

$u_2 = -149.31 + 0.00535 \times 1166.5 = -143.07$ Btu/lbm

$m = V/v_1 = 6 / 30.27 = 0.198$ lbm

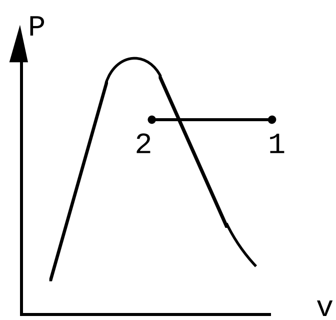
${}_1Q_2 = m(u_2 - u_1) = 0.198\ (-143.07 - 983.6) =$ **-223 Btu**





5.107E A cylinder fitted with a frictionless piston contains 4 lbm of superheated refrigerant R-134a vapor at 400 lbf/in.^{2}, 200 F. The cylinder is now cooled so the R-134a remains at constant pressure until it reaches a quality of 75%. Calculate the heat transfer in the process.

Solution:



C.V.: R-134a

$m_2 = m_1$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: P = const. $\Rightarrow$ ${}_1W_2 = \int PdV$

${}_1W_2 = P(V_2 - V_1) = Pm(v_2 - v_1)$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$

$= m(u_2 - u_1) + Pm(v_2 - v_1) = m(h_2 - h_1)$

State 1: Table C.11.2 $h_1 = 192.92$ Btu/lbm

State 2: Table C.11.1 $h_2 = 140.62 + 0.75 \times 43.74 = 173.425$ Btu/lbm

${}_1Q_2 = 4 \times (173.425 – 192.92) =$ **-77.98 Btu**

5.108E Ammonia at 30 F, quality 60% is contained in a rigid 8-ft^3 tank. The tank and ammonia are now heated to a final pressure of 140 lbf/in.^{2}. Determine the heat transfer for the process.

Solution:

C.V.: NH_3

$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

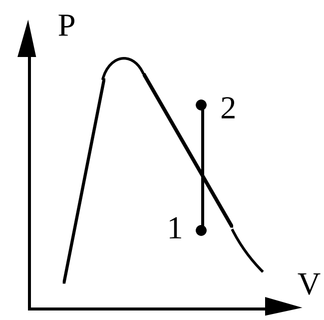
Process: Constant volume $\Rightarrow v_2 = v_1$ & ${}_1W_2 = \emptyset$

State 1: Table C.9.1

$v_1 = 0.02502 + 0.6 \times 4.7978 = 2.904$ ft^3/lbm

$u_1 = 75.06 + 0.6 \text{ x } 491.17 = 369.75$ Btu/lbm

$m = V/v_1 = 8/2.904 = 2.755$ lbm



State 2: P_2 , $v_2 = v_1$ $\Rightarrow$ $T_2 \cong 215$ F

$u_2 = h_2 - P_2v_2 = 717.61 - 140 \times 2.904 \times 144/778 = 642.36$ Btu/lbm

${}_1Q_2 = 2.755 \times (642.36 - 369.75) =$ **751 Btu**

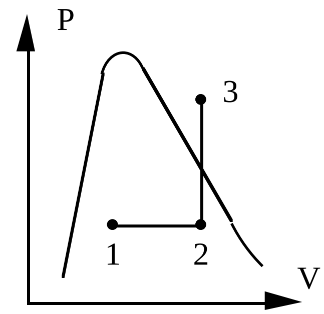
5.109E A vertical cylinder fitted with a piston contains 10 lbm of R-22 at 50 F, shown in Fig. P5.20. Heat is transferred to the system causing the piston to rise until it reaches a set of stops at which point the volume has doubled. Additional heat is transferred until the temperature inside reaches 120 F, at which point the pressure inside the cylinder is 200 lbf/in.^{2}.

a. What is the quality at the initial state?

b. Calculate the heat transfer for the overall process.

C.V. R-22. Control mass goes through process: 1 -> 2 -> 3

As piston floats pressure is constant (1 -> 2) and the volume is constant for the second part (2 -> 3)



So we have: $v_3 = v_2 = 2 \times v_1$

State 3: Table C.10.2 (P,T) $v_3 = 0.2959\ ft^3/lbm$

$u_3 = h - Pv = 117.0 - 200\times0.2959\times144/778$
$= 106.1$ Btu/lbm

So we can determine state 1 and 2 Table C.10.1:

$v_1 = 0.14795 = 0.01282 + x_1(0.5432)$ => $x_1 =$ **0.249**

$u_1 = 24.04 + 0.249\times74.75 = 42.6$ Btu/lbm

State 2: $v_2 = 0.2959\ ft^3/lbm$, $P_2 = P_1 = 98.7$ psia, this is still 2-phase.

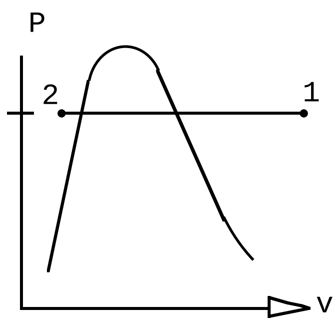
$${}_1W_3 = {}_1W_2 = \int_1^2 PdV = P_1(V_2 - V_1)$$

$$= 98.7 \times 10(0.295948 - 0.147974) \times 144/778 = 27.0 \text{ Btu}$$

${}_1Q_3 = m(u_3 - u_1) + {}_1W_3 = 10(106.1 - 42.6) + 27.0 =$ **662 Btu**

5.110E Twenty pound-mass of water in a piston/cylinder with constant pressure is at 1100 F and a volume of 22.6 ft^3. It is now cooled to 100 F. Show the *P–v* diagram and find the work and heat transfer for the process.

Solution:



Constant pressure ⇒ ${}_1W_2 = mP(v_2 - v_1)$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1)$

Properties from Table C.8.2 and C.8.3

State 1: $v_1 = 22.6/20 = 1.13\ ft^3/lbm$

$P_1 = 800\ lbf/in^2$, $h_1 = 1567.8$

State 2: 800 lbf/in^2, 100 F

⇒ $v_2 = 0.016092$, $h_2 = 70.15$ Btu/lbm

${}_1W_2 = 20 \times 800 \times(0.016092 - 1.13) \times 144/778 =$ **-3299 Btu**

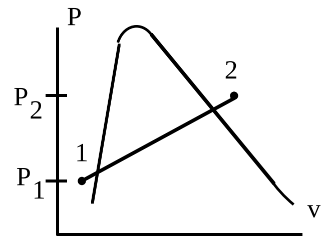
${}_1Q_2 = 20 \times(70.15 - 1567.8) =$ **-29953 Btu**

5.111E A piston/cylinder contains 2 lbm of liquid water at 70 F, and 30 lbf/in.^{2}. There is a linear spring mounted on the piston such that when the water is heated the pressure reaches 300 lbf/in.^{2} with a volume of 4 ft^3. Find the final temperature and plot the *P-v* diagram for the process. Calculate the work and the heat transfer for the process.

Solution:

Take CV as the water.

$m_2 = m_1 = m$; $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$



State 1: Compr. liq., use sat. liq. same T, Table C.8.1

$v = v_f = 0.01605$, $u = u_f = 38.09$ Btu/lbm

State 2: $v = V/m = 4/2 = 2$ ft^3/lbm and P = 300 psia

=> Sup. vapor T = 600 F ; u = 1203.2 Btu/lbm

Work is done while piston moves at linearly varying pressure, so we get

$${}_1W_2 = \int P\,dV = P_{avg}(V_2 - V_1) = 0.5x(30+3000)(4 - 0.0321)\ \frac{144}{778} = \mathbf{121.18\ Btu}$$

Heat transfer is found from energy equation

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2 \text{ x } (1203.2 - 38.09) + 121.18 = \mathbf{2451.4\ Btu}$$

5.112E A piston/cylinder arrangement has the piston loaded with outside atmospheric pressure and the piston mass to a pressure of 20 lbf/in.^{2}, shown in Fig P5.28. It contains water at 25 F, which is then heated until the water becomes saturated vapor. Find the final temperature and specific work and heat transfer for the process.

Solution:

C.V. Water in the piston cylinder.

Continuity: $m_2 = m_1$, Energy: $u_2 - u_1 = {}_1q_2 - {}_1w_2$

Process: P = const. = P_1, => ${}_1w_2 = \int_1^2 P\,dv = P_1(v_2 - v_1)$

State 1: T_1 , P_1 => Table C.8.4 compressed solid, take as saturated solid.

$v_1 = 0.01746$ ft^3/lbm, $u_1 = -146.84$ Btu/lbm

State 2: x = 1, $P_2 = P_1 = 20$ psia due to process => Table C.8.1

$v_2 = v_g(P_2) = 20.09$ ft^3/lbm, $T_2 =$ **228 F** ; $u_2 = 1082$ Btu/lbm

${}_1w_2 = P_1(v_2 - v_1) = 20(20.09 - 0.01746) \times 144/778 =$ **74.3 Btu/lbm**

${}_1q_2 = u_2 - u_1 + {}_1w_2 = 1082 - (-146.84) + 74.3 =$ **1303 Btu/lbm**

5.113E A piston/cylinder contains 2 lbm of water at 70 F with a volume of 0.1 ft^3, shown in Fig. P5.35. Initially the piston rests on some stops with the top surface open to the atmosphere, *P*o, so a pressure of 40 lbf/in.^{2} is required to lift it. To what temperature should the water be heated to lift the piston? If it is heated to saturated vapor find the final temperature, volume, and the heat transfer.

Solution:

C.V. Water. This is a control mass.

$$m_2 = m_1 = m ; \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$$

State 1: 20 C, $v_1 = V/m = 0.1/2 = 0.05$ ft^3/lbm

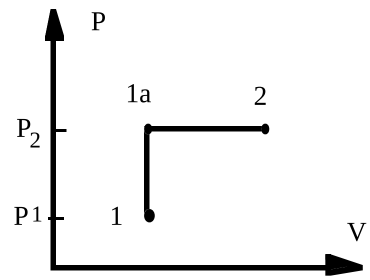
$x = (0.05 - 0.01605)/867.579 = 0.0003913$

$u_1 = 38.09 + 0.0003913 \times 995.64 = 38.13$ Btu/lbm

To find state 2 check on state 1a:

$P = 40$ psia, $v = v_1 = 0.05$ ft^3/lbm

Table C.8.1: $v_f < v < v_g = 10.501$



State 2 is saturated vapor at 40 psia as state 1a is two-phase. T_2 = **267.3 F**

$v_2 = v_g = 10.501$ ft^3/lbm , $V_2 = m\, v_2 = 21.0$ ft^3, $u_2 = u_g = 1092.27$ Btu/lbm

Pressure is constant as volume increase beyond initial volume.

${}_1W_2 = \int P\, dV = P_{lift} (V_2 - V_1) = 40\ (21.0 – 0.1) \times 144 / 778 = 154.75$ Btu

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2\ (1092.27 – 38.13) + 154.75 =$ **2263 Btu**

5.114E Two tanks are connected by a valve and line as shown in Fig. P5.38. The volumes are both 35 ft^3 with R-134a at 70 F, quality 25% in A and tank B is evacuated. The valve is opened and saturated vapor flows from A into B until the pressures become equal. The process occurs slowly enough that all temperatures stay at 70 F during the process. Find the total heat transfer to the R-134a during the process.

C.V.: A + B

State 1A: Table C.11.1, $u_{A1} = 98.27 + 0.25 \times 69.31 = 115.6$ Btu/lbm

$v_{A1} = 0.01313 + 0.25 \times 0.5451 = 0.1494$ ft^3/lbm => $m_{A1} = V_A/v_{A1} = 234.3$ lbm

Process: Constant T and total volume. $m_2 = m_{A1}$; $V_2 = V_A + V_B = 70$ ft^3

State 2: T_2 , $v_2 = V_2/m_2 = 70/234.3 = 0.2988$ ft^3/lbm =>

$x_2 = (0.2988 - 0.01313)/0.5451 = 0.524$; $u_2 = 98.27 + 0.524 * 69.31 = 134.6$

$${}_1Q_2 = m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} + {}_1W_2 = m_2(u_2 - u_{A1})$$

$$= 234.3 \times (134.6 - 115.6) = \textbf{4452 Btu}$$

5.115E A water-filled reactor with volume of 50 ft^3 is at 2000 lbf/in.^{2}, 560 F and placed inside a containment room, as shown in Fig. P5.41. The room is well insulated and initially evacuated. Due to a failure, the reactor ruptures and the water fills the containment room. Find the minimum room volume so the final pressure does not exceed 30 lbf/in.^{2}.

C.V.: Containment room and reactor.

Mass: $m_2 = m_1 = V_{reactor}/v_1 = 50/0.02172 = 2295.7$ lbm

Energy $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = \emptyset \;\Rightarrow\; u_2 = u_1 = 552.5$ Btu/lbm

State 2: 30 lbf/in.^{2}, $u_2 < ug \;\Rightarrow$ 2 phase Table C.8.1

$$u = 552.5 = 218.48 + x_2\, 869.41 \quad\Rightarrow\quad x_2 = 0.3842$$

$v_2 = 0.017 + 0.3842 \text{ x } 13.808 = 5.322$ ft^3/lbm

$V_2 = mv_2 = 2295.7 \text{ x } 5.322 =$ **12218 ft^3**

5.116E A piston/cylinder arrangement of initial volume 0.3 ft^3 contains saturated water vapor at 360 F. The steam now expands in a polytropic process with exponent *n* = 1 to a final pressure of 30 lbf/in.^{2}, while it does work against the piston. Determine the heat transfer in this process.

C.V. Water. This is a control mass.

State 1: Table C.8.1 P = 152.93 psia, $u_1 = 1111.4$ Btu/lbm

$v_1 = 2.961$ ft^3/lbm => $m = V/v_1 = 0.3/2.961 = 0.101$ lbm

Process: $Pv = \text{const.} = P_1v_1 = P_2v_2$; polytropic process n = 1.

$$\Rightarrow v_2 = v_1P_1/P_2 = 2.961 \times 152.93 / 30 = 15.094 \text{ ft}^3\text{/lbm}$$

State 2: P_2, v_2 Table C.8.2 $\Rightarrow$ $T_2 \cong 313.4$ F, $u_2 = 1112$ Btu/lbm

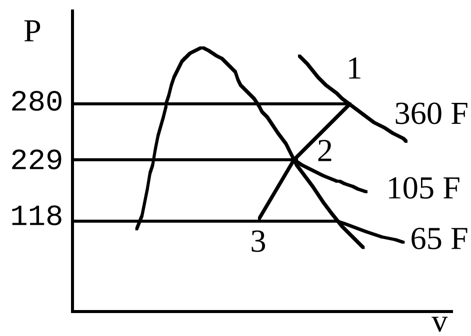
$${}_1W_2 = \int PdV = P_1V_1 \ln\frac{v_2}{v_1} = 152.93 \times 0.3 \times \frac{144}{778} \times \ln\frac{15.094}{2.961} = 13.79 \text{ Btu}$$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.101 \times (1112 - 1111.4) + 13.79 =$ **13.85 Btu**

5.117E Calculate the heat transfer for the process described in Problem 4.72.

A cylinder containing 2 lbm of ammonia has an externally loaded piston. Initially the ammonia is at 280 lbf/in.^{2}, 360 F and is now cooled to saturated vapor at 105 F, and then further cooled to 65 F, at which point the quality is 50%. Find the total work for the process, assuming a piecewise linear variation of *P* versus *V*.

Solution:



State 1: (T, P) Table C.9.2

$v_1 = 1.7672$ ft^3/lbm

State 2: (T, x) Table C.9.1 sat. vap.

$P_2 = 229$ psia, $v_2 = 1.311$ ft^3/lbm

State 3: (T, x) $P_3 = 118$ psia,

$v_3 = (0.02614+2.52895)/2 = 1.2775$

$u_3 = (113.96 + 572.29)/2 = 343.1$

$$_1W_3 = \int_1^3 PdV \approx \left(\frac{P_1 + P_2}{2}\right)m(v_2 - v_1) + \left(\frac{P_2 + P_3}{2}\right)m(v_3 - v_2)$$

$$= 2\left[\left(\frac{280 + 229}{2}\right)(1.311 - 1.7672) + \left(\frac{229 + 118}{2}\right)(1.2775 - 1.311)\right] \frac{144}{778} = \mathbf{-45.1\ Btu}$$

$$1: P_1,T_1 \;\Rightarrow\; u_1 = h_1 - P_1v_1 = 794.94 - 280 \times 1.767 \times \frac{144}{778} = 703.36$$

$$_1Q_3 = 2(343.1 - 703.36) - 45.1 = \mathbf{-766\ Btu}$$

5.118E Ammonia, NH_3, is contained in a sealed rigid tank at 30 F, *x* = 50% and is then heated to 200 F. Find the final state P_2, u_2 and the specific work and heat transfer.

Solution:

Cont.: $m_2 = m_1$; Energy: $E_2 - E_1 = {}_1Q_2$; $({}_1W_2 = 0)$

State 1: Table C.9.1, $u_1 = 75.06 + 0.5 \times 491.17 = 320.65$ Btu/lbm

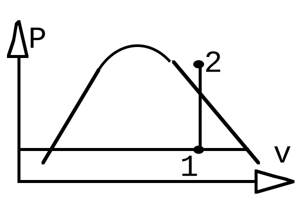
Process: Const. volume $v_2 = v_1 = 0.02502 + 0.5 \times 4.7945 = 2.422$ ft^3/lbm

State 2: v_2 , T_2 Table C.9.2

$\Rightarrow$ sup. Vap. Between 150 psia and 175 psia

$P_2 = 163$ lbf/in^2, $h_2 = 706.6$ linear interpolation

$u_2 = h_2 - P_2v_2 = 706.6 - 163 \times 2.422 \times 144/778 = 633.5$



$$_1w_2 = \mathbf{0}\ ; \qquad _1q_2 = u_2 - u_1 = 633.5 - 320.65 = \mathbf{312.85\ Btu/lbm}$$

5.119E A car with mass 3250 lbm drives with 60 mi/h when the brakes are applied to quickly decrease its speed to 20 mi/h. Assume the brake pads are 1 lbm mass with heat capacity of 0.2 Btu/lbm R and the brake discs/drums are 8 lbm steel where both masses are heated uniformly. Find the temperature increase in the brake assembly.

C.V. Car. Car looses kinetic energy and brake system gains internal u.

No heat transfer (short time) and no work term.

$$m = \text{constant}; \qquad E_2 - E_1 = 0 - 0 = m_{car}\,\tfrac{1}{2}(V_2^2 - V_1^2) + m_{brake}(u_2 - u_1)$$

The brake system mass is two different kinds so split it, also use C_v since we do not have a u table for steel or brake pad material.

$$m_{steel}\, C_v\, \Delta T \;+ m_{pad}\, C_v\, \Delta T \;= m_{car}\,\tfrac{1}{2}(V_2^2 - V_1^2)$$

$$(8\times0.11 + 1\times0.2)\ \Delta T = 3250 \times0.5\times3200\times1.46667^2\ /(32.174\times778) = 446.9 \text{ Btu}$$

$$\Rightarrow \qquad \Delta T = \mathbf{414\ F}$$

5.120E A copper block of volume 60 in.^{3} is heat treated at 900 F and now cooled in a 3-ft^3 oil bath initially at 70 F. Assuming no heat transfer with the surroundings, what is the final temperature?

C.V. Copper block and the oil bath.

$$m_{met}(u_2 - u_1)_{met} + m_{oil}(u_2 - u_1)_{oil} = {}_1Q_2 - {}_1W_2 = \emptyset$$

solid and liquid $\quad \Delta u \cong C_V\Delta T$

$$m_{met}C_{Vmet}(T_2 - T_{1,met}) + m_{oil}C_{Voil}(T_2 - T_{1,oil}) = \emptyset$$

$$m_{met} = V\rho = 60\times12^{-3} \times 555 = 19.271 \text{ lbm}$$

$$m_{oil} = V\rho = 3.5 \times 57 = 199.5 \text{ lbm}$$

Energy equation becomes

$$19.271 \times 0.092(T_2 - 900) + 199.5 \times 0.43(T_2 - 70) = \emptyset$$

$$\Rightarrow \; T_2 = \mathbf{86.8\ F}$$

5.121E An insulated cylinder is divided into two parts of 10 ft^3 each by an initially locked piston. Side A has air at 2 atm, 600 R and side B has air at 10 atm, 2000 R as shown in Fig. P5.64. The piston is now unlocked so it is free to move, and it conducts heat so the air comes to a uniform temperature $T_A = T_B$. Find the mass in both A and B and also the final T and P.

C.V. A + B . Then $_1Q_2 = \emptyset$, $_1W_2 = \emptyset$.

Force balance on piston: $P_A A = P_B A$, so final state in A and B is the same.

State 1A: $u_{A1} = 102.457$; $m_A = \frac{PV}{RT} = \frac{29.4 \times 10 \times 144}{53.34 \times 600} =$ **1.323 lbm**

State 1B: $u_{B1} = 367.642$; $m_B = \frac{PV}{RT} = \frac{147 \times 10 \times 144}{53.34 \times 2000} =$ **1.984 lbm**

$m_A(u_2 - u_1)_A + m_B(u_2 - u_1)_B = \emptyset$

$(m_A + m_B)u_2 = m_A u_{A1} + m_B u_{B1}$

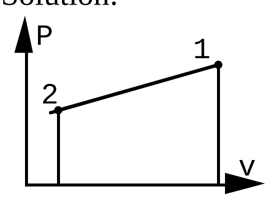
$= 1.323 \times 102.457 + 1.984 \times 367.642 = 864.95$ Btu

$u_2 = 864.95/3.307 = 261.55 \quad \Rightarrow \quad T_2 =$ **1475 R**

$P = m_{tot}RT_2/V_{tot} = \frac{3.307 \times 53.34 \times 1475}{20 \times 144} =$ **90.34 lbf/in²**

5.122E A cylinder with a piston restrained by a linear spring contains 4 lbm of carbon dioxide at 70 lbf/in.², 750 F. It is cooled to 75 F, at which point the pressure is 45 lbf/in.². Calculate the heat transfer for the process.

Solution:



Linear spring gives

$$_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$_1Q_2 = m(u_2 - u_1) + {}_1W_2$$

Equation of state: PV = mRT

State 1: $V_1 = mRT_1/P_1 = \frac{4 \times 35.1 \times (750 + 460)}{70 \times 144} = 16.85\ ft^3$

State 2: $V_2 = mRT_2/P_2 = \frac{4 \times 35.1 \times (75 + 460)}{45 \times 144} = 11.59\ ft^3$

$$_1W_2 = \frac{1}{2}(70 + 45)(11.59 - 16.85) \text{ x}144/778 = -55.98 \text{ Btu}$$

From Table C.7

$C_p(T_{avg}) = [(6927-0)/(1200-537)]/M = 10.45/44.01 = 0.2347$ Btu/lbm R

$\Rightarrow \; C_V = C_p - R = 0.2375 - 35.10/778 = 0.1924$

$_1Q_2 = mC_V(T_2 - T_1) + {}_1W_2 = 4\text{x } 0.1924(75 - 750) - 55.98 =$ **-575.46 Btu**

5.123E A piston/cylinder in a car contains 12 in.^{3} of air at 13 lbf/in.^{2}, 68 F, shown in Fig. P5.66. The air is compressed in a quasi-equilibrium polytropic process with polytropic exponent n = 1.25 to a final volume six times smaller. Determine the final pressure, temperature, and the heat transfer for the process.

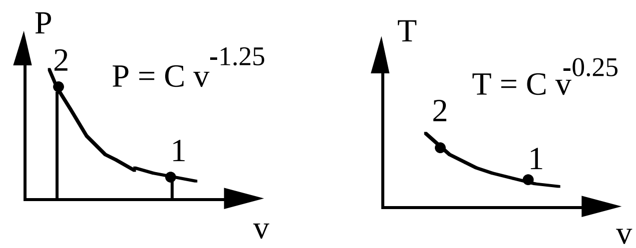
C.V. Air. This is a control mass going through a polytropic process.

Cont.: $m_2 = m_1$; Energy: $E_2 - E_1 = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: Pv^n = const. ; Ideal gas: $Pv = RT$

$$P_1v_1^n = P_2v_2^n \;\Rightarrow\; P_2 = P_1\left(\frac{v_1}{v_2}\right)^n = 13 \times (6)^{1.25} = \mathbf{122.08\ lbf/in^2}$$

$$T_2 = T_1(P_2v_2/P_1v_1) = 527.67(122.08/13 \times 6) = \mathbf{825.9\ R}$$



$$m = \frac{PV}{RT} = \frac{13 \times 12 \times 12^{-1}}{53.34 \times 527.67} = 4.619{\times}10^{-4}\ \text{lbm}$$

$${}_1w_2 = \int P dv = \frac{1}{1 - n}(P_2v_2 - P_1v_1) = \frac{R}{1 - n}(T_2 - T_1)$$

$$= 53.34 \left(\frac{825.9 - 527.67}{(1 - 1.25) \times 778}\right) = -81.79\ \text{Btu/lbm}$$

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = 141.64 - 90.05 - 81.79 = -30.2\ \text{Btu/lbm}$$

$${}_1Q_2 = m\ {}_1q_2 = 4.619{\times}10^{-4} \times (-30.2) = \mathbf{-0.0139\ Btu}$$

5.124E Water at 70 F, 15 lbf/in.^{2}, is brought to 30 lbf/in.^{2}, 2700 F. Find the change in the specific internal energy, using the water table and the ideal gas water table in combination.

State 1: Table C.8.1 $\quad u_1 \cong u_f = 38.09$

State 2: Highest T in Table C.8.2 is 1400 F

Using a Δu from the ideal gas table C.7, we get

$\bar{h}_{2700} - \bar{h}_{2000} = 26002 - 11769 = 14233$ Btu/lbmol= 790 Btu/lbm

$u_{2700} - u_{1400} = \Delta h - R(2700 - 1400) = 790 - 53.34 \times$ **Error! Reference source not found.** = 700.9

Since ideal gas change is at low P we use 1400 F, lowest P available 1 lbf/in^2 from steam tables, C.8.2, $\quad u_x = 1543.1$ Btu/lbm as the reference.

$u_2 - u_1 = (u_2 - u_x)_{ID.G.} + (u_x - u_1)$

$= 700.9 + 1543.1 - 38.09 =$ **2206 Btu/lbm**

5.125E Air in a piston/cylinder at 30 lbf/in.^{2}, 1080 R, is shown in Fig. P5.69. It is expanded in a constant-pressure process to twice the initial volume (state 2). The piston is then locked with a pin, and heat is transferred to a final temperature of 1080 R. Find *P*, *T*, and *h* for states 2 and 3, and find the work and heat transfer in both processes.

C.V. Air. Control mass $\quad m_2 = m_3 = m_1$

$1 \rightarrow 2$: $\quad u_2 - u_1 = {}_1q_2 - {}_1w_2$; $\quad {}_1w_2 = \int P dv = P_1(v_2 - v_1) = R(T_2 - T_1)$

Ideal gas $Pv = RT \Rightarrow T_2 = T_1 v_2/v_1 = 2T_1 =$ **2160 R**

$P_2 = P_1 = 30$ lbf/in^2 , $h_2 = 549.357 \quad {}_1w_2 = RT_1 = 74.05$ Btu/lbm

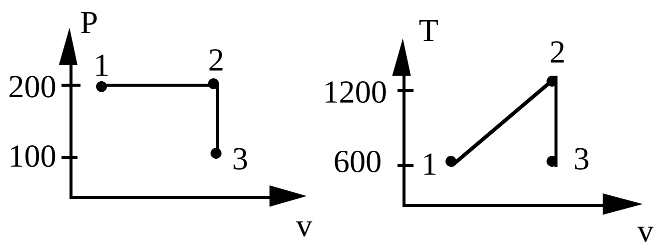
Table C.6 $\qquad$ **h_2 = 549.357 Btu/lbm**, $\qquad$ **$h_3 = h_1$ = 261.099 Btu/lbm**

${}_1q_2 = u_2 - u_1 + {}_1w_2 = h_2 - h_1 = 549.357 - 261.099 =$ **288.26 Btu/lbm**

$2 \rightarrow 3$: $\qquad v_3 = v_2 = 2v_1 \Rightarrow$ **${}_2w_3 = 0$,**

$P_3 = P_2T_3/T_2 = P_1/2 =$ **15 lbf/in^2**

${}_2q_3 = u_3 - u_2 = 187.058 - 401.276 =$ **-214.2 Btu/lbm**



5.126E Two containers are filled with air, one a rigid tank A, and the other a piston/cylinder B that is connected to A by a line and valve, as shown in Fig. P5.71. The initial conditions are: $m_A = 4$ lbm, $T_A = 1080$ R, $P_A = 75$ lbf/in.^{2} and $V_B = 17$ ft^3, $T_B = 80$ F, $P_B = 30$ lbf/in.^{2}. The piston in B is loaded with the outside atmosphere and the piston mass in the standard gravitational field. The valve is now opened, and the air comes to a uniform condition in both volumes. Assuming no heat transfer, find the initial mass in B, the volume of tank A, the final pressure and temperature and the work, ${}_1W_2$.

Cont.: $m_2 = m_1 = m_{A1} + m_{B1}$

Energy: $m_2u_2 - m_{A1}u_{A1} - m_{B1}u_{B1} = -{}_1W_2$; ${}_1W_2 = P_{B1}(V_2 - V_1)$

System: $P_B = \text{const} = P_{B1} = P_2$; Substance: $PV = mRT$

$m_{B1} = (PV/RT)_{B1} = 30 \times 17 \times 144/(53.34 \times 539.67) = \mathbf{2.551\ lbm}$

$V_A = m_{A1}RT_{A1}/P_{A1} = 4 \times 53.34 \times 1080/(75 \times 144) = \mathbf{21.336\ ft^3}$

$P_2 = P_{B1} = \mathbf{30\ lbf/in^2}$; C.7: $u_{A1} = 187.058$; $u_{B1} = 92.47$ Btu/lbm

$m_2u_2 + P_2V_2 = m_{A1}u_{A1} + m_{B1}u_{B1} + P_{B1}V_1 = m_2h_2 = 1078.52$ Btu

$\Rightarrow$ $h_2 = 164.63$ Btu/lbm $\Rightarrow$ $T_2 = 687.3$ R $\Rightarrow$ $V_2 = m_{tot}RT_2/P_2 = 55.6$ ft^3

${}_1W_2 = 30(55.6 - 38.336) \times 144/778 = \mathbf{95.86\ Btu}$

5.127E Oxygen at 50 lbf/in.^{2}, 200 F is in a piston/cylinder arrangement with a volume of 4 ft^3. It is now compressed in a polytropic process with exponent, *n* = 1.2, to a final temperature of 400 F. Calculate the heat transfer for the process.

Continuity: $m_2 = m_1$; Energy: $E_2 - E_1 = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: T, P and ideal gas, small change in T, so use Table C.4

$$\Rightarrow \quad m = \frac{P_1V_1}{RT_1} = \frac{50 \times 4 \times 144}{48.28 \times 659.67} = 0.9043 \text{ lbm}$$

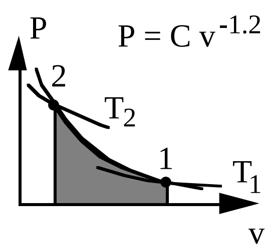
Process: PV^n = constant

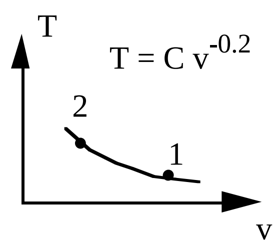
$${}_1W_2 = \frac{1}{1\text{-}n}(P_2V_2 - P_1V_1) = \frac{mR}{1\text{-}n}(T_2 - T_1) = \frac{0.9043 \times 48.28}{1 - 1.2} \times \frac{400 - 200}{778}$$

$$= -\ 56.12 \text{ Btu}$$

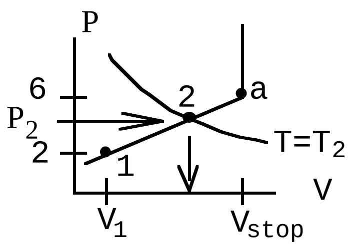
$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 \cong mC_v(T_2 - T_1) + {}_1W_2$$

$$= 0.9043 \times 0.158\ (400 - 200) - 56.12 = \mathbf{-\ 27.54\ Btu}$$





5.128E A piston/cylinder contains 4 lbm of air at 100 F, 2 atm, as shown in Fig. P5.75. The piston is loaded with a linear spring, mass, and the atmosphere. Stops are mounted so that V_{stop} = 100 ft^3, at which point P = 6 atm is required to balance the piston forces. The air is now heated to a final pressure of 60 lbf/in.^{2}. Find the final temperature, volume, and the work and heat transfer. Find the work done on the spring.



From the physical setup the balance of forces on the piston gives P vs. V linear from 1 to a, see figure.
To find state 2: From P_2 to line to V_2 so we need V_1 to fix the line location.

$$V_1 = mRT_1/P_1 = \frac{4 \times 53.34 \times 559.67}{2 \times 14.7 \times 144} = 28.2 \text{ ft}^3$$

$$V_2 = V_1 + [\,(P_2 - P_1)/(P_a - P_1)]\ x\ (V_a - V_1)$$

$$= 28.2 + (100 - 28.2)(60 - 2 \times 14.7) / [(6\text{-}2) \times 14.7] = 65.6 \text{ ft}^3$$

$$T_2 = T_1\ P_2V_2 / P_1V_1 = 559.67 \times 60 \times 65.6 / (29.4 \times 28.2) = 2657 \text{ R}$$

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(29.4 + 60)(65.6 - 28.2) \times 144 / 778$$

$$= \mathbf{309.43\ Btu}$$

Since T is very large we do not use constant Cv, so energy eq. and Table C.6

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 4 \times (508.71 - 95.53) + 309.43 = \mathbf{1962\ Btu}$$

$$W_{spring} = {}_1W_2 - W_{atm} = {}_1W_2 - P_0(V_2 - V_1)$$

$$= 309.43 - 14.7 \times (65.6 - 28.2) \times 144 / 778 = \mathbf{207.7\ Btu}$$

5.129E An air pistol contains compressed air in a small cylinder, as shown in Fig. P5.77. Assume that the volume is 1 in.^{3}, pressure is 10 atm, and the temperature is 80 F when armed. A bullet, *m* = 0.04 lbm, acts as a piston initially held by a pin (trigger); when released, the air expands in an isothermal process (*T* = constant). If the air pressure is 1 atm in the cylinder as the bullet leaves the gun, find

a. The final volume and the mass of air.
b. The work done by the air and work done on the atmosphere.
c. The work to the bullet and the bullet exit velocity.

C.V. Air. Air ideal gas:

$$m_{air} = P_1V_1/RT_1 = \frac{10 \times 14.7 \times 1}{53.34 \times 539.67 \times 12} = \mathbf{4.26 \times 10^{-5}\ lbm}$$

Process: $PV = \text{const} = P_1V_1 = P_2V_2 \Rightarrow V_2 = V_1P_1/P_2 = \mathbf{10\ in^3}$

$${}_1W_2 = \int PdV = P_1V_1 \int (1/V)\, dV = P_1V_1 \ln(V_2/V_1) = \mathbf{0.0362\ Btu}$$

$${}_1W_{2,ATM} = P_0(V_2 - V_1) = \mathbf{0.0142\ Btu}$$

$$W_{bullet} = {}_1W_2 - {}_1W_{2,ATM} = 0.022\ \text{Btu} = \frac{1}{2} m_{bullet}(\mathbf{V}_{ex})^2$$

$$\mathbf{V}_{ex} = (2W_{bullet}/m_B)^{1/2} = (2 \times 0.022 \times 778 \times 32.174 / 0.04)^{1/2} = \mathbf{165.9\ ft/s}$$

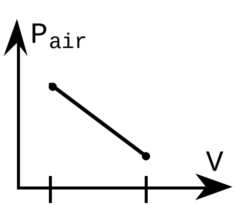
5.130E A 30-ft high cylinder, cross-sectional area 1 ft^2, has a massless piston at the bottom with water at 70 F on top of it, as shown in Fig. P5.79. Air at 540 R, volume 10 ft^3 under the piston is heated so that the piston moves up, spilling the water out over the side. Find the total heat transfer to the air when all the water has been pushed out.

The water on top is compressed liquid and has mass

$V_{H2O} = V_{tot} - V_{air} = 30 \times 1 - 10 = 20\ ft^3$

$m_{H2O} = V_{H2O}/v_f = 20/0.016051 = 1246$ lbm

Initial air pressure is: $P_1 = P_0 + m_{H2O}g/A = 14.7 + \frac{g/g_c}{1 \times 144} = 23.353$ psia



and then $m_{air} = \frac{PV}{RT} = \frac{23.353 \times 10 \times 144}{53.34 \times 540} = 1.1675$ lbm

State 2: $P_2 = P_0 = 14.7\ lbf/in^2$, $V_2 = 30 \times 1 = 30\ ft^3$

$${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(23.353 + 14.7)(30 - 10) \times 144 / 778 = 70.43\ \text{Btu}$$

State 2: $P_2, V_2 \Rightarrow T_2 = \frac{T_1P_2V_2}{P_1V_1} = \frac{540 \times 14.7 \times 30}{23.353 \times 10} = 1019.7$ R

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1.1675 \times 0.171\ (1019.7 - 540) + 70.43 = \mathbf{166.2\ Btu}$$

5.131E A cylinder fitted with a frictionless piston contains R-134a at 100 F, 80% quality, at which point the volume is 3 Gal. The external force on the piston is now varied in such a manner that the R-134a slowly expands in a polytropic process to 50 lbf/in.^{2}, 80 F. Calculate the work and the heat transfer for this process.

Solution:

C.V. The mass of R-134a. Properties in Table C.11.1

$v_1 = v_f + x_1\, v_{fg} = 0.01387 + 0.8 \times 0.3278 = 0.2761 \text{ ft}^3/\text{lbm}$

$u_1 = 108.51 + 0.8 \times 62.77 = 158.73$ Btu/lbm; $\quad P_1 = 138.926$ psia

$m = V/v_1 = 3 \times 231 \times 12^{-3} / 0.2761 = 0.401/ 0.2761 = 1.4525$ lbm

State 2: $\quad v_2 = 1.0563$ (sup.vap.);

$u_2 = 181.1 - 50 \times 1.0563 \times 144/778 = 171.32$

Process: $\quad n = \ln \frac{P_1}{P_2} / \ln \frac{V_2}{V_1} = \ln \frac{138.926}{50} / \ln \frac{1.0563}{9.2761} = 0.7616$

$${}_1W_2 = \int P\, dV = \frac{P_2 V_2 - P_1 V_1}{1 - n}$$

$$= \frac{50 \times 1.0563 - 138.926 \times 0.2761}{1 - 0.7616} \times 1.4525 \times \frac{144}{778} = \mathbf{16.3\ Btu}$$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1.4525\,(171.32 - 158.73) + 16.3 = \mathbf{34.6\ Btu}$

5.132E A piston cylinder contains argon at 20 lbf/in.^{2}, 60 F, and the volume is 4 ft^3. The gas is compressed in a polytropic process to 100 lbf/in.^{2}, 550 F. Calculate the heat transfer during the process.

Find the final volume, then knowing P_1, V_1, P_2, V_2 the polytropic exponent can be determined. Argon is an ideal monatomic gas (Cv is constant).

$$V_2 = V_1 = (P_1/P_2)/(T_2/T_1) = 4 \times \frac{20}{100} \times \frac{1009.67}{519.67} = 1.554 \text{ ft}^3$$

Process: : $PV^{1.25}$ = const. => $\quad n = \ln \frac{P_1}{P_2} / \ln \frac{V_2}{V_1} = \ln \frac{100}{20} / \ln \frac{4}{1.554} = 1.702$

$${}_1W_2 = \frac{1}{1\text{-}n}(P_2V_2 - P_1V_1) = \frac{100 \times 1.554 - 20 \times 4}{1\text{-}1.702} \times \frac{144}{778} = -19.9 \text{ Btu}$$

$m = PV/RT = 20 \times 4 \times 144 / (38.68 \times 519.67) = 0.5731$ lbm

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m\, Cv\, (T_2 - T_1) + {}_1W_2$

$= 0.5731 \text{ x } 0.0745\text{x}(550 - 60) - 19.9 = \mathbf{1.0\ Btu}$

5.133E Water at 300 F, quality 50% is contained in a cylinder/piston arrangement with initial volume 2 ft^3. The loading of the piston is such that the inside pressure is linear with the square root of volume as $P = 14.7 + CV^{0.5}$ lbf/in.^{2}. Now heat is transferred to the cylinder to a final pressure of 90 lbf/in.^{2}. Find the heat transfer in the process.

Continuity: $m_2 = m_1$ Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

State 1: $v_1 = 3.245$, $u_1 = 684.76 \quad \Rightarrow \quad m = V/v_1 = 0.616$ lbm

Process equation $\Rightarrow$ $P_1 - 14.7 = CV_1^{1/2}$ so

$$(V_2/V_1)^{1/2} = (P_2 - 14.7)/(P_1 - 14.7)$$

$$V_2 = V_1 \times \left[\frac{P_2 - 14.7}{P_1 - 14.7}\right]^2 = 2 \times \left[\frac{90 - 14.7}{66.98 - 14.7}\right]^2 = 4.149 \text{ ft}^3$$

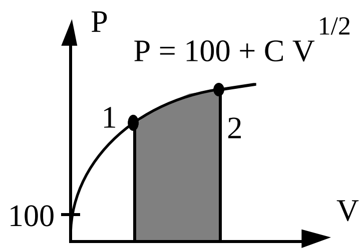
$$_1W_2 = \int PdV = \int (14.7 + CV^{1/2})dV = 14.7\times(V_2 - V_1) + \frac{2}{3}C(V_2^{1.5} - V_1^{1.5})$$

$$= (14.7)(V_2 - V_1)(1\text{-}2/3) + (2/3)(P_2V_2 - P_1V_1)$$

$$_1W_2 = \left[\frac{14.7}{3}(4.149\text{-}2) + \frac{2}{3}(90\times4.149\text{-}66.98\times2)\right]\frac{144}{778} = 31.5 \text{ Btu}$$

State 2: $P_2, v_2 = V_2/m = 6.7354 \quad \Rightarrow \quad u_2 = 1204.66, \quad T_2 \cong 573.6$

$$_1Q_2 = 0.616 \times (1204.66 - 684.76) + 31.5 = \mathbf{351.8\ Btu}$$



5.134E A closed cylinder is divided into two rooms by a frictionless piston held in place by a pin, as shown in Fig. P5.85. Room A has 0.3 ft^3 air at 14.7 lbf/in.^{2}, 90 F, and room B has 10 ft^3 saturated water vapor at 90 F. The pin is pulled, releasing the piston and both rooms come to equilibrium at 90 F. Considering a control mass of the air and water, determine the work done by the system and the heat transfer to the cylinder.

$P_2 = P_{G\ H_2O\ \text{at}\ 90°F} = P_{A2} = P_{B2}$

Air, I.G.: $P_{A1}V_{A1} = m_A R_A T = P_{A2}V_{A2} = P_{G\ H_2O\ \text{at}\ 90°F}\ V_{A2}$

$\rightarrow V_{A2} = \dfrac{14.7 \times 0.3}{0.6988} = 6.31\ \text{ft}^3$

$V_{B2} = V_{A1} + V_{B1} - V_{A2} = 0.30 + 10 - 6.31 = 3.99\ \text{ft}^3$

$m_B = \dfrac{V_{B1}}{v_{B1}} = \dfrac{10}{467.7} = 0.02138\ \text{lbm} \quad \rightarrow \quad v_{B2} = 186.6\ \text{ft}^3/\text{lbm}$

$186.6 = 0.016099 + x_{B2} \times (467.7 - 0.016) \quad => \quad x_{B2} = 0.39895$

System A+B: $\mathbf{W_{12} = 0;}$ $\quad \mathbf{\Delta U_A = 0}$ $\quad$ (IG & $\Delta T = 0$)

$u_{B2} = 58.07 + 0.39895 \times 982.2 = 449.9$ Btu/lbm; $\quad u_{B1} = 1040.2$

${}_1Q_2 = 0.02138\ (449.9 - 1040.2) =$ **-12.6 Btu**

5.135E A small elevator is being designed for a construction site. It is expected to carry four 150 lbm workers to the top of a 300-ft-tall building in less than 2 min. The elevator cage will have a counterweight to balance its mass. What is the smallest size (power) electric motor that can drive this unit?

$m = 4 \times 150 = 600$ lbm ; $\quad \Delta Z = 300$ ft ; $\quad \Delta t = 2$ minutes

$-\dot{W} = \Delta\dot{PE} = m\ \dfrac{g\ \Delta Z}{g_C\ \Delta t} = \dfrac{600 \times 32.174 \times 300}{32.174 \times 2 \times 60}\ \dfrac{1}{550} =$ **2.73 hp**

5.136E A computer in a closed room of volume 5000 ft^3 dissipates energy at a rate of 10 hp. The room has 100 lbm of wood, 50 lbm of steel and air, with all material at 540 R, 1 atm. Assuming all the mass heats up uniformly how long time will it take to increase the temperature 20 F?

C.V. Air, wood and steel. $m_2 = m_1$; $U_2 - U_1 = {}_1Q_2 = \dot{Q}\Delta t$

The total volume is nearly all air, but we can find volume of the solids.

$V_{wood} = m/\rho = 100/44.9 = 2.23\ ft^3$; $V_{steel} = 50/488 = 0.102\ ft^3$

$V_{air} = 5000 - 2.23 - 0.102 = 4997.7\ ft^3$

$$m_{air} = PV/RT = 14.7\times4997.7\times144/(53.34\times540) = 367.3\ lbm$$

We do not have a u table for steel or wood so use heat capacity.

$$\Delta U = [m_{air}\ C_v + m_{wood}\ C_v + m_{steel}\ C_v\ ]\Delta T$$

$$= (367.3\times0.171 + 100\times0.3 + 50\times0.11)\ 20$$

$$= 1256.2 + 600 +110 = 1966\ Btu = \dot{Q} \times \Delta t = 10\times(550/778)\times\Delta t$$

$\Rightarrow$ $\Delta t = [1966/10](778/550) = 278$ sec = **4.6 minutes**

CHAPTER 6

The new chapter 6 corresponds to the second half of chapter 5 in the 4th edition text.

New	Old	New	Old	New	Old
1	83	25	112	49	117
2	new	26	113	50	119
3	new	27	new	51	120
4	84	28	new	52	139
5	85	29	92	53	121
6	new	30	96	54	122
7	new	31	new	55	123
8	103	32	115	56	124
9	86	33	88	57	126
10	89 mod	34	new	58	127
11	97	35	93	59	129
12	98	36	87	60	131
13	99	37	101	61	132
14	94	38	102	62	134
15	95	39	104a	63	135
16	new	40	104b	64	136
17	100	41	105	65	137
18	new	42	106	66	new
19	90	43	107	67	new
20	91	44	108	68	new
21	new	45	109	69	118
22	new	46	114	70	125
23	110	47	116	71	128
24	111	48	new	72	130

The advanced problems start with number 6.69.

The english unit problem correspondence to the fourth edition chapter 5 is

New	Old	New	Old	New	Old
73	177	83	191	93	193
74	178	84	192	94	194
75	new	85	new	95	195
76	179	86	182	96	196
77	187	87	186	97	197
78	188	88	180	98	198
79	184	89	183	99	new
80	185	90	189	100	200
81	new	91	190a	101	201
82	181	92	190b	102	202

6.1 Air at 35°C, 105 kPa, flows in a 100 mm × 150 mm rectangular duct in a heating system. The volumetric flow rate is 0.015 m^3/s. What is the velocity of the air flowing in the duct?

$$\dot{V} = \dot{m}v = A\mathbf{V} \qquad \text{with} \qquad A = 100 \text{ x } 150\text{x}10^{-6} = 0.015 \text{ m}^2$$

$$\mathbf{V} = \frac{\dot{V}}{A} = \frac{0.015 \text{ m}^3\text{/s}}{0.015 \text{ m}^2} = \mathbf{1.0 \text{ m/s}}$$

$$\left(\text{Ideal gas so note:} \quad \begin{array}{l} v = \dfrac{RT}{P} = \dfrac{0.287 \text{ x } 308.2}{105} = 0.8424 \text{ m}^3\text{/kg} \\ \dot{m} = \dfrac{\dot{V}}{v} = \dfrac{0.015}{0.8424} = 0.0178 \text{ kg/s} \end{array} \right)$$

6.2 A boiler receives a constant flow of 5000 kg/h liquid water at 5 MPa, 20°C and it heats the flow such that the exit state is 450°C with a pressure of 4.5 MPa. Determine the necessary minimum pipe flow area in both the inlet and exit pipe(s) if there should be no velocities larger than 20 m/s.

Mass flow rate $\quad \dot{m}_i = \dot{m}_e = (A\mathbf{V}/v)_{\,i} = (A\mathbf{V}/v)_{\,e} = 5000 \; \dfrac{1}{3600} \;$ kg/s

Table B.1.4 $\quad v_i = 0.001 \text{ m}^3\text{/kg}, \;\; v_e = 0.07074 \text{ m}^3\text{/kg}$, both $\mathbf{V} \le 20$ m/s

$$A_i \ge \; v_i \, \dot{m}/\mathbf{V}_i = 0.001 \times \frac{5000}{3600} / 20 = 6.94 \times 10^{-5} \text{ m}^2 = \mathbf{0.69 \text{ cm}^2}$$

$$A_e \ge \; v_e \, \dot{m}/\mathbf{V}_e = 0.07074 \times \frac{5000}{3600} / 20 = 4.91 \times 10^{-3} \text{ m}^2 = \mathbf{49 \text{ cm}^2}$$

6.3 A natural gas company distributes methane gas in a pipeline flowing at 200 kPa, 275 K. They have carefully measured the average flow velocity to be 5.5 m/s in a 50 cm diameter pipe. If there is a ± 2% uncertainty in the velocity measurement how would you qoute the mass flow rate?

$$\dot{m} = A\mathbf{V}/v = \int PV \, dA = \frac{\pi}{4} D^2 \; \times \mathbf{V}/v$$

$$v = 0.70931 \text{ m}^3\text{/kg} \;\; \text{superheated vapor Table B.7.2}$$

$$\dot{m} = \; \frac{\pi}{4} 0.5^2 \; \times 5.5/0.70931 = 1.522 \text{ kgs}^{-1} \pm 2 \text{ \%}$$

$$\mathbf{1.52 \text{ kgs}^{-1} \; \pm 2 \text{ \%} \quad \text{or} \quad 1.49 < \; \dot{m} < \; 1.55 \text{ kgs}^{-1}}$$

6.4 Nitrogen gas flowing in a 50-mm diameter pipe at 15°C, 200 kPa, at the rate of 0.05 kg/s, encounters a partially closed valve. If there is a pressure drop of 30 kPa across the valve and essentially no temperature change, what are the velocities upstream and downstream of the valve?

Same inlet and exit area: $A = \frac{\pi}{4}(0.050)^2 = 0.001963 \text{ m}^2$

Ideal gas: $v_i = \frac{RT_i}{P_i} = \frac{0.2968 \text{ x } 288.2}{200} = 0.4277 \text{ m}^3/\text{kg}$

$\mathbf{V}_i = \frac{\dot{m}v_i}{A} = \frac{0.05 \text{ x } 0.4277}{0.001963} = \mathbf{10.9 \text{ m/s}}$

Ideal gas: $v_e = \frac{RT_e}{P_e} = \frac{0.2968 \text{ x } 288.2}{170} = 0.5032 \text{ m}^3/\text{kg}$

$\mathbf{V}_e = \frac{\dot{m}v_e}{A} = \frac{0.05 \text{ x } 0.5032}{0.001963} = \mathbf{12.8 \text{ m/s}}$

6.5 Saturated vapor R-134a leaves the evaporator in a heat pump system at 10°C, with a steady mass flow rate of 0.1 kg/s. What is the smallest diameter tubing that can be used at this location if the velocity of the refrigerant is not to exceed 7 m/s?

Table B.5.1: $v_g = 0.04945 \text{ m}^3/\text{kg}$

$A_{MIN} = \dot{m}v_g/\mathbf{V}_{MAX} = 0.1\text{x}0.04945/7 = 0.000706 \text{ m}^2 = (\pi/4)\ D^2_{MIN}$

$D_{MIN} = \mathbf{0.03 \text{ m} = 30 \text{ mm}}$

6.6 Steam at 3 MPa, 400°C enters a turbine with a volume flow rate of 5 m^3/s. An extraction of 15% of the inlet mass flow rate exits at 600 kPa, 200°C. The rest exits the turbine at 20 kPa with a quality of 90%, and a velocity of 20 m/s. Determine the volume flow rate of the extraction flow and the diameter of the final exit pipe.

Inlet flow : $\dot{m}_i = \dot{V}/v = 5/0.09936 = 50.32 \text{ kg/ s}$ (Table B.1.3)

Extraction flow : $\dot{m}_e = 0.15\ \dot{m}_i = 7.55 \text{ kg/ s}$; $v = 0.35202 \text{ m}^3/\text{kg}$

$\dot{V}_{ex} = \dot{m}_e v = 7.55 \times 0.35202 = \mathbf{2.658 \text{ m}^3/\text{ s}}$

Exit flow : $\dot{m} = 0.85\ \dot{m}_i = 42.77 \text{ kg /s}$

Table B.1.2 $v = 0.001017 + 0.9 \times 7.64835 = 6.8845 \text{ m}^3/\text{kg}$

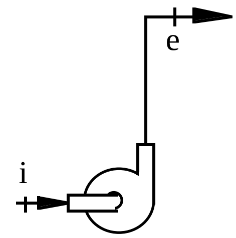
$\dot{m} = A\mathbf{V}/v \Rightarrow$ $A = (\pi/4)\ D^2 = \dot{m}\ v/\mathbf{V} = 42.77 \times 6.8845/20 = 14.723$

$\Rightarrow \mathbf{D = 4.33 \text{ m}}$

6.7 A pump takes 10°C liquid water in from a river at 95 kPa and pumps it up to an irrigation canal 20 m higher than the river surface. All pipes have diameter of 0.1 m and the flow rate is 15 kg/s. Assume the pump exit pressure is just enough to carry a water column of the 20 m height with 100 kPa at the top. Find the flow work into and out of the pump and the kinetic energy in the flow.

Both states are compressed liquid so Table B.1.1: $v_i = v_f = 0.001\ m^3/kg$

Flow rates in and out are the same, pipe size the same so same velocity.



$$\mathbf{V}_i = \mathbf{V}_e = \dot{m}v/\left(\frac{\pi}{4}D^2\right) = 15 \times 0.001/\left(\frac{\pi}{4}0.1^2\right) = 1.91\ m/s$$

$$KE_i = \frac{1}{2}\mathbf{V}_i^2 = KE_e = \frac{1}{2}\mathbf{V}_e^2 = \frac{1}{2}(1.91)^2\ m^2/s^2 = \mathbf{1.824\ J/kg}$$

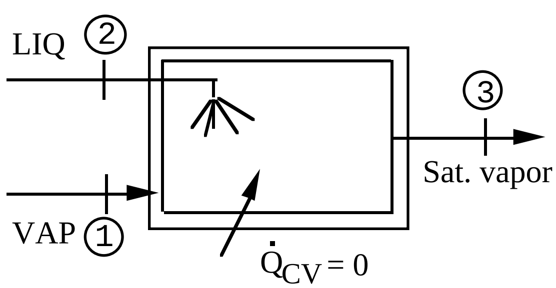
Flow work at the boundary: $\dot{m}Pv$; the P's are different

$$\dot{W}_{flow,\ i} = \dot{m}_i P_i v_i = 15 \times 95 \times 0.001 = \mathbf{1.425\ kW}$$

$$P_e = P_o + Hg/v = 100 + (20 \times 9.807/0.001)/1000 = 100 + 196 = 296\ kPa$$

$$\dot{W}_{flow,\ e} = \dot{m}P_e v_e = 15 \times 296 \times 0.001 = \mathbf{4.44\ kW}$$

6.8 A desuperheater mixes superheated water vapor with liquid water in a ratio that produces saturated water vapor as output without any external heat transfer. A flow of 0.5 kg/s superheated vapor at 5 MPa, 400°C and a flow of liquid water at 5 MPa, 40°C enter a desuperheater. If saturated water vapor at 4.5 MPa is produced, determine the flow rate of the liquid water.



Cont.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy Eq.:

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

$$0.5 \text{ x } 3195.7 + \dot{m}_2 \text{ x } 171.97$$

$$= (0.5 + \dot{m}_2)\ 2797.9$$

$\Rightarrow$ $\dot{m}_2 = \mathbf{0.0757\ kg/s}$

6.9 Carbon dioxide enters a steady-state, steady-flow heater at 300 kPa, 15°C, and exits at 275 kPa, 1200°C, as shown in Fig. P6.9. Changes in kinetic and potential energies are negligible. Calculate the required heat transfer per kilogram of carbon dioxide flowing through the heater.

C.V. Heater SSSF single inlet and exit. Energy Eq.: $q + h_i = h_e$

Table A.8: $q = h_e - h_i = \dfrac{60145 - (-348.3)}{44.01} = \mathbf{1374.5\ kJ/kg}$

(If we use C_{P0} from A.5 then $q \cong 0.842(1200 - 15) = 997.8$ kJ/kg)

Too large ΔT, T_{ave} to use C_{p0} at room temperature.

6.10 Saturated liquid nitrogen at 500 kPa enters a SSSF boiler at a rate of 0.005 kg/s and exits as saturated vapor. It then flows into a superheater also at 500 kPa where it exits at 500 kPa, 275 K. Find the rate of heat transfer in the boiler and the superheater.

C.V.: boiler SSSF, single inlet and exit, neglict KE, PE energies in flow

Continuity Eq.: $\dot{m}_1 = \dot{m}_2 = \dot{m}_3$ (SSSF)

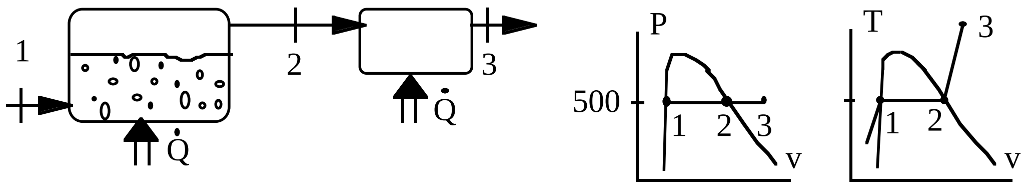


Table B.6: h_1 = -87.095 kJ/kg, h_2 = 86.15 kJ/kg, h_3 = 284.06 kJ/kg

$q_{boiler} = h_2 - h_1 = 86.15 - (-87.095) = 173.25$ kJ/kg

$\dot{Q}_{boiler} = 0.005 \times 173.25 =$ **0.866 kW**

$q_{sup\ heater} = h_3 - h_2 = 284.06 - 86.15 = 197.9$ kJ/kg

$\dot{Q}_{sup\ heater} = 0.005 \times 197.9 =$ **0.99 kW**

6.11 A steam pipe for a 1500-m tall building receives superheated steam at 200 kPa at ground level. At the top floor the pressure is 125 kPa and the heat loss in the pipe is 110 kJ/kg. What should the inlet temperature be so that no water will condense inside the pipe?

C.V. PIPE from 0 to 1500 m, no ΔKE, SSSF, single inlet and exit.

Energy Eq.: $q + h_i = h_e + gZ_e$

No condensation means: Table B.1.2, $h_e = h_g$ at 125 kPa = 2685.4 kJ/kg

$h_i = h_e + gZ_e - q = 2685.4 + 9.807 \text{ x } 1500/1000 - (-110) = 2810.1$ kJ/kg

At 200 kPa: T ~ **170°C** Table B.1.3

6.12 In a steam generator, compressed liquid water at 10 MPa, 30°C, enters a 30-mm diameter tube at the rate of 3 L/s. Steam at 9 MPa, 400°C exits the tube. Find the rate of heat transfer to the water.

Constant diameter tube: $A_i = A_e = \frac{\pi}{4}(0.03)^2 = 0.0007068 \text{ m}^2$

Table B.1.4 $\dot{m} = \dot{V}_i/v_i = 0.003/0.0010003 = 3.0$ kg/s

$\mathbf{V}_i = \dot{V}_i/A_i = 0.003/0.0007068 = 4.24$ m/s

$\mathbf{V}_e = \mathbf{V}_i \text{ x } v_e/v_i = 4.24 \text{ x } 0.02993/0.0010003 = 126.86$ m/s

$$\dot{Q} = \dot{m}\left[(h_e - h_i) + \left(\mathbf{V}_e^2 - \mathbf{V}_i^2\right)/2\right]$$

$$= 3.0\left[3117.8 - 134.86 + \frac{126.86^2 - 4.24^2}{2 \text{ x } 1000}\right] = \mathbf{8973\ kW}$$

6.13 A heat exchanger, shown in Fig. P6.13, is used to cool an air flow from 800 to 360K, both states at 1 MPa. The coolant is a water flow at 15°C, 0.1 MPa. If the water leaves as saturated vapor, find the ratio of the flow rates $\dot{m}_{H_2O}/\dot{m}_{air}$

C.V. Heat exchanger, SSSF, 1 inlet and exit for air and water each. The two flows exchange energy with no heat transfer to/from the outside.

$$\dot{m}_{air}h_{ai} + \dot{m}_{H_2O}h_{fi} = \dot{m}_{air}h_{ae} + \dot{m}_{H_2O}h_{ge}$$

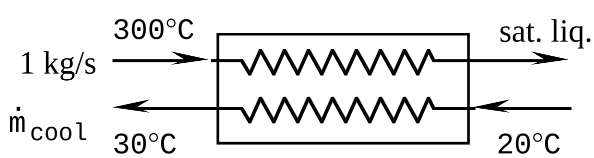
Table A.7: $h_{ai} = 822.202$, $h_{ae} = 360.863$ kJ/kg

Table B.1: $h_{fi} = 62.99$ (at 15°C), $h_{ge} = 2675.5$ (at 100 kPa)

$$\dot{m}_{H_2O}/\dot{m}_{air} = (h_{ai} - h_{ae})/(h_{ge} - h_{fi})$$

$$= (822.202 - 360.863)/(2675.5 - 62.99) = \mathbf{0.1766}$$

6.14 A condenser (heat exchanger) brings 1 kg/s water flow at 10 kPa from 300°C to saturated liquid at 10 kPa, as shown in Fig. P6.14. The cooling is done by lake water at 20°C that returns to the lake at 30°C. For an insulated condenser, find the flow rate of cooling water.



C.V. Heat exchanger

$$\dot{m}_{cool}h_{20} + \dot{m}_{H_2O}h_{300} = \dot{m}_{cool}h_{30} + \dot{m}_{H_2O}h_{f\ 10kPa}$$

Table B.1.1: $h_{20} = 83.96$ kJ/kg , $h_{30} = 125.79$ kJ/kg

Table B.1.3: $h_{300,\ 10kPa} = 3076.5$ kJ/kg, B.1.2: $h_{f,\ 10\ kPa} = 191.83$ kJ/kg

$$\dot{m}_{cool} = \dot{m}_{H_2O}\frac{h_{300} - h_{f,\ 10kPa}}{h_{30} - h_{20}} = 1 \text{ x } \frac{3076.5 - 191.83}{125.79 - 83.96} = \mathbf{69\ kg/s}$$

6.15 Two kg of water at 500 kPa, 20°C is heated in a constant pressure process (SSSF) to 1700°C. Find the best estimate for the heat transfer.

C.V. Heater; 1 inlet and exit, no work term, no ΔKE, ΔPE .

Continuity: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$, Energy: $q + h_{in} = h_{ex} \Rightarrow q = h_{ex} - h_{in}$

steam tables only go up to 1300°C so use an intermediate state at lowest pressure (closest to ideal gas) h_X(1300°C, 10 kPa) from Table B.1.3 and table A.8 for the high T change Δh

$$h_{ex} - h_{in} = (h_{ex} - h_X) + (h_X - h_{in})$$

$$= (71423 - 51629)/18.015 + 5409.7 - 83.96 = 6424.5 \text{ kJ/kg}$$

$$Q = m(h_{ex} - h_{in}) = 2 \times 6424.5 = \mathbf{12849\ kJ}$$

6.16 A mixing chamber with heat transfer receives 2 kg/s of R-22 at 1 MPa, 40°C in one line and 1 kg/s of R-22 at 30°C, quality 50% in a line with a valve. The outgoing flow is at 1 MPa, 60°C. Find the rate of heat transfer to the mixing chamber.

C.V. Mixing chamber. SSSF with 2 flows in and 1 out, heat transfer in.

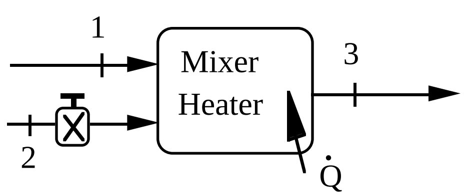


Table B.4:

$h_1 = 271.04$, $h_3 = 286.97$

$h_2 = 81.25 + 0.5 \times 177.87 = 170.18$

Cont. Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{Q} = \dot{m}_3 h_3$

$$\dot{m}_3 = 2 + 1 = 3 \text{ kg/s}$$

$$\dot{Q} = 3 \times 286.973 - 2 \times 271.04 - 1 \times 170.18 = \mathbf{148.66\ kW}$$

6.17 Compressed liquid R-22 at 1.5 MPa, 10°C is mixed in a steady-state, steady-flow process with saturated vapor R-22 at 1.5 MPa. Both flow rates are 0.1 kg/s, and the exiting flow is at 1.2 MPa and a quality of 85%. Find the rate of heat transfer to the mixing chamber.

C.V. Mixing chamber, SSSF, no work term.

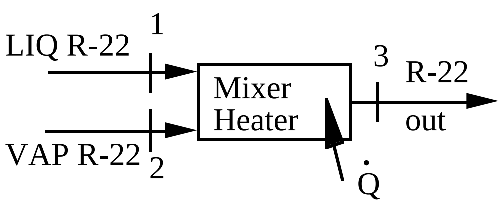


Table B.4.1 :

$h_1 = h_f$ at 10° C = 56.5 kJ/kg

$h_2 = h_g$ at 1.5 MPa = 261.0 kJ/kg

$h_3 = 81.65 + 0.85 \times 177.5 = 232.5$

Cont. Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$, Energy Eq.: $\dot{Q}_{CV} + \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

$$\dot{Q}_{CV} = 0.2 \times 232.5 - 0.1 \times 56.5 - 0.1 \times 261.0 = \mathbf{+14.8\ kW}$$

6.18 Nitrogen gas flows into a convergent nozzle at 200 kPa, 400 K and very low velocity. It flows out of the nozzle at 100 kPa, 330 K. If the nozzle is insulated find the exit velocity.

C.V. Nozzle SSSF one inlet and exit, insulated so it is adiabatic.

Energy Eq.: $h_1 + \varnothing = h_2 + \frac{1}{2}\mathbf{V}_2^2$

$\mathbf{V}_2^2 = 2\,(h_1 - h_2) \cong 2\,C_{P N_2}\,(T_1 - T_2) = 2 \times 1.042\,(400 - 330)$

$= 145.88$ kJ/kg $= 145\,880$ J/kg $\Rightarrow$ $\mathbf{V}_2 =$ **381.94 m/s**

6.19 Superheated vapor ammonia enters an insulated nozzle at 20°C, 800 kPa, shown in Fig. P6.19, with a low velocity and at the steady rate of 0.01 kg/s. The ammonia exits at 300 kPa with a velocity of 450 m/s. Determine the temperature (or quality, if saturated) and the exit area of the nozzle.

C.V. Nozzle, SSSF, 1 inlet and 1 exit , insulated so no heat transfer.

Energy Eq.: $q + h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2$, $q = 0$, $\mathbf{V}_i = 0$

Table B.2.2: $h_i = 1464.9 = h_e + 450^2/(2 \times 1000)$ $\Rightarrow$ $h_e = 1363.6$ kJ/kg

$P_e = 300$ kPa Sat. state at -9.2°C : $1363.6 = 138.0 + x_e \times 1293.8$,

=> $x_e =$ **0.947**, $v_e = 0.001536 + x_e \times 0.4064 = 0.3864$

$A_e = \dot{m}_e v_e/\mathbf{V}_e = 0.01 \times 0.3864 / 450 =$ **8.56×10^{-6} m^2**

6.20 A diffuser, shown in Fig. P6.20, has air entering at 100 kPa, 300 K, with a velocity of 200 m/s. The inlet cross-sectional area of the diffuser is 100 mm^2. At the exit, the area is 860 mm^2, and the exit velocity is 20 m/s. Determine the exit pressure and temperature of the air.

$\dot{m}_i = A_i\mathbf{V}_i/v_i = \dot{m}_e = A_e\mathbf{V}_e/v_e$, $h_i + (1/2)\mathbf{V}_i^2 = h_e + (1/2)\mathbf{V}_e^2$

$h_e - h_i = (1/2) \times 200^2/1000 - (1/2) \times 20^2/1000 = 19.8$ kJ/kg

$T_e = T_i + 19.8/1.35 =$ **319.73 K**

$v_e = v_i(A_e\mathbf{V}_e/A_i\mathbf{V}_i) = (RT_i/P_i)\,(A_e\mathbf{V}_e/A_i\mathbf{V}_i) = RT_e/P_e$

$P_e = P_i(T_e/T_i)\,(A_i\mathbf{V}_i/A_e\mathbf{V}_e)$

$= 100(319.73/300)\,(100 \times 200)/(860 \times 20) =$ **123.93 kPa**

6.21 A diffuser receives an ideal gas flow at 100 kPa, 300 K with a velocity of 250 m/s and the exit velocity is 25 m/s. Determine the exit temperature if the gas is argon, helium or nitrogen.

C.V. Diffuser: $\dot{m}_i = \dot{m}_e$ & assume no heat transfer $\Rightarrow$

Energy Eq.: $h_i + \frac{1}{2}\mathbf{V}_i^2 = \frac{1}{2}\mathbf{V}_e^2 + h_e \;\Rightarrow\; h_e = h_i + \frac{1}{2}\mathbf{V}_i^2 - \frac{1}{2}\mathbf{V}_e^2$

$$h_e - h_i \approx C_p\,(T_e - T_i) = \frac{1}{2}(\mathbf{V}_i^2 - \mathbf{V}_e^2) = \frac{1}{2}(250^2 - 25^2)$$

$$= 30937.5 \text{ J/kg} = 30.938 \text{ kJ/kg}$$

Argon $C_p = 0.52$; $\Delta T = 30.938/0.52 = 59.5$ $\mathbf{T_e = 359.5\ K}$

Helium$C_p = 5.913$; $\Delta T = 30.938/5.193 = 5.96$ $\mathbf{T_e = 306\ K}$

Nitrogen $C_p = 1.042$; $\Delta T = 30.938/1.042 = 29.7$ $\mathbf{T_e = 330\ K}$

6.22 The front of a jet engine acts as a diffuser receiving air at 900 km/h, -5°C, 50 kPa, bringing it to 80 m/s relative to the engine before entering the compressor. If the flow area is reduced to 80% of the inlet area find the temperature and pressure in the compressor inlet.

C.V. Diffuser, SSSF, 1 inlet, 1 exit, no q, w. Cont.: $\dot{m}_i = \dot{m}_e = (A\mathbf{V}/v)$

Energy Eq.: $\dot{m}\,(h_i + \frac{1}{2}\mathbf{V}_i^2) = \dot{m}\,(\frac{1}{2}\mathbf{V}_e^2 + h_e)$

$$h_e - h_i = C_p\,(T_e - T_i) = \frac{1}{2}\mathbf{V}_i^2 - \frac{1}{2}\mathbf{V}_e^2 = \frac{1}{2}\left(\frac{900 \times 1000}{3600}\right)^2 - \frac{1}{2}(80)^2$$

$$= 28050 \text{ J/kg} = 28.05 \text{ kJ/kg}$$

$\Delta T = 28.05/1.004 = 27.9 \;\Rightarrow\;$ $T_e = -5 + 27.9 = 22.9$ °C

$A_i\mathbf{V}_i/v_i = A_e\mathbf{V}_e/v_e \;\Rightarrow\;$ $v_e = v_i \times A_e\mathbf{V}_e/A_i\mathbf{V}_i$

$v_e = v_i \times (0.8 \times 80/250) = v_i \times 0.256$

Ideal gas: $Pv = RT$ => $RT_e/P_e = RT_i \times 0.256/P_i$

$P_e = P_i\,(T_e/T_i)/0.256 = 50 \times 296/268 \times 0.256 =$ **215.7 kPa**

6.23 Helium is throttled from 1.2 MPa, 20°C, to a pressure of 100 kPa. The diameter of the exit pipe is so much larger than the inlet pipe that the inlet and exit velocities are equal. Find the exit temperature of the helium and the ratio of the pipe diameters.

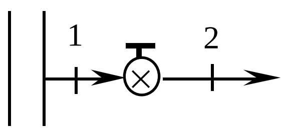
C.V. Throttle. SSSF, Process with: $q = w = 0$;

Energy Eq.: $h_i = h_e$, Ideal gas => $T_i = T_e =$ **20°C**

$\dot{m} = \frac{A\mathbf{V}}{RT/P}$ But $\dot{m}$, $\mathbf{V}$, T are constant => $P_iA_i = P_eA_e$

$$\Rightarrow \quad \frac{D_e}{D_i} = \left(\frac{P_i}{P_e}\right)^{1/2} = \left(\frac{1.2}{0.1}\right)^{1/2} = \mathbf{3.464}$$

6.24 Water flowing in a line at 400 kPa, saturated vapor, is taken out through a valve to 100 kPa. What is the temperature as it leaves the valve assuming no changes in kinetic energy and no heat transfer?



C.V. Valve (SSSF)

Cont.: $\dot{m}_1 = \dot{m}_2$; Energy: $\dot{m}_1 h_1 + \dot{Q} = \dot{m}_2 h_2 + \dot{W}$

Small surface area: $\dot{Q} = 0$; No shaft: $\dot{W} = 0$

Table B.1.2: $h_2 = h_1 = 2738.6$ kJ/kg $\Rightarrow$ $\mathbf{T_2 = 131.1°C}$

6.25 Methane at 3 MPa, 300 K, is throttled to 100 kPa. Calculate the exit temperature assuming no changes in the kinetic energy and ideal-gas behavior. Repeat the answer for real-gas behavior.

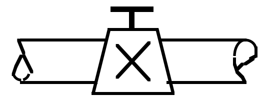
C.V. Throttle (valve, restriction), SSSF, 1 inlet and exit, no q, w

Energy Eq.: $h_i = h_e$ => Ideal gas $T_i = T_e =$ **300 K**

Real gas : $\left.\begin{array}{l} h_i = h_e = 598.71 \\ P_e = 0.1 \text{ MPa} \end{array}\right\}$ Table B.7 $T_e =$ **13.85°C** (= **287 K**)

6.26 Water at 1.5 MPa, 150°C, is throttled adiabatically through a valve to 200 kPa. The inlet velocity is 5 m/s, and the inlet and exit pipe diameters are the same. Determine the state and the velocity of the water at the exit.

CV: valve. $\dot{m}$ = const, A = const



$\Rightarrow$ $\mathbf{V}_e = \mathbf{V}_i(v_e/v_i)$

$$h_i + \frac{1}{2}\mathbf{V}_i^2 = \frac{1}{2}\mathbf{V}_e^2 + h_e \quad \text{or} \quad (h_e - h_i) + \frac{1}{2}\mathbf{V}_i^2\left[\left(\frac{v_e}{v_i}\right)^2 - 1\right] = 0$$

$$h_e - 632.87 + \frac{(5)^2}{2 \text{ x } 1000}\left[\left(\frac{v_e}{0.00109}\right)^2 - 1\right] = 0$$

Table B.1.2: $h_e = 504.7 + x_e \text{ x } 2201.9$, $v_e = 0.001061 + x_e \text{ x } 0.8846$

Substituting and solving, x_e = **0.04885**

$\mathbf{V}_e$ = 5 (0.04427 / 0.00109) = **203 m/s**

6.27 An insulated mixing chamber receives 2 kg/s R-134a at 1 MPa, 100°C in a line with low velocity. Another line with R-134a as saturated liquid 60°C flows through a valve to the mixing chamber at 1MPa after the valve. The exit flow is saturated vapor at 1 MPa flowing at 20 m/s. Find the flow rate for the second line.

C.V. Mixing chamber. SSSF, 2 inlets, 1 exit, no q, w.

Cont.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3(h_3 + \frac{1}{2}\mathbf{V}_3^2)$

$$\dot{m}_2 (h_2 - h_3 - \frac{1}{2}\mathbf{V}_3^2) = \dot{m}_1 (h_3 + \frac{1}{2}\mathbf{V}_3^2 - h_1)$$

1: Table B.5.2: 1MPa, 100°C, h_1 = 483.36 kJ/kg

2: Table B.5.1: x = ∅, 60°C, h_2 = 287.79 kJ/kg

3: Table B.5.1: x = 1, 1 MPa, 20 m/s, h_3 = 419.54 kJ/kg

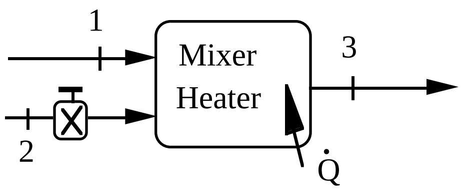
$$\dot{m}_2 = 2 \times [419.54 + \frac{1}{2}20^2 \times \frac{1}{1000} - 483.36] / [287.79 - 419.54 - \frac{1}{2}\frac{20^2}{1000}]$$

$= 2 \times (-63.82 + 0.2) / (-131.75 - 0.2) =$ **0.964 kg/s**

Notice how kinetic energy was insignificant.

6.28 A mixing chamber receives 2 kg/s R-134a at 1 MPa, 100°C in a line with low velocity and 1 kg/s from a line with R-134a as saturated liquid 60°C flows through a valve to the mixing chamber at 1 MPa after the valve. There is heat transfer so the exit flow is saturated vapor at 1 MPa flowing at 20 m/s. Find the rate of heat transfer and the exit pipe diameter.

Cont.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 + \dot{Q} = \dot{m}_3(h_3 + \frac{1}{2}\mathbf{V}_3^2)$



1: Table B.5.2: 1MPa, 100°C,

h_1 = 483.36 kJ/kg

2: Table B.5.1: x = ∅, 60°C,

h_2 = 287.79 kJ/kg

3: Table B.5.1 x = 1, 1 MPa, 20 m/s, h_3 = 419.54; v_3 = 0.02038

$\dot{m}_3$ = 1 + 2 = 3 kg/s

$\dot{Q} = 3(419.54 + \frac{1}{2}20^2/1000) - 2 \times 483.36 - 1 \times 287.79 =$ **4.71 kW**

$A_e = \dot{m}_3 v_3/\mathbf{V}_3 = 3 \times 0.02038/20 = 0.003057\ m^2$,

$D_e = [\,\frac{4}{\pi} A_e\,]^{1/2}$ = **0.062 m**

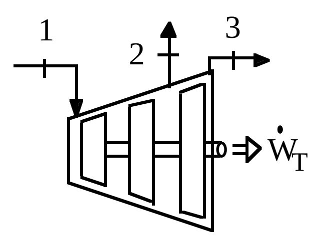
6.29 A steam turbine receives water at 15 MPa, 600°C at a rate of 100 kg/s, shown in Fig. P6.29. In the middle section 20 kg/s is withdrawn at 2 MPa, 350°C, and the rest exits the turbine at 75 kPa, and 95% quality. Assuming no heat transfer and no changes in kinetic energy, find the total turbine power output.

C.V. Turbine SSSF, 1 inlet and 2 exit flows.

Table B.1.3 h_1 = 3582.3 kJ/kg, h_2 = 3137 kJ/kg

Table B.1.2 : $h_3 = h_f + x_3 h_{fg} = 384.3 + 0.95 \times 2278.6$

= 2549.1 kJ/kg



Cont.: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$; Energy: $\dot{m}_1 h_1 = \dot{W}_T + \dot{m}_2 h_2 + \dot{m}_3 h_3$

$\dot{m}_3 = \dot{m}_1 - \dot{m}_2$ = 80 kg/s , $\dot{W}_T = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3$ = **91.565 MW**

6.30 A small, high-speed turbine operating on compressed air produces a power output of 100 W. The inlet state is 400 kPa, 50°C, and the exit state is 150 kPa, –30°C. Assuming the velocities to be low and the process to be adiabatic, find the required mass flow rate of air through the turbine.

C.V. Turbine, no heat transfer, no ΔKE, no ΔPE

$h_{in} = h_{ex} + w_T \;\Rightarrow\; w_T = h_{in} - h_{ex} \cong C_p(T_{in} - T_{ex})$

$= 1.004(50 - (-30)) = 80.3$ kJ/kg

$\dot{W} = \dot{m}w_T \quad \Rightarrow \quad \dot{m} = \dot{W}/w_T = 0.1/80.3 =$ **0.00125 kg/s**

6.31 A steam turbine receives steam from two boilers. One flow is 5 kg/s at 3 MPa, 700°C and the other flow is 15 kg/s at 800 kPa, 500°C. The exit state is 10 kPa, with a quality of 96%. Find the total power out of the adiabatic turbine.

C.V. whole turbine SSSF, 2 inlets, 1 exit, no heat transfer $\dot{Q} = 0$

Continuity Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 5 + 15 = 20$ kg/s

Energy Eq.: $\dot{m}_1h_1 + \dot{m}_2h_2 = \dot{m}_3h_3 + \dot{W}_T$

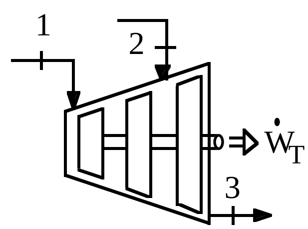


Table B.1.3: $h_1 = 3911.7$ kJ/kg, $h_2 = 3480.6$ kJ/kg

Table B.1.2: $h_3 = 191.8 + 0.96 \times 2392.8$

$= 2488.9$ kJ/kg

$\dot{W}_T = 5 \times 3911.7 + 15 \times 3480.6 - 20 \times 2488.9$

$= 21990$ kW = **21.99 MW**

6.32 A small turbine, shown in Fig. P6.32, is operated at part load by throttling a 0.25 kg/s steam supply at 1.4 MPa, 250°C down to 1.1 MPa before it enters the turbine and the exhaust is at 10 kPa. If the turbine produces 110 kW, find the exhaust temperature (and quality if saturated).

C.V. Turbine, SSSF, no heat transfer, specific work: $w = \frac{110}{0.25} = 440$ kJ/kg

Energy Eq.: $h_1 = h_2 = h_3 + w = 2927.2$ (B.1.3)

$\Rightarrow \quad h_3 = 2927.2 - 440 = 2487.2$ kJ/kg

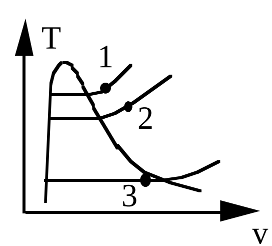
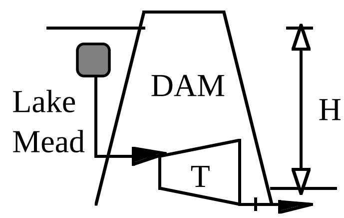


Table B.1.2: $2487.2 = 191.83 + x_3 \times 2392.8$

$\Rightarrow \quad T = 45.8°C, \quad x_3 =$ **0.959**

6.33 Hoover Dam across the Colorado River dams up Lake Mead 200 m higher than the river downstream. The electric generators driven by water-powered turbines deliver 1300 MW of power. If the water is 17.5°C, find the minimum amount of water running through the turbines.

C.V.: H_2O pipe + turbines,



Continuity: $\dot{m}_{in} = \dot{m}_{ex}$;

$\dot{m}_{in}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}_{ex}(h + \mathbf{V}^2/2 + gz)_{ex} + \dot{W}_T$

Water states: $h_{in} \cong h_{ex}$; $v_{in} \cong v_{ex}$ so

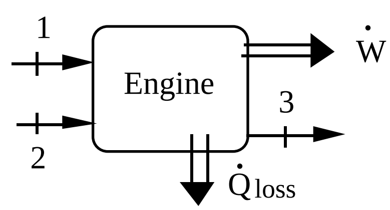
$w_T = gz_{in} - gz_{ex} = 9.807 \text{ x } 200/1000 = 1.961 \text{ kJ/kg}$

$$\dot{m} = \dot{W}_T/w_T = \frac{1300\text{x}10^3 \text{ kW}}{1.961 \text{ kJ/kg}} = 6.63\text{x}10^5 \text{ kg/s}$$

$\dot{V} = \dot{m}v = 6.63\text{x}10^5 \text{ x } 0.001001 = \mathbf{664\ m^3/s}$

6.34 A large SSSF expansion engine has two low velocity flows of water entering. High pressure steam enters at point 1 with 2.0 kg/s at 2 MPa, 500°C and 0.5 kg/s cooling water at 120 kPa, 30°C enters at point 2. A single flow exits at point 3 with 150 kPa, 80% quality, through a 0.15 m diameter exhaust pipe. There is a heat loss of 300 kW. Find the exhaust velocity and the power output of the engine.

C.V. : Engine (SSSF)



Constant rates of flow, $\dot{Q}_{loss}$ and $\dot{W}$

State 1: Table B.1.3: $h_1 = 3467.6$

State 2: Table B.1.1: $h_2 = 125.77$

$h_3 = 467.1 + 0.8 \times 2226.5 = 2248.3 \text{ kJ/kg}$

$v_3 = 0.00105 + 0.8 \times 1.15825 = 0.92765 \text{ m}^3\text{/kg}$

Continuity : $\dot{m}_1 + \dot{m}_2 = \dot{m}_3 = 2 + 0.5 = 2.5 \text{ kg/s} = (AV/v) = (\pi/4)D^2V/v$

Energy Eq. : $\dot{m}_1h_1 + \dot{m}_2h_2 = \dot{m}_3(h_3 + 0.5\ V^2) + \dot{Q}_{loss} + \dot{W}$

$\mathbf{V} = \dot{m}_3v_3 / [(\pi/4)D^2] = 2.5 \times 0.92765/(0.7854 \times 0.15^2) = \mathbf{131.2\ m/s}$

$0.5\ \mathbf{V}^2 = 0.5 \times 131.2 \times 131.2/1000 = 8.6$ kJ/kg (remember units factor 1000)

$\dot{W} = 2 \times 3467.6 + 0.5 \times 125.77 - 2.5\ (2248.3 + 8.6) - 300 = \mathbf{1056\ kW}$

6.35 A small water pump is used in an irrigation system. The pump takes water in from a river at 10°C, 100 kPa at a rate of 5 kg/s. The exit line enters a pipe that goes up to an elevation 20 m above the pump and river, where the water runs into an open channel. Assume the process is adiabatic and that the water stays at 10°C. Find the required pump work.

C.V. pump + pipe. SSSF, 1 inlet, 1 exit. Cont.: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$

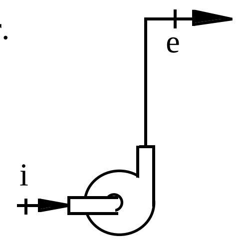
Assume same velocity in and out, same height, no heat transfer.

Energy Eq.:

$$\dot{m}(h_{in} + (1/2)\mathbf{V}_{in}^2 + gz_{in}) = \dot{m}(h_{ex} + (1/2)\,\mathbf{V}_{ex}^2 + gz_{ex}) + \dot{W}$$

$$\dot{W} = \dot{m}(gz_{in} - gz_{ex}) = 5 \times 9.807 \times (0 - 20)/1000 = \mathbf{-0.98\ kW}$$

I.E. 0.98 kW required input



6.36 The compressor of a large gas turbine receives air from the ambient at 95 kPa, 20°C, with a low velocity. At the compressor discharge, air exits at 1.52 MPa, 430°C, with velocity of 90 m/s. The power input to the compressor is 5000 kW. Determine the mass flow rate of air through the unit.

C.V. Compressor, SSSF energy Eq.: $q + h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2 + w$

Here $q \cong 0$ and $\mathbf{V}_i \cong 0$ so for const C_{Po}

$$-w = C_{Po}(T_e - T_e) + \mathbf{V}_e^2/2 = 1.004(430 - 20) + \frac{(90)^2}{2 \times 1000} = 415.5 \text{ kJ/kg}$$

$$\dot{m} = \frac{5000}{415.5} = \mathbf{12.0\ kg/s}$$

6.37 Two steady flows of air enters a control volume, shown in Fig. P6.37. One is 0.025 kg/s flow at 350 kPa, 150°C, state 1, and the other enters at 350 kPa, 15°C, both flows with low velocity. A single flow of air exits at 100 kPa, –40°C through a 25-mm diameter pipe, state 3. The control volume rejects 1.2 kW heat to the surroundings and produces 4.5 kW of power. Determine the flow rate of air at the inlet at state 2.

$$A_3 = \frac{\pi}{4} D_3^2 = \frac{\pi}{4}(0.025)^2 = 4.909\text{x}10^{-4} \text{ m}^2$$

$$v_3 = RT_3/P_3 = \frac{0.287 \text{ x } 233.2}{100} = 0.6693 \text{ m}^3\text{/kg}$$

$$\mathbf{V}_3 = \frac{(\dot{m}_1+\dot{m}_2)v_3}{A_3} = \frac{(0.025 + \dot{m}_2)0.6693}{4.909\text{x}10^{-4}} = 1363.5(0.025 + \dot{m}_2)$$

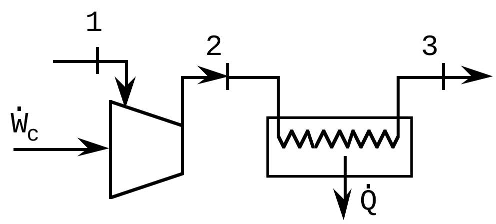
Energy Eq.: $\dot{Q}_{CV} + \dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3(h_3 + \mathbf{V}_3^2/2) + \dot{W}_{CV}$

$$-1.2 + 0.025 \text{ x } 1.004 \text{ x } 423.2 + \dot{m}_2 \text{ x } 1.004 \text{ x } 288.2$$

$$= (0.025 + \dot{m}_2)\left[1.004 \text{ x } 233.2 + \frac{(1363.5(0.025 + \dot{m}_2))^2}{2 \text{ x } 1000}\right] + 4.5$$

Solving, $\dot{m}_2$ = **0.01815 kg/s**

6.38 An air compressor takes in air at 100 kPa, 17°C and delivers it at 1 MPa, 600 K to a constant-pressure cooler, which it exits at 300 K. Find the specific compressor work and the specific heat transfer.



C.V. air compressor q = 0

Cont.: $\dot{m}_2 = \dot{m}_1$

Energy: $h_1 + w_c = h_2$

Table A.7:

$w_{c\ in} = h_2 - h_1$ = 607.02 - 290.17 = **316.85 kJ/kg**

C.V. cooler w = ∅ Cont.: $\dot{m}_3 = \dot{m}_1$ Energy: $h_2 = q_{out} + h_3$

$q_{out} = h_2 - h_3$ = 607.02 - 300.19 = **306.83 kJ/kg**

6.39 The following data are for a simple steam power plant as shown in Fig. P6.39.

State	1	2	3	4	5	6	7
P MPa	6.2	6.1	5.9	5.7	5.5	0.01	0.009
T °C		45	175	500	490		40

State 6 has $x_6 = 0.92$, and velocity of 200 m/s. The rate of steam flow is 25 kg/s, with 300 kW power input to the pump. Piping diameters are 200 mm from steam generator to the turbine and 75 mm from the condenser to the steam generator. Determine the power output of the turbine and the heat transfer rate in the condenser.

Turbine $A_5 = (\pi/4)(0.2)^2 = 0.03142 \text{ m}^2$

$\mathbf{V}_5 = \dot{m}v_5/A_5 = 25 \text{ x } 0.06163/0.03142 = 49 \text{ m/s}$

$h_6 = 191.83 + 0.92 \text{ x } 2392.8 = 2393.2$

$w_T = 3404.2 - 2393.2 - (200^2 - 49^2)/(2 \text{ x } 1000) = 992.2$

$\dot{W}_T = \dot{m}w_T = 25 \text{ x } 992.2 = \mathbf{24805 \text{ kW}}$

6.40 For the same steam power plant as shown in Fig. P6.39 and Problem 6.39, determine the rate of heat transfer in the economizer which is a low temperature heat exchanger and the steam generator. Determine also the flow rate of cooling water through the condenser, if the cooling water increases from 15° to 25°C in the condenser.

Condenser $A_7 = (\pi/4)(0.075)^2 = 0.004418 \text{ m}^2$

$\mathbf{V}_7 = \dot{m}v/A_7 = 25 \text{ x } 0.001008/0.004418 = 5.7 \text{ m/s}$

$q_{COND} = 167.57\text{-}2393.2 - (200^2 - 5.7^2)/(2\text{x}1000) = -2245.6 \text{ kJ/kg}$

$\dot{Q}_{COND} = 25 \text{ x } (-2245.6) = -56140 \text{ kW} = \dot{m}_{H_2O}(h_{out} - h_{in})_{H_2O}$

$$=> \qquad \dot{m}_{H_2O} = \frac{56140}{104.9 - 63.0} = \mathbf{1339.9 \text{ kg/s}}$$

Economizer $\mathbf{V}_2 = 5.7$ m/s, $\mathbf{V}_3 = 6.3 \text{ m/s} \approx \mathbf{V}_2$

$q_{ECON} = h_{out} - h_{in} = 743.95 - 193.76 = 550.19 \text{ kJ/kg}$

$\dot{Q}_{ECON} = 25(550.19) = \mathbf{13755 \text{ kW}}$

Generator $\mathbf{V}_4 = 25 \text{ x } 0.06023/0.03142 = 47.9 \text{ m/s}$

$q_{GEN} = 3425.7 - 743.95 + (47.9^2 - 6.3^2)/(2\text{x}1000) = 2682.9 \text{ kJ/kg}$

$\dot{Q}_{GEN} = 25 \text{ x } (2682.9) = \mathbf{67072 \text{ kW}}$

6.41 Cogeneration is often used where a steam supply is needed for industrial process energy. Assume a supply of 5 kg/s steam at 0.5 MPa is needed. Rather than generating this from a pump and boiler, the setup in Fig. P6.41 is used so the supply is extracted from the high-pressure turbine. Find the power the turbine now cogenerates in this process.

C.V. Turbine, SSSF, 1 inlet and 2 exit flows, assume adiabatic, $\dot{Q}_{CV} = 0$

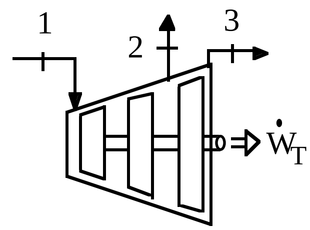
Supply state 1: 20 kg/s at 10 MPa, 500C

Process steam 2: 5 kg/s, 0.5 MPa, 155 C,

Exit state 3: 20 kPa, x = 0.9

Table B.1: $h_1 = 3373.7$, $h_2 = 2755.9$,

$h_3 = 251.4 + 0.9 \times 2358.3 = 2373.9$



Energy Eq.: $\dot{Q}_{CV} + \dot{m}_1h_1 = \dot{m}_2h_2 + \dot{m}_3h_3 + \dot{W}_{CV}$;

$\dot{W}_{CV} = 20 \times 3373.7 - 5 \times 2755.9 - 15 \times 2373.9 =$ **18.084 MW**

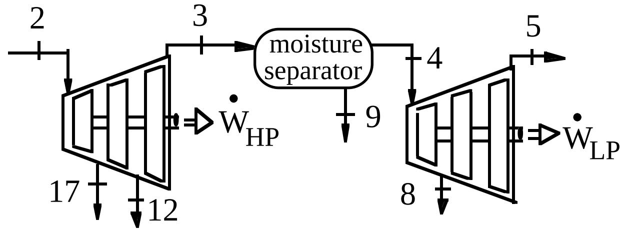
6.42 A somewhat simplified flow diagram for a nuclear power plant shown in Fig. 1.4 is given in Fig. P6.42. Mass flow rates and the various states in the cycle are shown in the accompanying table. The cycle includes a number of heaters in which heat is transferred from steam, taken out of the turbine at some intermediate pressure, to liquid water pumpedfrom the condenser on its way to the steam drum. The heat exchanger in the reactor supplies 157 MW, and it may be assumed that there is no heat transfer in the turbines.

a. Assume the moisture separator has no heat transfer between the two turbinesections, determine the enthalpy and quality (h_4, x_4).

b. Determine the power output of the low-pressure turbine.

c. Determine the power output of the high-pressure turbine.

d. Find the ratio of the total power output of the two turbines to the total power delivered by the reactor.



a) Moisture Separator, SSSF, no heat transfer, no work

Mass: $\dot{m}_3 = \dot{m}_4 + \dot{m}_9$, Energy: $\dot{m}_3 h_3 = \dot{m}_4 h_4 + \dot{m}_9 h_9$;

$62.874 \times 2517 = 58.212 \times h_4 + 4.662 \times 558$

$h_4 = 2673.9 = 566.18 + x_4 \times 2160.6$ => $x_4 =$ **0.9755**

b) Low Pressure Turbine, SSSF no heat transfer

$\dot{m}_4 h_4 = \dot{m}_5 h_5 + \dot{m}_8 h_8 + \dot{W}_{CV(LP)}$

$58.212 \times 2673.9 = 55.44 \times 2279 + 2.772 \times 2459 + \dot{W}_{CV(LP)}$

$\dot{W}_{CV(LP)} = 22489$ kW = **22.489 MW**

c) High Pressure Turbine, SSSF no heat transfer

$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_{12} h_{12} + \dot{m}_{17} h_{17} + \dot{W}_{CV(HP)}$

$75.6 \text{x} 2765 = 62.874 \text{x} 2517 + 8.064 \text{x} 2517 + 4.662 \text{x} 2593 + \dot{W}_{CV(HP)}$

$\dot{W}_{CV(HP)} = 18\,394$ kW = **18.394 MW**

d) $(\dot{W}_{HP} + \dot{W}_{LP})/\dot{Q}_{REACT} = 40.883/157 =$ **0.26**

6.43 Consider the powerplant as described in the previous problem.
a.Determine the quality of the steam leaving the reactor.
b.What is the power to the pump that feeds water to the reactor?

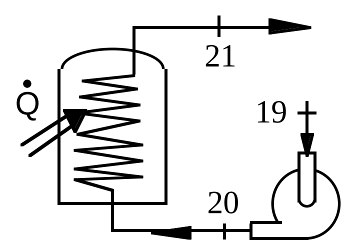
a) Reactor: Cont.: $\dot{m}_{20} = \dot{m}_{21}$; $\dot{Q}_{CV} = 157$ MW

Energy Eq.: $\dot{Q}_{CV} + \dot{m}_{20} h_{20} = \dot{m}_{21} h_{21}$

$157000 + 1386 \times 1221 = 1386 \times h_{21}$

$h_{21} = 1334.3 = 1282.4 + x_{21} \times 1458.3$

=> $x_{21} =$ **0.0349**



b) C.V. Reactor feedwater pump

Cont. $\dot{m}_{19} = \dot{m}_{20}$ Energy Eq.: $\dot{m}_{19} h_{19} = \dot{m}_{19} h_{20} + \dot{W}_{Cv,P}$

Table B.1: $h_{19} = h(277°\text{C}, 7240 \text{ kPa}) = 1219.8$, $h_{20} = 1221$

$\dot{W}_{Cv,P} = \dot{m}_{19}(h_{19} - h_{20}) = 1386(1219.8 - 1221) =$ **-1663.2 kW**

6.44 Consider the powerplant as described in Problem 6.42.
a. Determine the temperature of the water leaving the intermediate pressure heater, T_{13}, assuming no heat transfer to the surroundings.
b. Determine the pump work, between states 13 and 16.

a) Intermediate Pressure Heater

Energy Eq.: $\dot{m}_{11}h_{11} + \dot{m}_{12}h_{12} + \dot{m}_{15}h_{15} = \dot{m}_{13}h_{13} + \dot{m}_{14}h_{14}$

$75.6 \text{x} 284.6 + 8.064 \text{x} 2517 + 4.662 \text{x} 584 = 75.6 \text{x} h_{13} + 12.726 \text{x} 349$

$h_{13} = 530.35 \rightarrow T_{13} = \mathbf{126.3°C}$

b) The high pressure pump

Energy Eq.: $\dot{m}_{13}h_{13} = \dot{m}_{16}h_{16} + \dot{W}_{Cv,P}$

$\dot{W}_{Cv,P} = \dot{m}_{13}(h_{13} - h_{16}) = 75.6(530.35 - 565) = \mathbf{-2620\ kW}$

6.45 Consider the powerplant as described in Problem 6.42.
a. Find the power removed in the condenser by the cooling water (not shown).
b. Find the power to the condensate pump.
c. Do the energy terms balance for the low pressure heater or is there a heat transfer not shown?

a) Condenser: $\dot{Q}_{CV} + \dot{m}_5h_5 + \dot{m}_{10}h_{10} = \dot{m}_6h_6$

$\dot{Q}_{CV} + 55.44 \text{ x } 2279 + 20.16 \text{ x } 142.51 = 75.6 \text{ x } 138.3$

$\dot{Q}_{CV} = -118765 \text{ kW} = \mathbf{-118.77\ MW}$

b) The condensate pump

$\dot{W}_{Cv,P} = \dot{m}_6(h_6 - h_7) = 75.6(138.31 - 140) = \mathbf{-127.8\ kW}$

c) Low pressure heater Assume no heat transfer

$\dot{m}_{14}h_{14} + \dot{m}_8h_8 + \dot{m}_7h_7 + \dot{m}_9h_9 = \dot{m}_{10}h_{10} + \dot{m}_{11}h_{11}$

LHS = 12.726x349 + 2.772x2459 + 75.6x140 + 4.662x558 = 24443 kW

RHS = (12.726 + 2.772 + 4.662) x 142.51 + 75.6 x 284.87 = 24409 kW

A slight imbalance, but OK.

6.46 A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Fig. P6.46. The high-pressure water at 1.5 MPa, 180°C, is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 400 kPa. The liquid is discarded while the saturated vapor feeds the turbine and exits at 10 kPa, 90% quality. If the turbine should produce 1 MW, find the required mass flow rate of hot geothermal water in kilograms per hour.

$$h_1 = 763.5 = 604.74 + x \text{ x } 2133.8 \Rightarrow \quad x = 0.07439 = \dot{m}_2/\dot{m}_1$$

Table B.1.2: $h_2 = 2738.6$; $h_3 = 191.83 + 0.9 \text{ x } 2392.8 = 2345.4$

$$\dot{W} = \dot{m}_2(h_2 - h_3) \qquad \dot{m}_2 = \frac{1000}{2738.6 - 2345.4} = 2.543$$

$\Rightarrow \dot{m}_1 = 34.19$ kg/s = **123075 kg/h**

6.47 A R-12 heat pump cycle shown in Fig. P6.47 has a R-12 flow rate of 0.05 kg/s with 4 kW into the compressor. The following data are given

State	1	2	3	4	5	6
P kPa	1250	1230	1200	320	300	290
T °C	120	110	45		0	5

Calculate the heat transfer from the compressor, the heat transfer from the R-12 in the condenser and the heat transfer to the R-12 in the evaporator.

a) CV: Compressor

$$\dot{Q}_{COMP} = \dot{m}(h_1 - h_e) + \dot{W}_{COMP}$$

$$= 0.05(260.023 - 191.009) - 4.0 = \mathbf{-0.549\ kW}$$

b) CV: Condenser

$$\dot{Q}_{COND} = \dot{m}(h_3 - h_2) = 0.05(79.647 - 252.720) = \mathbf{-8.654\ kW}$$

c) CV: Evaporator $\quad h_4 = h_3 = 79.647$ (from valve)

$$\dot{Q}_{EVAP} = \dot{m}(h_5 - h_4) = 0.05(187.583 - 79.647) = \mathbf{5.397\ kW}$$

6.48 A rigid 100-L tank contains air at 1 MPa, 200°C. A valve on the tank is now opened and air flows out until the pressure drops to 100 kPa. During this process, heat is transferred from a heat source at 200°C, such that when the valve is closed, the temperature inside the tank is 50°C. What is the heat transfer?

1 : 1 MPa, 200°C, $m_1 = P_1V_1/RT_1 = 1000 \times 0.1/(0.287 \times 473.1) = 0.736$ kg

2 : 100 kPa, 50°C, $m_2 = P_2V_2/RT_2 = 100 \times 0.1/(0.287 \times 323.1) = 0.1078$ kg

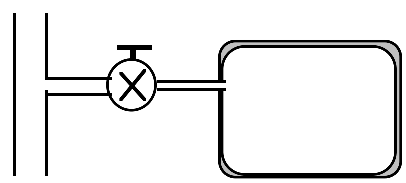
$m_{ex} = m_1 - m_2 = 0.628$ kg, $\quad m_2u_2 - m_1u_1 = - m_{ex} h_{ex} + {}_1Q_2$

Table A.7: $u_1 = 340.0$ kJ/kg, $u_2 = 231.0$ kJ/kg,

$h_{e\ ave} = (h_1 + h_2)/2 = (475.8 + 323.75)/2 = 399.8$ kJ/kg

${}_1Q_2 = 0.1078 \times 231.0 - 0.736 \times 340.0 + 0.628 \times 399.8 =$ **+25.7 kJ**

6.49 A 25-L tank, shown in Fig. P6.49, that is initially evacuated is connected by a valve to an air supply line flowing air at 20°C, 800 kPa. The valve is opened, and air flows into the tank until the pressure reaches 600 kPa.Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the line temperature and the final temperature using constant specific heats.



a) C.V. Tank: Continuity Eq.: $m_i = m_2$

Energy Eq.: $m_ih_i = m_2u_2$

$u_2 = h_i = 293.64$ (Table A.7)

$\Rightarrow T_2 =$ **410.0 K**

$$m_2 = \frac{P_2V}{RT_2} = \frac{600 \text{ x } 0.025}{0.287 \text{ x } 410} = \mathbf{0.1275\ kg}$$

b) Assuming constant specific heat,

$$h_i = u_i + RT_i = u_2\,, \quad RT_i = u_2 - u_i = C_{Vo}(T_2 - T_i)$$

$$C_{Vo}T_2 = (\ C_{Vo} + R\ )T_i = C_{Po}T_i\ , \quad T_2 = \left(\frac{C_{Po}}{C_{Vo}}\right)T_i = kT_i$$

For $T_i = 293.2$K & constant C_{Po}, $\quad T_2 = 1.40 \text{x} 293.2 =$ **410.5K**

6.50 A 100-L rigid tank contains carbon dioxide gas at 1 MPa, 300 K. A valve is cracked open, and carbon dioxide escapes slowly until the tank pressure has dropped to 500 kPa. At this point the valve is closed. The gas remaining inside the tank may be assumed to have undergone a polytropic expansion, with polytropic exponent *n* = 1.15. Find the final mass inside and the heat transferred to the tank during the process.

$$m_1 = \frac{P_1V}{RT_1} = \frac{1000 \text{ x } 0.1}{0.18892 \text{ x } 300} = 1.764 \text{ kg}$$

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{(n-1)/n} = 300\left(\frac{500}{1000}\right)^{(0.15/1.15)} = 274 \text{ K}$$

$$m_2 = \frac{P_2V}{RT_2} = \frac{500 \text{ x } 0.1}{0.18892 \text{ x } 274} = \mathbf{0.966\ kg}$$

$$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_{e\ AVE}$$

$$= m_2C_{Vo}T_2 - m_1C_{Vo}T_1 + (m_1 - m_2)C_{Po}(T_1 + T_2)/2$$

$$= 0.966 \text{ x } 0.6529 \text{ x } 274 - 1.764 \text{ x } 0.6529 \text{ x } 300$$

$$+ (1.764 - 0.966) \text{ x } 0.8418 \text{ x}(300 + 274)/2 = \mathbf{+20.1\ kJ}$$

6.51 A 1-m^3 tank contains ammonia at 150 kPa, 25°C. The tank is attached to a line flowing ammonia at 1200 kPa, 60°C. The valve is opened, and mass flows in until the tank is half full of liquid, by volume at 25°C. Calculate the heat transferred from the tank during this process.

C.V. Tank. USUF as flows comes in.

Table B.2.2: $m_1 = V/v_1 = 1/0.9552 = 1.047$ kg

$m_{LIQ2} = 0.5/0.001658 = 301.57$, $m_{VAP2} = 0.5/0.12816 = 3.901$

$m_2 = 305.47$, $x_2 = m_{VAP2}/m_2 = 0.01277$,

Table B.2.1: $u_2 = 296.6 + 0.01277 \times 1038.4 = 309.9$ kJ/kg

$u_1 = 1380.6$, $h_i = 1553.4$, $m_i = m_2 - m_1 = 304.42$ kg

$$Q_{CV} + m_ih_i = m_2u_2 - m_1u_1$$

$$Q_{CV} = 305.47 \text{ x } 309.9 - 1.047 \text{ x } 1380.6 - 304.42 \text{ x } 1553.4 = \mathbf{-379666\ kJ}$$

6.52 A nitrogen line, 300 K and 0.5 MPa, shown in Fig. P6.52, is connected to a turbine that exhausts to a closed initially empty tank of 50 m^3. The turbine operates to a tank pressure of 0.5 MPa, at which point the temperature is 250 K. Assuming the entire process is adiabatic, determine the turbine work.

C.V. turbine & tank $\Rightarrow$ USUF

Conservation of mass: $m_i = m_2 \Rightarrow m$

Energy Eq: $m_i h_i = m_2 u_2 + W_{CV}$; $W_{CV} = m(h_i - u_2)$

Table B.6 : i : P_i = 0.5 MPa, T_i = 300K, Nitrogen; h_i = 310.276 kJ/kg

2: P_2 = 0.5 MPa, T_2 = 250 K, $u_2 = h_2 - P_2 v_2$

u_2 = 257.799 - 500(0.14782) = 180.89 kJ/kg

$m_2 = V/v_2$ = 50/0.14782 = 338.25 kg

W_{CV} = 338.25(310.276 - 180.89) = 43764.8 kJ = **43.765 MJ**

6.53 An evacuated 150-L tank is connected to a line flowing air at room temperature, 25°C, and 8 MPa pressure. The valve is opened allowing air to flow into the tank until the pressure inside is 6 MPa. At this point the valve is closed. This filling process occurs rapidly and is essentially adiabatic. The tank is then placed in storage where it eventually returns to room temperature. What is the final pressure?

C.V. Tank: $m_i = m_2$ Energy Eq.: $m_i h_i = m_2 u_2$

constant C_{Po}: $T_2 = (C_P/C_V)\, T_i = kT_i$= 1.4 x 298.2 = 417.5 K

Process: constant volume cooling to T_3:

$P_3 = P_2 \times T_3/T_2$ = 6.0 x 298.15/ 417.5 = **4.29 MPa**

6.54 A 0.5-m diameter balloon containing air at 200 kPa, 300 K, is attached by a valve to an air line flowing air at 400 kPa, 400 K. The valve is now opened, allowing air to flow into the balloon until the pressure inside reaches 300 kPa, at which point the valve is closed. The final temperature inside the balloon is 350 K. The pressure is directly proportional to the diameter of the balloon. Find the work and heat transfer during the process.

C.V. Balloon $m_2 - m_1 = m_{in}$ $m_2 u_2 - m_1 u_1 = m_{in} h_{in} + {}_1Q_2 - {}_1W_2$

Process: $P \sim D \sim (V)^{1/3} \Rightarrow P(V)^{-1/3}$ = constant. Polytropic, n = -1/3

$D_2 = D_1 \times P_2/P_1$ = 0.5 x 300/200 = 0.75 m

$V_1 = \frac{\pi}{6} D_1^3 = 0.0654\ m^3$, $V_2 = \frac{\pi}{6} D_2^3 = 0.221\ m^3$

$$_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{300x0.221 - 200x0.0654}{1 + 1/3} = \mathbf{39.92\ kJ}$$

$m_2 = P_2V_2/RT_2 = (300 \times 0.221)/(0.287 \times 350) = 0.66$ kg

$m_1 = P_1V_1/RT_1 = (200 \times 0.0654)/(0.287 \times 300) = 0.152$ kg

$_1Q_2 = 0.66x250.32 - 0.152x214.364 - 0.508x401.299 + 39.92 = \mathbf{-31.31\ kJ}$

6.55 A 500-L insulated tank contains air at 40°C, 2 MPa. A valve on the tank is opened, and air escapes until half the original mass is gone, at which point the valve is closed. What is the pressure inside then?

$m_1 = P_1V/RT_1 = 2000 \times 0.5/0.287 \times 313.2 = 11.125$ kg;

$m_e = m_1 - m_2$, $m_2 = m_1/2 \Rightarrow m_e = m_2 = 5.5625$ kg

1st law: $0 = m_2u_2 - m_1u_1 + m_eh_{e\ AV}$

$0 = 5.5625x0.717\ T_2 - 11.125x0.717x313.2 + 5.5625x1.004\ (313.2 + T_2)/2$

Solving, $T_2 = 239.4$ K

$$P_2 = \frac{m_2RT_2}{V} = \frac{5.5625 \times 0.287 \times 239.4}{0.5} = \mathbf{764\ kPa}$$

6.56 A steam engine based on a turbine is shown in Fig. P6.56. The boiler tank has a volume of 100 L and initially contains saturated liquid with a very small amount of vapor at 100 kPa. Heat is now added by the burner, and the pressure regulator does not open before the boiler pressure reaches 700 kPa, which it keeps constant. The saturated vapor enters the turbine at 700 kPa and is discharged to the atmosphere as saturated vapor at 100 kPa. The burner is turned off when no more liquid is present in the as boiler. Find the total turbine work and the total heat transfer to the boiler for this process.

State 1: Table B.1.1, $m_1 = V/v_1 = 0.1/0.001043 = 95.877$ kg

$m_2 = V/v_g = 0.1/0.2729 = 0.366$ kg, $m_e = 95.511$ kg

$W_{turb} = m_e(h_{in} - h_{ex}) = 95.511 \times (2763.5 - 2675.5) = \mathbf{8405\ kJ}$

$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_e$

$= 0.366 \times 2572.5 - 95.877 \times 417.36 + 95.511 \times 2763.5$

$= 224871\ \text{kJ} = \mathbf{224.9\ MJ}$

6.57 A 2-m^3 insulated vessel, shown in Fig. P6.57, contains saturated vapor steam at 4 MPa. A valve on the top of the tank is opened, and steam is allowed to escape. During the process any liquid formed collects at the bottom of the vessel, so that only saturated vapor exits. Calculate the total mass that has escaped when the pressure inside reaches 1 MPa.

C.V. Vessel: Mass flows out. $m_e = m_1 - m_2$

$0 = m_2u_2 - m_1u_1 + (m_1\text{-}m_2)h_e$ or $m_2(h_e\text{-}u_2) = m_1(h_e\text{-}u_1)$

But $h_e \approx (h_{G1}+h_{G2})/2 = (2801.4+2778.1)/2 = 2789.8$

$m_1 = V/v_1 = 40.177$ kg, $m_2 = V/v_2$

$$\Rightarrow \quad \frac{2}{v_2}(2789.8\text{-}u_2) = 40.177(2789.8\text{-}2602.3) = 7533.19$$

But $v_2 = .001\,127 + .193\,313\,x_2$ and $u_2 = 761.7 + 1822\,x_2$

Substituting and solving, $x_2 = 0.7936$

$\Rightarrow m_2 = V/v_2 = 12.94$ kg, $m_e =$ **27.24 kg**

6.58 A 1-m^3 insulated, 40-kg rigid steel tank contains air at 500 kPa, and both tank and air are at 20°C. The tank is connected to a line flowing air at 2 MPa, 20°C. The valve is opened, allowing air to flow into the tank until the pressure reaches 1.5 MPa and is then closed. Assume the air and tank are always at the same temperature and find the final temperature.

1st law: $m_ih_i = (m_2u_2 - m_1u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST}$

$$m_{1\ AIR} = \frac{P_1V}{RT_1} = \frac{500 \text{ x } 1}{0.287 \text{ x } 293.2} = 5.94 \text{ kg}$$

$$m_{2\ AIR} = \frac{P_2V}{RT_2} = \frac{1500 \text{ x } 1}{0.287 \text{ x } T_2}$$

$m_i = (m_2 - m_1)_{AIR} = (5226.5/T_2) - 5.94$

$$[(5226.5/T_2) - 5.94] \text{ x } 1.004 \text{ x } 293.15 = \frac{5226.5}{T_2} \text{ x } 0.717 \text{ x } T_2$$

$$- 5.94 \text{ x } 0.717 \text{ x } 293.15 + 40 \text{ x } 0.48\,(T_2 - 293.15)$$

Solving, $T_2 = 321.3$ K = **48.1°C**

6.59 A 750-L rigid tank, shown in Fig. P6.59, initially contains water at 250°C, 50% liquid and 50% vapor, by volume. A valve at the bottom of the tank is opened, and liquid is slowly withdrawn. Heat transfer takes place such that the temperature remains constant. Find the amount of heat transfer required to the state where half the initial mass is withdrawn.

CV: vessel

$m_{LIQ1} = \frac{0.375}{0.001251} = 299.76$ kg; $m_{VAP1} = \frac{0.375}{0.05013} = 7.48$ kg

$m_1 = 307.24$ kg; $m_e = m_2 = 153.62$ kg

$v_2 = \frac{0.75}{153.62} = 0.004882 = 0.001251 + x_2 \text{ x } 0.04888$

$x_2 = 0.07428$; $u_2 = 1080.39 + 0.07428 \text{ x } 1522 = 1193.45$

$m_1u_1 = 299.76 \text{ x } 1080.39 + 7.48 \text{ x } 2602.4 = 343324$ kJ

$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_e$

$= 153.62 \text{ x } 1193.45 - 343324 + 153.62 \text{ x } 1085.36 =$ **6744 kJ**

6.60 An initially empty bottle, $V = 0.25$ m^3, is filled with water from a line at 0.8 MPa, 350°C. Assume no heat transfer and that the bottle is closed when the pressure reaches line pressure. Find the final temperature and mass in the bottle.

C.V. bottle + valve, ${}_1Q_2 = 0$, ${}_1W_2 = 0$, USUF

Continuity Eq.: $m_2 - m_1 = m_i$; $m_1 = 0$; Energy Eq.: $m_2u_2 = m_ih_i$

State 2: $P_2 = P_{line}$, $u_2 = h_i = 3161.7$ kJ/kg

$\Rightarrow$ $\mathbf{T_2 \cong 520°C}$, $v_2 = 0.4554$

$m_2 = V/v_2 = 0.25/0.4554 =$ **0.549 kg**

6.61 A supply line of ammonia at 0°C, 450 kPa is used to fill a 0.05-m^3 container initially storing ammonia at 20°C, 100 kPa. The supply line valve is closed when the pressure inside reaches 290.9 kPa. Find the final mass and temperature in the container.

C.V. Container + valve, ${}_1W_2 = \emptyset$, USUF. Assume ${}_1Q_2 = \emptyset$

State 1: $v_1 = 1.4153$ m^3/kg, $m_1 = V/v_1 = 0.0353$ kg

$u_1 = h_1 - P_1 v_1 = 1516.1 - 100 \text{ x } 1.4153 = 1374.6$ kJ/kg

Cont.: $m_2 - m_1 = m_i$; Energy Eq.: $m_2u_2 - m_1u_1 = m_ih_i$

$m_2u_2 = (m_2 - m_1)h_i + m_1u_1 \Rightarrow m_2(u_2 - h_i) = m_1(u_1 - h_i)$

Inlet $h_i = 180.36$ kJ/kg and State 2: P_2, energy eq.

$m_2(u_2 - 180.36) = 0.0353(1374.6 - 180.36) = 42.157$

Assume saturated mixture:

$m_2 = V/v_2 = V/(u_{f2} + x_2 v_{fg})$; $u_2 = u_f + x_2 u_{fg}$

$134.063 + x_2 \times 1175.26 - 180.36 = 42.157(0.001534 + x_2 \times 0.41684)/0.05$

$x_2 = 0.05777$ => Therefore, state 2 is saturated $\Rightarrow v_2 = 0.02561\ m^3/kg$

$T_2 =$ **-10°C** $m_2 = V/v_2 =$ **1.952 kg**

6.62 An insulated spring-loaded piston/cylinder, shown in Fig. P6.62, is connected to an air line flowing air at 600 kPa, 700 K by a valve. Initially the cylinder is empty and the spring force is zero. The valve is then opened until the cylinder pressure reaches 300 kPa. By noting that $u_2 = u_{line} + C_V(T_2 - T_{line})$ and $h_{line} - u_{line} = RT_{line}$ find an expression for T_2 as a function of P_2, P_o, T_{line}. With P = 100 kPa, find T_2.

C.V. Air in cylinder, insulated so $_1Q_2 = 0$

Cont.: $m_2 - m_1 = m_{in}$; Energy Eq.: $m_2u_2 - m_1u_1 = m_{in}h_{line} - {}_1W_2$

$m_1 = 0 \Rightarrow m_{in} = m_2$; $m_2u_2 = m_2h_{line} - \frac{1}{2}(P_0 + P_2)m_2v_2$

$$\Rightarrow \quad u_2 + \frac{1}{2}(P_0 + P_2)v_2 = h_{line}$$

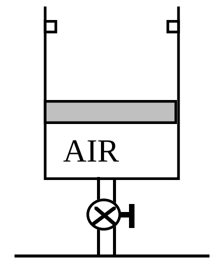
$$C_V(T_2 - T_{line}) + u_{line} + \frac{1}{2}(P_0 + P_2)RT_2/P_2 = h_{line}$$

$$\boldsymbol{\left[C_V + \frac{1}{2}\frac{P_0 + P_2}{P_2}R\right]T_2 = (R + C_V)T_{line}}$$

with #'s: $T_2 = \dfrac{R + C_V}{\frac{2}{3}R + C_V}T_{line}$; $C_V/R = 1/(k-1)$, $k = 1.4$

$$T_2 = \frac{k - 1 + 1}{\frac{2}{3}k - \frac{2}{3} + 1}T_{line} = \frac{3k}{2k + 1}T_{line} = 1.105\ T_{line} = \mathbf{773.7\ K}$$

6.63 A mass-loaded piston/cylinder, shown in Fig. P6.63, containing air is at 300 kPa, 17°C with a volume of 0.25 m^3, while at the stops V = 1 m^3. An air line, 500 kPa, 600 K, is connected by a valve that is then opened until a final inside pressure of 400 kPa is reached, at which point T = 350 K. Find the air mass that enters, the work, and heat transfer.



Open to P_2 = 400 kPa, T_2 = 350 K

$$m_1 = \frac{300 \times 0.25}{0.287 \times 290.2} = 0.90 \text{ kg}$$

$P_1 \rightarrow$ const P to stops, then const V to P_2

$$m_2 = \frac{400 \times 1}{0.287 \times 350} = 3.982 \text{ kg}$$

m_i = 3.982 - 0.90 = **3.082 kg**

CV: inside of cylinder

$_1W_2 = P_1(V_2 - V_1) = 300(1 - 0.25) =$ **225 kJ**

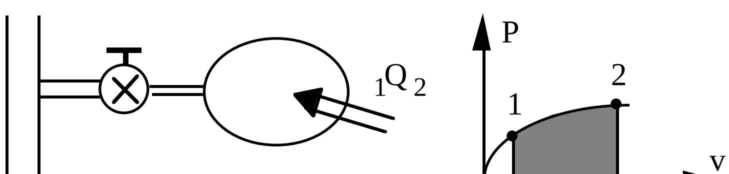
$Q_{CV} + m_ih_i = m_2u_2 - m_1u_1 + {_1W_2}$

$Q_{CV} = 3.982 \times 0.717 \times 350 - 0.90 \times 0.717 \times 290.2 + 225$

$- 3.082 \times 1.004 \times 600 =$ **-819.2 kJ**

6.64 An elastic balloon behaves such that pressure is proportional to diameter and the balloon contains 0.5 kg air at 200 kPa, 30°C. The balloon is momentarily connected to an air line at 400 kPa, 100°C. Air is let in until the volume doubles, during which process there is a heat transfer of 50 kJ out of the balloon. Find the final temperature and the mass of air that enters the balloon.

$m_2 - m_1 = m_i, \quad m_2u_2 - m_1u_1 = m_ih_i + {_1Q_2} - {_1W_2}$



Process: $P \sim D \sim V^{1/3}$

so $P = P_1(V/V_1)^{1/3}$

$V_1 = mRT_1/P_1 = 0.5 \times 0.287 \times 303.15/200 =$ **0.2175 m^3**

$P_2 = P_1(V_2/V_1)^{1/3} = 200 \times 2^{1/3} = 251.98$ kPa

$_1W_2 = \int PdV = P_1V_1^{-1/3}(3/4)(V_2^{4/3} - V_1^{4/3}) = (3/4)(P_2V_2 - P_1V_1)$

$= (3/4)(251.98 \times 0.435 - 200 \times 0.2175) = 49.583$ kJ

$m_2u_2 = m_1u_1 + (m_2 - m_1)h_i + {_1Q_2} - {_1W_2}$

$$m_2u_2 - m_2h_i = m_1u_1 - m_1h_i + {}_1Q_2 - {}_1W_2 \qquad h_i = u_i + RT_i$$

$$m_2(u_2 - u_i - RT_i) = m_1(u_1 - u_i - RT_i) + {}_1Q_2 - {}_1W_2$$

$$(P_2V_2/RT_2)(C_V(T_2 - T_i) - RT_i) = m_1(C_V(T_1 - T_i) - RT_i) + {}_1Q_2 - {}_1W_2$$

$$= 0.5(0.7165(30 - 100) - 0.287 \times 373.15) - 50 - 49.583$$

$$= -178.2$$

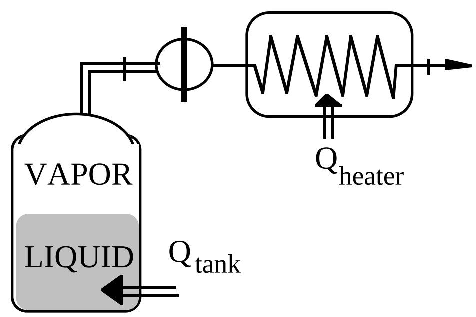
$\Rightarrow T_2 = 316.5 \text{ K} = \mathbf{43.4°C} \quad m_2 = P_2V_2/RT_2 = 1.207 \text{ kg}$

$m_i = m_2 - m_1 = \mathbf{0.707\ kg}$

6.65 A 2-m^3 storage tank contains 95% liquid and 5% vapor by volume of liquified natural gas (LNG) at 160 K, as shown in Fig. P6.65. It may be assumed that LNG has the same properties as pure methane. Heat is transferred to the tank and saturated vapor at 160 K flows into the a steady flow heater which it leaves at 300 K. The process continues until all the liquid in the storage tank is gone. Calculate the total amount of heat transfer to the tank and the total amount of heat transferred to the heater.

CV: Tank, flow out, USUF.

$$Q_{Tank} = m_2u_2 - m_1u_1 + m_eh_e$$



At 160 K, from Table B.7:

$$m_f = V_f/v_f = \frac{0.95 \times 2}{0.00297} = 639.73 \text{ kg}, \quad m_g = V_g/v_g = \frac{0.05 \times 2}{0.03935} = 2.541 \text{ kg}$$

$m_1 = 642.271$ kg, $\qquad m_2 = V/v_{g2} = 2/0.03935 = 50.826$ kg

$$m_1u_1 = 639.73(-106.35) + 2.541(207.7) = -67507 \text{ kJ}$$

$$m_e = m_1 - m_2 = 591.445 \text{ kg}$$

$$Q_{Tank} = 50.826 \times 207.7 - (-67507) + 591.445 \times 270.3$$

$$= \mathbf{+237931\ kJ}$$

CV: Heater, SSSF, $P = P_{G\ 160\ K} = 1593$ kPa

$$Q_{Heater} = m_{e\ Tank}(h_e - h_i)_{Heater}$$

$$= 591.445(612.9 - 270.3) = \mathbf{202629\ kJ}$$

6.66 A spherical balloon is constructed of a material such that the pressure inside is proportional to the balloon diameter to the power 1.5. The balloon contains argon gas at 1200 kPa, 700°C, at a diameter of 2.0 m. A valve is now opened, allowing gas to flow out until the diameter reaches 1.8 m, at which point the temperature inside is 600°C. The balloon then continues to cool until the diameter is 1.4 m.

a) How much mass was lost from the balloon?
b) What is the final temperature inside?
c) Calculate the heat transferred from the balloon during the overall process.

C.V. Balloon. Process 1 - 2 - 3. Flow out in 1- 2, USUF.

Process: $P \propto D^{3/2}$ and since $V \propto D^3$ => $P = C\,V^{1/2}$

State 1: $T_1 = 700^oC$, $P_1 = 1200$ kPa, $V_1 = (\pi/6)\,D_1^3 = 4.188\ m^3$

$m_1 = P_1V_1/RT_1 = 1200x4.1888/(0.20813x973.15) = 24.816$ kg

State 2: $T_2 = 600^oC$, $V_2 = (\pi/6)\,D_2^3 = 3.0536\ m^3$

$$P_2 = P_1\,(V_2/V_1)^{1/2} = 1200\,(3.0536/4.1888)^{1/2} = 1025 \text{ kPa}$$

$m_3 = m_2 = P_2V_2/RT_2 = 1025x3.0536/(0.20813x873.15) = 17.222$ kg

a) $m_E = m_1 - m_2 =$ **7.594 kg**

State 3: $D_3 = 1.4$ m => $V_3 = (\pi/6)\,D_3^3 = 1.4368\ m^3$

$$P_3 = 1200\,(1.4368/4.1888)^{1/2} = 703 \text{ kPa}$$

b) $T_3 = P_3V_3/m_3R =$ 703x1.4368/(17.222x0.20813) = **281.8 K**

c) Process is polytropic with n = -1/2 so the work becomes

$$_1W_3 = \int P\,dV = \frac{P_3V_3 - P_1V_1}{1-n} = \frac{703x1.4368 - 1200x4.1888}{1-(-0.5)} = -2677.7 \text{ kJ}$$

$$_1Q_3 = m_3\,u_3 - m_1u_1 + m_eh_e + {}_1W_3$$

= 17.222x0.312x281.8 - 24.816x0.312x973.15

+ 7.594x0.52x(973.15+873.15)/2 - 2677.7

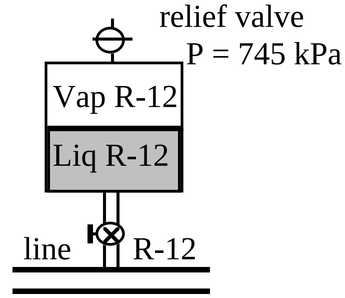
= 1515.2 – 7539.9 + 3647.7 – 2677.7 = **-5054.7 kJ**

6.67 A rigid tank initally contains 100 L of saturated-liquid R-12 and 100 L of saturated-vapor R-12 at 0°C. A valve on the bottom of the tank is connected to a line flowing R-12 at 10°C, 900 kPa. A pressure-relief valve on the top of the tank is set at 745 kPa (when tank pressure reaches that value, mass escapes such that the tank pressure cannot exceed 745 kPa). The line valve is now opened, allowing 10 kg of R-12 to flow in from the line, and then this valve is closed. Heat is transferred slowly to the tank, until the final mass inside is 100 kg, at which point the process is stopped.

a) How much mass exits the pressure-relief valve during the overall process?

b) How much heat is transferred to the tank?

C.V. Tank. There is both an inlet flow from the line and en exit flow through the relief valve, USUF, no work.



Continuity: $m_2 - m_1 = m_i - m_e$

Energy: $m_2 u_2 - m_1 u_1 = m_i h_i - m_e h_e + {}_1Q_2$

a) To find the exit mass find initial mass at state 1:

$$m_{liq} = V/v = \frac{0.10}{0.000716} = 139.665 \text{ kg}$$

$$m_{vap} = V/v = \frac{0.10}{0.055389} = 1.805 \text{ kg}$$

$m_1 = m_{liq} + m_{vap} = 141.47$ kg,

$m_e = m_1 - m_2 + m_i = 141.47 - 100 + 10 =$ **51.47 kg**

$u_1 = (139.665 \text{x} 35.83 + 1.805 \text{x} 170.44)/141.47 = 37.55$ kJ/kg

b) Since $m_e > 0$, $T_2 = T_{G\ 745kPa} = 30^oC$

State 2: $v_2 = V/m_2 = 0.20/100 = 0.002 = 0.000774 + x_2\ 0.022734$

$x_2 = 0.05393$ => $u_2 = 64.02 + 0.05393 \text{x} 118.09 = 70.39$ kJ/kg

Inlet state: comp. liq. ($P_G = 423$ kPa) => $h_i \approx h_{F10°C} = 45.37$ kJ/kg

Exit state: sat. vapor => $h_E = h_{G30°C} = 199.62$ kJ/kg

${}_1Q_2 = m_2 u_2 - m_1 u_1 + m_e h_e - m_i h_i$

$= 100 \text{x} 70.39 - 141.47 \text{x} 37.55 + 51.47 \text{ x} 199.62 - 10 \text{x} 45.37 =$ **11548 kJ**

6.68 A cylinder with a constant load on the piston contains water at 500 kPa, 20 °C and volume of 1 L. The bottom of the cylinder is connected with a line and valve to a steam supply line carrying steam at 1 MPa, 200 °C. The valve is now opened for a short time to let steam in to a final volume of 10 L. The final uniform state is two-phase and there is no heat transfer in the process. What is the final mass inside the cylinder?

Mass: $m_2 - m_1 = m$; Energy: $m_2u_2 - m_1u_1 = m_i\, h_{line} + {}_1Q_2 - {}_1W_2$

1: 500 kPa, 20°C, 1 L, $v_1 = 0.0010$, $h_1 = 83.94$

2: 10 L, Constant load on piston $P_2 = P_1 = 500$ kPa

$_1Q_2 = 0$; $h_{line} = 2827.86$

$_1W_2 = \int P\, dV = P(V_2 - V_1) = P_2V_2 - P_1V_1 = m_2P_2v_2 - P_1m_1v_1$

$m_2u_2 + m_2P_2\, v_2 - [m_1\, v_1 + P_1\, m_1\, v_1] = m_i\, h_{line} + {}_1Q_2 - {}_1W_2$

$m_2h_2 - m_1h_1 = m_ih_{line}$; $V_2 = m_2v_2$

$m_2(h_2 - h_{line}) = m_1(h_1 - h_{line})$; $m_2 = V_2/v_2$; $m_1 = V_1/v_1$

$\Rightarrow$ $V_2(h_2 - h_{line}) = (v_2V_1/v_1)\,(h_1 - h_{line})$

2 phase $\Rightarrow$ x_2 is the single unknown at 500 kPa

$0.01(640.21 + x_2\ 2108.47 - 2827.86)$

$= (0.001093 + x_2 \text{ x } 0.3738)\ (0.001/0.001)(83.94 - 2827.86)$

$- 21.8765 + 21.0847\, x_2 = - 2.9991 - 1025.6773\, x_2$

$x_2 = 0.018034$ => $v_2 = 0.001093 + x_2\, 0.3738 = 0.007834$

$m_2 = V_2\,/v_2 = 0.01/0.007834 =$ **1.276 kg**

Advanced problems

6.69 A 2-m^3 insulated tank containing ammonia at −20°C, 80% quality, is connected by a valve to a line flowing ammonia at 2 MPa, 60°C. The valve is opened, allowing ammonia to flow into the tank. At what pressure should the valve be closed if the manufacturer wishes to have 15 kg of ammonia inside at the final state?

CV: Tank   USUF process

$Q_{CV} + m_i h_i = m_2 u_2 - m_1 u_1 + W_{CV}$; $Q_{CV} = W_{CV} = 0$

$m_1 = \frac{V}{v_1} = \frac{2}{0.49927} = 4.006$ kg, $m_i = m_2 - m_1 = 15 - 4.006 = 10.994$ kg

$u_1 = 1057.5$, $h_i = 1509.9$

$u_2 = \frac{m_i h_i + m_1 u_1}{m_2} = \frac{10.994x1509.9 + 4.006x1057.5}{15} = 1389.1$ kJ/kg

$v_2 = V/m_2 = 2/15 = 0.1333$ kg   Therefore, v_2, u_2 fix state 2.

By trial and error, P_2 = **1081 kPa** & T_2 = 50.4°C

6.70 Air is contained in the insulated cylinder shown in Fig. P6.70. At this point the air is at 140 kPa, 25°C, and the cylinder volume is 15 L. The piston cross-sectional area is 0.045 m^2, and the spring is linear with spring constant 35 kN/m. The valve is opened, and air from the line at 700 kPa, 25°C, flows into the cylinder until the pressure reaches 700 kPa, and then the valve is closed. Find the final temperature.

$m_2 = m_1 + m_i$ 1st law: $m_i h_i = m_2 u_2 - m_1 u_1 + W_{CV}$

Ideal gas, const. specific heat:

$(m_2 - m_1)C_{Po}T_i = m_2 C_{Vo} T_2 - m_1 C_{Vo} T_1 + W_{CV}$ Also $P_2V_2 = m_2RT_2$

Linear spring relation: $P_2 = P_1 + (K/A^2)(V_2 - V_1)$

$$\text{or } 700 = 140 + \frac{35}{(0.045)^2}(V_2 - 0.015);\ V_2 = 0.0474\ m^3$$

$$700 \times 0.0474 = m_2 \times 0.287 \times T_2;\ m_2 = 115.61/T_2$$

$$\text{Also } m_1 = \frac{P_1V_1}{RT_1} = \frac{140 \times 0.015}{0.287 \times 298.2} = 0.02454\ \text{kg}$$

$$W_{CV} = \int PdV = \int \left[P_1 + (K/A^2)(V - V_1)\right] dV$$

$$= 140(0.0474 - 0.015) + \frac{17284}{2}(0.0474^2 - 0.015^2)$$

$$- 259.26\,(0.0474 - 0.015) = 13.6\ \text{kJ}$$

$$\left(\frac{115.61}{T_2} - 0.02454\right) \times 1.0035 \times 298.2$$

$$= 115.61 \times 0.7165 - 0.02454 \times 0.7165 \times 298.2 + 13.6$$

Solving, $T_2 = 351$ K = **77.8°C**

6.71 An inflatable bag, initially flat and empty, is connected to a supply line of saturated vapor R-22 at ambient temperature of 10°C. The valve is opened, and the bag slowly inflates at constant temperature to a final diameter of 2 m. The bag is inflated at constant pressure, $P_o = 100$ kPa, until it becomes spherical at $D_o = 1$ m. After this the pressure and diameter are related according to A maximum pressure of 500 kPa is recorded for the whole process. Find the heat transfer to the bag during the inflation process.

R-22 10°C = T_0 x = 1.0 P_0 = 100 kPa

Balloon spherical at D_0 = 1 m

For $D > D_0$, $P = P_0 + C(D^{*\,-1} - D^{*\,-7})$, $D^* = D/D_0$

slowly inflates (T = const) D_2 = 2 m , P_{MAX} = 500 kPa

$$\frac{dP_{MAX}}{dD^*} = C(-D^{*\,-2}_{MAX} + 7D^{*\,-8}_{MAX}) = 0 \quad D^*_{MAX} = 7^{1/6} = 1.38309$$

$\Rightarrow$ 500 = 100 + C(0.72302 - 0.10329), C = 645.44

$\Rightarrow P_2 = 100 + 645.44(2^{-1} - 2^{-7}) =$ **417.7 kPa**

$$V = (\pi/6)D^3, \quad dV = (\pi/2)D^2\, dD = (\pi/2)D_0^3\, D^{*\,2}\, dD^*$$

$$W = \int PdV = P_0\,(\pi/6)D_0^3 + \int_{D^*=1}^{D^*=2} P\frac{\pi}{2}D_0^3\, D^{*\,2}\, dD^*$$

$$= P_0(\pi/6)D_0^3 + \int \frac{\pi}{2} D_0^3[P_0 + C(D^{*\,-1} - D^{*\,-7})]\, D^{*\,2}\, dD^*$$

$$= P_0\frac{\pi}{6}D_0^3 + \frac{\pi}{2}D_0^3\, P_0\, \frac{1}{3}(8-1) + \int \frac{\pi}{2} D_0^3\, C(D^* - D^{*\,-5})\, dD^*$$

$$= (\pi/6)P_0(1)^3(8) + (\pi/2)D_0^3\, C\Big[\frac{D^{*\,2}}{2} + \frac{D^{*\,-4}}{4}\Big|_1^2$$

$$= \frac{\pi}{6}x100x8 + \frac{\pi}{2}(1)^3x645.44\,\Big[\frac{4}{2} + \frac{1}{64} - \frac{1}{2} - \frac{1}{4}\Big] = 1702 \text{ kJ}$$

$m_2 = m_i = V_2/v_2 = 4.1888/0.060157 = 69.63$ kg

$u_2 = 233.55$ kJ/kg, $h_i = 253.42$ kJ/kg

$Q_{CV} = mu_2 - 0 - m_ih_i + W_{CV} = 69.63(233.55 - 253.42) + 1702.0$

= -1383.5 + 1702.0 = **+318.5 kJ**

6.72 A cylinder, shown in Fig. P6.72, fitted with a piston restrained by a linear spring contains 1 kg of R-12 at 100°C, 800 kPa. The spring constant is 50 kN/m, and the piston cross-sectional area is 0.05 m^2. A valve on the cylinder is opened and R-12 flows out until half the initial mass is left. Heat is transferred so the final temperature of the R-12 is 10°C. Find the final state of the R-12, (P_2, x_2), and the heat transfer to the cylinder.

C.V. The R-12. Flow out, use average so USUF.

Process (linear spring): $P_2 - P_1 = \frac{k_S}{A^2}(V_2 - V_1) = \frac{k_S}{A^2}(m_2v_2 - m_1v_1)$

$$P_2 - 800 = \frac{50}{(0.05)^2}\left(\frac{1}{2}v_2 - 1 \text{ x } 0.029588\right) \text{----} \boxed{*}$$

If state 2 is 2-phase: P_2 = 423 kPa

Equation $\boxed{*}$ => v_2 = 0.021476 2-phase OK

0.021476 = 0.000733 + x_2 x 0.04018 => x_2 = **0.51625**

h_2 = 45.337 + 0.51625x 146.265 = 120.85 h_1 = 249.26

$$W_{CV} = \int_1^2 PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(800 + 423)(0.010738 - 0.029588) = -11.5 \text{ kJ}$$

u_1 = 249.26 - 800 x 0.029588 = 225.59

u_2 = 120.85 - 423 x 0.021476 = 111.77

$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_{e\ AVE} + W_{CV}$

= 0.5 x 111.77 - 1 x 225.59 + 0.5 x 185.06 - 11.5 = **-88.7 kJ**

ENGLISH UNIT PROBLEMS

6.73E Air at 95 F, 16 lbf/in.^{2}, flows in a 4 in. × 6 in. rectangular duct in a heating system. The volumetric flow rate is 30 cfm (ft^3/min). What is the velocity of the air flowing in the duct?

$$A = 4 \times 6 \times \frac{1}{144} = 0.167 \text{ ft}^2$$

$$\dot{V} = \dot{m}v = A\mathbf{V} \qquad \mathbf{V} = \frac{\dot{V}}{A} = \frac{30}{60 \times 0.167} = \mathbf{3.0\ ft/s}$$

$$\left(\begin{array}{l} \text{note ideal gas:} \quad v = \dfrac{RT}{P} = \dfrac{53.34 \times 554.7}{16 \times 144} = 12.842 \text{ ft}^3/\text{lbm} \\ \qquad\qquad \dot{m} = \dfrac{\dot{V}}{v} = \dfrac{30}{60 \times 12.842} = 0.0389 \text{ lbm/s} \end{array} \right)$$

6.74E Saturated vapor R-134a leaves the evaporator in a heat pump at 50 F, with a steady mass flow rate of 0.2 lbm/s. What is the smallest diameter tubing that can be used at this location if the velocity of the refrigerant is not to exceed 20 ft/s?

Table C.11.1: $v_g = 0.792 \text{ ft}^3/\text{lbm}$

$$\dot{m} = A\mathbf{V}/v \;\Rightarrow\; A = \dot{m}v/\mathbf{V} = 0.2 \times 0.792/20 = 0.00792 \text{ ft}^2$$

$$A = \frac{\pi}{4}D^2 \;\Rightarrow\; D = \mathbf{0.1004\ ft} = \mathbf{1.205\ in}$$

6.75E A pump takes 40 F liquid water from a river at 14 lbf/in.^{2} and pumps it up to an irrigation canal 60 ft higher than the river surface. All pipes have diameter of 4 in. and the flow rate is 35 lbm/s. Assume the pump exit pressure is just enough to carry a water column of the 60 ft height with 15 lbf/in.^{2} at the top. Find the flow work into and out of the pump and the kinetic energy in the flow.

Flow work $\dot{m}Pv$; $\quad v_i = v_f = 0.01602$

$$\dot{W}_{flow,\,i} = \dot{m}Pv = 35 \times 14 \times 0.01602 \times 144/778 = 1.453 \text{ Btu/s}$$

$$\mathbf{V}_i = \mathbf{V}_e = \dot{m}v/\left(\frac{\pi}{4}D^2\right) = 35 \times 0.01602 \;\; 144/\left(\frac{\pi}{4}4^2\right) = 6.425 \text{ ft/s}$$

$$KE_i = \frac{1}{2}\mathbf{V}_i^2 = KE_e = \frac{1}{2}\mathbf{V}_e^2 = \frac{1}{2}(6.425)^2 \text{ ft}^2/\text{s}^2 = 20.64 \text{ ft}^2/\text{s}^2$$

$$= 20.64/(32.174\text{x}778) = 0.000825 \text{ Btu/lbm}$$

$$P_e = P_o + Hg/v = 15 + 60 \times 32.174/(32.174 \times 0.01602 \times 144) = 15 + 26$$

$$= 41 \text{ lbf/in}^2$$

$$\dot{W}_{flow,\,e} = \dot{m}P_e v_e = 35 \times 41 \times 0.01602 \times 144/778 = 4.255 \text{ Btu/s}$$

6.76E Carbon dioxide gas enters a steady-state, steady-flow heater at 45 lbf/in.^{2} 60 F, and exits at 40 lbf/in.^{2}, 1800 F. It is shown in Fig. P6.9, where changes in kinetic and potential energies are negligible. Calculate the required heat transfer per lbm of carbon dioxide flowing through the heater.

C.V. heater: $q + h_i = h_e$

Table C.7: $q = h_e - h_i = \dfrac{20470.8 - (-143.4)}{44.01} =$ **468.4 Btu/lbm**

(Use C_{P0} then $q \cong 0.203(1800 - 60) = 353.2$ Btu/lbm)

Too large ΔT, T_{ave} to use C_{p0} at room temperature.

6.77E In a steam generator, compressed liquid water at 1500 lbf/in.^{2}, 100 F, enters a 1-in. diameter tube at the rate of 5 ft^3/min. Steam at 1250 lbf/in.^{2}, 750 F exits the tube. Find the rate of heat transfer to the water.

$A_i = A_e = \dfrac{\pi}{4}\dfrac{(1)^2}{144} = 0.00545 \text{ ft}^2$

$\mathbf{V}_i = \dot{V}_i/A_i = 5/0.00545\times 60 = 15.3$ ft/s

$\mathbf{V}_e = \mathbf{V}_i\times v_e/v_i = 15.3\times 0.503/0.016058 = 479.3$ ft/s

$\dot{m} = 5\times 60/0.016058 = 18\ 682$ lbm/h

$\dot{Q} = \dot{m}[(h_e-h_i) + (\mathbf{V}_e^2-\mathbf{V}_i^2)/2\times g_c]$

$= 18\ 682[1342.4-71.99 + \dfrac{479.3^2-15.3^2}{2\times 32.174\times 778}] = \mathbf{2.382}\times 10^{\mathbf{7}}$ **Btu/h**

6.78E A heat exchanger is used to cool an air flow from 1400 to 680 R, both states at 150 lbf/in.^{2}. The coolant is a water flow at 60 F, 15 lbf/in.^{2} and it is shown in Fig. P6.13. If the water leaves as saturated vapor, find the ratio of the flow rates $\dot{m}_{H_2O}/\dot{m}_{air}$

C.V. Heat exchanger

$$\dot{m}_{air}h_{ai} + \dot{m}_{H_2O}h_{fi} = \dot{m}_{air}h_{ae} + \dot{m}_{H_2O}h_{ge}$$

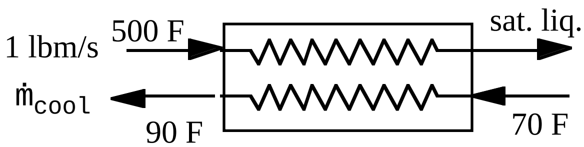
Table C.6: $h_{ai} = 343.016$ Btu/lbm, $h_{ae} = 162.86$ Btu/lbm

Table C.8: $h_{fi} = 28.08$, $h_{ge} = 1150.9$ (at 15 psia)

$\dot{m}_{H_2O}/\dot{m}_{air} = (h_{ai} - h_{ae})/(h_{ge} - h_{fi})$

$= (343.016 - 162.86)/(1150.9 - 28.08) =$ **0.1604**

6.79E A condenser, as the heat exchanger shown in Fig. P6.14, brings 1 lbm/s water flow at 1 lbf/in.^{2} from 500 F to saturated liquid at 1 lbf/in.^{2}. The cooling is done by lake water at 70 F that returns to the lake at 90 F. For an insulated condenser, find the flow rate of cooling water.



C.V. Heat exchanger

$$\dot{m}_{cool}h_{70} + \dot{m}_{H_2O}h_{500} = \dot{m}_{cool}h_{90} + \dot{m}_{H_2O}h_{f\,1}$$

Table C.8.1,2: $h_{70} = 38.09$, $h_{90} = 58.07$, $h_{500,1} = 1288.5$, $h_{f,1} = 69.74$

$$\dot{m}_{cool} = \dot{m}_{H_2O} \frac{h_{500} - h_{f,\,1}}{h_{90} - h_{70}} = 1 \times \frac{1288.5 - 69.74}{58.07 - 38.09} = \mathbf{61\ lbm/s}$$

6.80E Four pound-mass of water at 80 lbf/in.^{2}, 70 F is heated in a constant pressure process (SSSF) to 2600 F. Find the best estimate for the heat transfer.

C.V. Water; $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$

$$q + h_{in} = h_{ex} \;\Rightarrow\; q = h_{ex} - h_{in}$$

steam tables only go up to 1400 F so use an intermediate state at lowest pressure (closest to ideal gas)

h_X(1400F, 1 psia) from Table C.8 and Table C.7 for the Δh at high T

$$h_{ex} - h_{in} = (h_{ex} - h_X) + (h_X - h_{in})$$

$$= (24832 - 11776)/18.015 + 1748.1 - 38.09$$

$$= 2434.7 \text{ Btu/lbm}$$

$$Q = m(h_{ex} - h_{in}) = 4 \times 2434.7 = \mathbf{9739\ Btu}$$

6.81E Nitrogen gas flows into a convergent nozzle at 30 lbf/in.^{2}, 600 R and very low velocity. It flows out of the nozzle at 15 lbf/in.^{2}, 500 R. If the nozzle is insulated find the exit velocity.

C.V. Nozzle : Continuity Eq.: $\dot{m}_i = \dot{m}_e$

With $q = 0$; $w = 0$ then Energy Eq.:, $h_i + 0 = h_e + (1/2)\mathbf{V}_e^2$

$$(1/2)\mathbf{V}_e^2 = h_i - h_e = C_P\,(T_i - T_e) = 0.249 \times (600 - 500) = 24.9 \text{ Btu/lbm}$$

$$\mathbf{V}_e^2 = 2 \times 24.9 \times 778 \times 32.174 \text{ ft}^2/\text{s}^2 = 1\,246\,562 \text{ ft}^2/\text{s}^2$$

$$\mathbf{V_e = 1116\ ft/s}$$

6.82E A diffuser shown in Fig. P6.20 has air entering at 14.7 lbf/in.^{2}, 540 R, with a velocity of 600 ft/s. The inlet cross-sectional area of the diffuser is 0.2 in.^{2}. At the exit, the area is 1.75 in.^{2}, and the exit velocity is 60 ft/s. Determine the exit pressure and temperature of the air.

Cont: $\dot{m}_i = A_i\mathbf{V}_i/v_i = \dot{m}_e = A_e\mathbf{V}_e/v_e$, Energy: $h_i + (1/2)\mathbf{V}_i^2 = h_e + (1/2)\mathbf{V}_e^2$

$h_e - h_i = (1/2)x(600^2 - 60^2)/(32.174x778) = 7.119$ Btu/lbm

$T_e = T_i + 7.119/0.24 = 569.7$ R

$v_e = v_i(A_e\mathbf{V}_e/A_i\mathbf{V}_i) = (RT_i/P_i)(A_e\mathbf{V}_e/A_i\mathbf{V}_i) = RT_e/P_e$

$P_e = P_i(T_e/T_i)(A_i\mathbf{V}_i/A_e\mathbf{V}_e) = 14.7(569.7/540)[0.2 \times 600/1.75\times 60] =$ **17.72 lbf/in.^{2}**

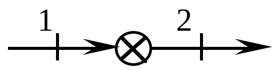
6.83E Helium is throttled from 175 lbf/in.^{2}, 70 F, to a pressure of 15 lbf/in.^{2}. The. diameter of the exit pipe is so much larger than the inlet pipe that the inlet and exit velocities are equal. Find the exit temperature of the helium and the ratio of the pipe diameters.

Energy Eq.: $h_e = h_i$, Ideal gas $\rightarrow T_e = T_i =$ **75 F** , $\dot{m} = A\mathbf{V}/(RT/P)$

But $\dot{m}$, $\mathbf{V}$ & T constant $\Rightarrow$ $D_2/D_1 = (P_1/P_2)^{1/2} = (175/15)^{1/2} =$ **3.416**

6.84E Water flowing in a line at 60 lbf/in.^{2}, saturated vapor, is taken out through a valve to 14.7 lbf/in.^{2}. What is the temperature as it leaves the valve assuming no changes in kinetic energy and no heat transfer?

C.V. Valve (SSSF)



Cont.: $\dot{m}_1 = \dot{m}_2$; Energy: $\dot{m}_1h_1 + \dot{Q} = \dot{m}_2h_2 + \dot{W}$

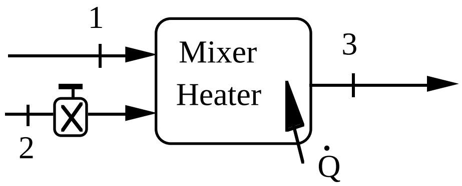
Small surface area: $\dot{Q} = 0$; No shaft: $\dot{W} = 0$

Table C.8.1 $h_2 = h_1 = 1178 \Rightarrow$ **T_2 = 254.6 F**

6.85E An insulated mixing chamber receives 4 lbm/s R-134a at 150 lbf/in.^{2}, 220 F in a line with low velocity. Another line with R-134a as saturated liquid 130 F flows through a valve to the mixing chamber at 150 lbf/in.^{2} after the valve. The exit flow is saturated vapor at 150 lbf/in.^{2} flowing at 60 ft/s. Find the mass flow rate for the second line.

Cont.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 (h_3 + \frac{1}{2}\mathbf{V}_3^2)$

$$\dot{m}_2 (h_2 - h_3 - \frac{1}{2}\mathbf{V}_3^2) = \dot{m}_1 (h_3 + \frac{1}{2}\mathbf{V}_3^2 - h_1)$$



1: Table C.11.1: 150 psia, 220 F, $h_1 = 209.63$ Btu/lbm

2: Table C.11.1: $x = \varnothing$, 130 F, $h_2 = 119.88$ Btu/lbm

State 3: $x = 1$, 150 psia, $h_3 = 180.61$

$$\frac{1}{2}\mathbf{V}_3^2 = \frac{1}{2} \times 60^2 /(32.174 \times 778) = 0.072 \text{ Btu/lbm}$$

$$\dot{m}_2 = \dot{m}_1 (h_3 + \frac{1}{2}\mathbf{V}_3^2 - h_1)/ (h_2 - h_3 - \frac{1}{2}\mathbf{V}_3^2)$$

$$= 4 (180.61 + 0.072 - 209.63)/ (119.88 - 180.61 - 0.072) = \mathbf{1.904 \text{ lbm/s}}$$

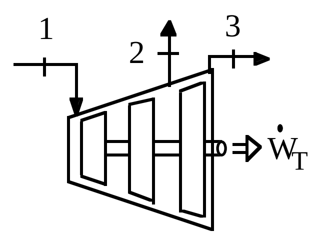
6.86E A steam turbine receives water at 2000 lbf/in.^{2}, 1200 F at a rate of 200 lbm/s as shown in Fig. P6.29. In the middle section 40 lbm/s is withdrawn at 300 lbf/in.^{2}, 650 F and the rest exits the turbine at 10 lbf/in.^{2}, 95% quality. Assuming no heat transfer and no changes in kinetic energy, find the total turbine work.

C.V. Turbine SSSF, 1 inlet and 2 exit flows.

Table C.8.2 $h_1 = 1598.6$, $h_2 = 1341.6$ Btu/lbm

Table C.8.1 : $h_3 = h_f + x_3 h_{fg} = 161.2 + 0.95 \times 982.1$

$= 1094.2$ Btu/lbm



Cont.: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$ => $\dot{m}_3 = 160$ lbm/s

Energy: $\dot{m}_1 h_1 = \dot{W}_T + \dot{m}_2 h_2 + \dot{m}_3 h_3$

$$\dot{W}_T = \dot{m}_1 h_1 - \dot{m}_2 h_2 - \dot{m}_3 h_3 = \mathbf{9.1 \times 10^4 \text{ Btu/s}}$$

6.87E A small, high-speed turbine operating on compressed air produces a power output of 0.1 hp. The inlet state is 60 lbf/in.^{2}, 120 F, and the exit state is 14.7 lbf/in.^{2}, −20 F. Assuming the velocities to be low and the process to be adiabatic, find the required mass flow rate of air through the turbine.

$$\dot{m}h_i = \dot{m}h_e + \dot{W}$$

$$h_i - h_e = \cong C_p(T_{in} - T_{ex}) = 0.24(120 - (-20)) = 33.6 \text{ Btu/lbm}$$

$$\dot{m} = 0.1 \times 550/(778 \times 33.6) = \mathbf{0.0021\ lbm/s} = \mathbf{7.57\ lbm/h}$$

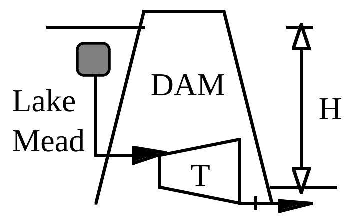
6.88E Hoover Dam across the Colorado River dams up Lake Mead 600 ft higher than the river downstream. The electric generators driven by water-powered turbines deliver 1.2×10^6 Btu/s. If the water is 65 F, find the minimum amount of water running through the turbines.

C.V.: H_2O pipe + turbines, SSSF.

Continuity: $\dot{m}_{in} = \dot{m}_{ex}$;

$$\dot{m}_{in}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}_{ex}(h + \mathbf{V}^2/2 + gz)_{ex} + \dot{W}_T$$

Water states: $h_{in} \cong h_{ex}$; $v_{in} \cong v_{ex}$ so



$$w_T = g(z_{in} - z_{ex}) = (g/g_c) \times 600/778 = 0.771 \text{ Btu/lbm}$$

$$\dot{m} = \dot{W}_T/w_T = 1.2\times10^6/0.771 = 1.556\times10^6 \text{ lbm/s}$$

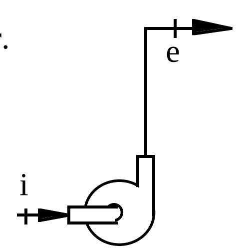
$$\dot{V} = \dot{m}v = 1.556\times10^6 \times 0.016043 = \mathbf{24963\ ft^3/s}$$

6.89E A small water pump is used in an irrigation system. The pump takes water in from a river at 50 F, 1 atm at a rate of 10 lbm/s. The exit line enters a pipe that goes up to an elevation 60 ft above the pump and river, where the water runs into an open channel. Assume the process is adiabatic and that the water stays at 50 F. Find the required pump work.

C.V. pump + pipe: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m}$

Assume same velocity in and out, same height, no heat transfer.

Energy Eq.:

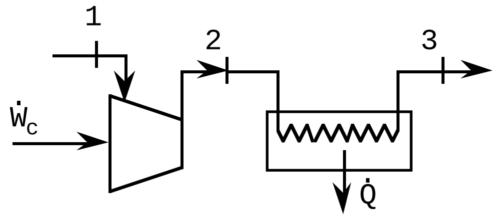


$$\dot{m}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}(h + \mathbf{V}^2/2 + gz)_{ex} + \dot{W}$$

$$\dot{W} = \dot{m}g(z_{in} - z_{ex}) = 10 \text{ x } (g/g_c) \text{x } (-60)/778 = \mathbf{-0.771\ Btu/s}$$

I.E. 0.771 Btu/s required input

6.90E An air compressor takes in air at 14 lbf/in.^{2}, 60 F and delivers it at 140 lbf/in.^{2}, 1080 R to a constant-pressure cooler, which it exits at 560 R. Find the specific compressor work and the specific heat transfer.



C.V. air compressor q = 0

Cont.: $\dot{m}_2 = \dot{m}_1$

Energy: $h_1 + w_c = h_2$

$$w_c = h_2 - h_1 = 261.1 - 124.3 = \mathbf{136.8\ Btu/lbm}$$

C.V. cooler $w = \emptyset$ Cont.: $\dot{m}_3 = \dot{m}_1$ Energy: $h_2 = q + h_3$

$$q = h_2 - h_3 = 261.1 - 133.98 = \mathbf{127.12\ Btu/lbm}$$

6.91E The following data are for a simple steam power plant as shown in Fig. P6.39.

State	1	2	3	4	5	6	7
P psia	900	890	860	830	800	1.5	1.4
T F		115	350	920	900		110

State 6 has $x_6 = 0.92$, and velocity of 600 ft/s. The rate of steam flow is 200000 lbm/h, with 400 hp input to the pump. Piping diameters are 8 in. from steam generator to the turbine and 3 in. from the condenser to the steam generator. Determine the power output of the turbine and the heat transfer rate in the condenser.

Turbine: $$\mathbf{V}_5 = \frac{200000 \times 0.964}{3600 \times 0.349} = 153 \text{ ft/s}$$

$$h_6 = 1111.0 - 0.08 \times 1029 = 1028.7$$

$$w = 1455.6 - 1028.7 - \frac{6^2 - 1.53^2}{5} = 420.2 \text{ Btu/lbm}$$

$$\dot{W}_{TURB} = \frac{420.2 \times 200000}{2545} = \mathbf{33000\ hp}$$

6.92E For the same steam power plant as shown in Fig. P6.39 and Problem 6.91 determine the rate of heat transfer in the economizer which is a low temperature heat exchanger and the steam generator. Determine also the flow rate of cooling water through the condenser, if the cooling water increases from 55 to 75 F in the condenser.

Condenser: $\mathbf{V}_7 = \dfrac{200000 \times 0.01617}{3600 \times 0.0491} = 18$ ft/s

$$q = 78.02 - 1028.7 + \frac{0.18^2 - 6^2}{5} = -957.9 \text{ Btu/lbm}$$

$\dot{Q}_{COND} = 200000(-957.9) = \mathbf{-1.916 \times 10^8}$ **Btu/h**

Economizer $\mathbf{V}_3 \approx \mathbf{V}_2$, Liquid v ~ const

$q = 323.0 - 85.3 = 237.7$ Btu/lbm

$\dot{Q}_{ECON} = 200000(237.7) = \mathbf{4.75 \times 10^7}$ **Btu/h**

Generator:

$\mathbf{V}_3 \approx 20$ ft.s , $\mathbf{V}_4 = 153 \times \dfrac{0.9505}{0.964} =$ **151 ft/s**

$$q = 1467.8 - 323.0 + \frac{1.51^2 - 0.2^2}{5} = \mathbf{1145.2 \text{ Btu/lbm}}$$

$\dot{Q}_{GEN} = 200000 \times (1145.2) = \mathbf{2.291 \times 10^8}$ **Btu/h**

6.93E A proposal is made to use a geothermal supply of hot water to operate a steam turbine, as shown in Fig. P6.46. The high pressure water at 200 lbf/in.^{2}, 350 F, is throttled into a flash evaporator chamber, which forms liquid and vapor at a lower pressure of 60 lbf/in.^{2}. The liquid is discarded while the saturated vapor feeds the turbine and exits at 1 lbf/in.^{2}, 90% quality. If the turbine should produce 1000 hp, find the required mass flow rate of hot geothermal water in pound-mass per hour.

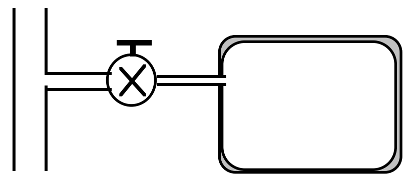
$h_1 = 321.8 = 262.25 + x \times 915.8$ => $x = 0.06503 = \dot{m}_2/\dot{m}_1$

$h_2 = 1178.0$, $h_3 = 69.74 + 0.9 \times 1036 = 1002.1$

$\dot{W} = \dot{m}_2(h_2 - h_3)$ => $\dot{m}_2 = \dfrac{1000 \times 2545}{1178.0 - 1002.1} = 14472$

$\Rightarrow \dot{m}_1 =$ **222539 lbm/h**

6.94E A 1-ft^3 tank, shown in Fig. P6.49, that is initially evacuated is connected by a valve to an air supply line flowing air at 70 F, 120 lbf/in.^{2}. The valve is opened, and air flows into the tank until the pressure reaches 90 lbf/in.^{2}. Determine the final temperature and mass inside the tank, assuming the process is adiabatic. Develop an expression for the relation between the line temperature and the final temperature using constant specific heats.



a) C.V. Tank, USUF:

Continuity Eq.: $m_i = m_2$

Energy Eq.: $m_i h_i = m_2 u_2$

$u_2 = h_i = 293.64$ (Table C.6)

$\Rightarrow T_2 =$ **740 R**

$$m_2 = \frac{P_2 V}{RT_2} = \frac{90 \times 144 \times 1}{53.34 \times 740} = \mathbf{0.3283\ lbm}$$

Assuming constant specific heat,

$h_i = u_i + RT_i = u_2$, $RT_i = u_2 - u_i = C_{Vo}(T_2 - T_i)$

$C_{Vo}T_2 = (C_{Vo} + R)T_i = C_{Po}T_i$, $T_2 = (C_{Po}/C_{Vo})\ T_i = kT_i$

For $T_i = 529.7$ R & constant C_{Po}, $T_2 = 1.40 \times 529.7 =$ **741.6 R**

6.95E A 20-ft^3 tank contains ammonia at 20 lbf/in.^{2}, 80 F. The tank is attached to a line flowing ammonia at 180 lbf/in.^{2}, 140 F. The valve is opened, and mass flows in until the tank is half full of liquid, by volume at 80 F. Calculate the heat transferred from the tank during this process.

$m_1 = V/v_1 = 20/16.765 = 1.193$ lbm

$m_{f2} = V_{f2}/v_{f2} = 10/0.026677 = 374.855$, $m_{g2} = V_{g2}/v_{g2} = 10/1.9531 = 5.120$

$m_2 = m_{f2} + m_{g2} = 379.975$ lbm => $x_2 = m_{g2}/\ m_2 = 0.013475$

Table C.9.1.1, $u_2 = 130.9 + 0.013475 \times 443.4 = 136.9$ Btu/lbm

$u_1 = 595.0$, $h_i = 667.0$

$m_i = m_2 - m_1 = 378.782$ lbm , $Q_{CV} + m_i h_i = m_2 u_2 - m_1 u_1$

$Q_{CV} = 379.975 \times 136.9 - 1.193 \times 595.0 - 378.782 \times 667.0 =$ **-201339 Btu**

6.96E A 18-ft^3 insulated tank contains air at 100 F, 300 lbf/in.^{2}. A valve on the tank is opened, and air escapes until half the original mass is gone, at which point the valve is closed. What is the pressure inside then?

$m_1 = P_1V/RT_1 = 300 \times 18 \times 144/53.34 \times 559.67 = 26.05$ lbm;

$m_e = m_1 - m_2,\ \ m_2 = m_1/2 \ \Rightarrow\ m_e = m_2 = 13.025$ lbm

1st law: $0 = m_2u_2 - m_1u_1 + m_eh_{e\ AV}$

$\Rightarrow 0 = 13.025 \times 0.171\ T_2 - 26.05 \times 0.171 \times 559.67$

$+ 13.025 \times 0.24\ (559.67 + T_2)/2$ Solving, $T_2 = 428$ R

$$P_2 = \frac{m_2RT_2}{V} = P_1T_2/2T_1 = 300 \times 428/2 \times 559.67 = \mathbf{114.7\ lbf/in^2}$$

6.97E Air is contained in the insulated cylinder shown in Fig. P6.70. At this point the air is at 20 lbf/in.^{2}, 80 F, and the cylinder volume is 0.5 ft^3. The piston cross-sectional area is 0.5 ft^2, and the spring is linear with spring constant 200 lbf/in. The valve is opened, and air from the line at 100 lbf/in.^{2}, 80 F, flows into the cylinder until the pressure reaches 100 lbf/in.^{2}, and then the valve is closed. Find the final temperature.

$m_2 = m_1 + m_i$ $\quad$ 1st law: $\quad m_ih_i = m_2u_2 - m_1u_1 + W_{CV}$

Ideal gas, constant specific heat:

$$(m_2 - m_1)C_{Po}T_i = m_2C_{Vo}T_2 - m_1C_{Vo}T_1 + W_{CV}$$

Linear spring relation:

$$P_2 = P_1 + \frac{K}{A^2}(V_2 - V_1) \text{ or } 100 = 20 + \frac{200}{(0.5)^2 \times 12}(V_2 - 0.5)$$

$V_2 = 1.7$ ft^3, Also $P_2V_2 = m_2RT_2$

$100 \times 144 \times 1.7 = m_2 \times 53.34 \times T_2;\ m_2 = 458.94/T_2$

$$\text{Also } m_1 = \frac{P_1V_1}{RT_1} = \frac{20 \times 144 \times 0.5}{53.34 \times 540} = 0.05 \text{ lbm}$$

$$\left(\frac{458.94}{T_2} - 0.05\right) \times 0.24 \times 540 = 458.94 \times 0.171$$

$$- 0.05 \times 0.171 \times 540 + 60 \times \frac{144}{778}(1.7 - 0.5)$$

Solving, $T_2 =$ **635 R = 175.3 F**

6.98E A 35-ft^3 insulated, 90-lbm rigid steel tank contains air at 75 lbf/in.^{2}, and both tank and air are at 70 F. The tank is connected to a line flowing air at 300 lbf/in.^{2}, 70 F. The valve is opened, allowing air to flow into the tank until the pressure reaches 250 lbf/in.^{2} and is then closed. Assume the air and tank are always at the same temperature and find the final temperature.

$1^{\underline{st}}$ law: $\quad m_i h_i = (m_2u_2 - m_1u_1)_{AIR} + m_{ST}(u_2 - u_1)_{ST}$

$$m_{1\ AIR} = \frac{P_1V}{RT_1} = \frac{75 \times 144 \times 35}{53.34 \times 530} = 13.37 \text{ lbm}$$

$$m_{2\ AIR} = \frac{P_2V}{RT_2} = \frac{250 \times 144 \times 35}{53.34 \times T_2} = \frac{23622}{T_2}$$

$$m_i = (m_2 - m_1)_{AIR} = \frac{23622}{T_2} - 13.37$$

$$\left(\frac{23\,622}{T_2} - 13.37\right) \times 0.24 \times 530 = \frac{23622}{T_2} \times 0.171 \times T_2$$

$$- 13.37 \times 0.171 \times 530 + 90 \times 0.107(T_2 - 530)$$

Solving, $T_2 =$ **589.3 R**

6.99E A cylinder fitted with a piston restrained by a linear spring contains 2 lbm of R-22 at 220 F, 125 lbf/in.^{2}. The system is shown in Fig. P6.72 where the spring constant is 285 lbf/in., and the piston cross-sectional area is 75 in.^{2}. A valve on the cylinder is opened and R-22 flows out until half the initial mass is left. Heat is transferred so the final temperature of the R-22 is 30 F. Find the final state of the R-22, (P_2, x_2), and the heat transfer to the cylinder.

$$P_2 - P_1 = (k_S/A^2)(V_2 - V_1) = (k_S/A^2)(m_2v_2 - m_1v_1)$$

$$v_1 = 0.636, \quad h_1 = 138.96, \quad u_1 = 138.96 - 125 \times 0.636(144/778) = 124.25$$

$$P_2 - 125 = (285 \times 144 \times 12 / 75^2)(1 \times v_2 - 2 \times 0.636)$$

If state 2 is 2-phase,

$$P_2 = P_{sat}(30F) = 69.591 \text{ lbf/in}^2 \quad \Rightarrow v_2 = 0.63913 < v_g \rightarrow \text{2-phase OK}$$

$$0.63913 = 0.01243 + x_2 \times 0.7697 \quad \Rightarrow \quad x_2 = 0.8142$$

$$u_2 = 18.45 + 0.8142 \times 78.76 = 82.58$$

$$W_{CV} = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

$$= \frac{1}{2}(125 + 69.591)\ (1{\times}0.63913 - 2{\times}0.636)(144/778) = \mathbf{-11.4\ Btu}$$

$$u_1 = 138.96 - 125 \times 0.636(144/778) = 124.25$$

$h_{e\ AVG} = (h_1 + h_2)/2 = (138.96 + 82.58 + 8.23)/2 = 114.9$

$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_{e\ AVE} + W_{CV}$

$= 1\times\ 82.58 - 2 \times 124.25 + 1 \times 114.9 \times 11.4 =$ **$-\ 62.42$** Btu

6.100E An initially empty bottle, $V = 10\ ft^3$, is filled with water from a line at 120 $lbf/in.^2$, 500 F. Assume no heat transfer and that the bottle is closed when the pressure reaches line pressure. Find the final temperature and mass in the bottle.

C.V. bottle + valve, ${}_1Q_2 = 0$, ${}_1W_2 = 0$, USUF

$m_2 - \underline{m}_1 = m_i$; $m_2u_2 = m_ih_i$

State 2: $P_2 = P_{line}$, $u_2 = h_i = 1277.1$ Btu/lbm

$\Rightarrow$ **$T_2 \cong 764$ F**, $v_2 = 6.0105$

$m_2 = V/v_2 = 10/6.0105 =$ **1.664 lbm**

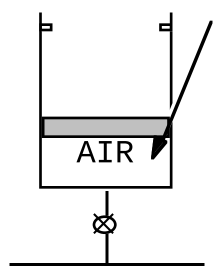
6.101E A mass-loaded piston/cylinder containing air is at 45 $lbf/in.^2$, 60 F with a volume of 9 ft^3, while at the stops $V = 36\ ft^3$. An air line, 75 $lbf/in.^2$, 1100 R, is connected by a valve, as shown in Fig. P6.63. The valve is then opened until a final inside pressure of 60 $lbf/in.^2$ is reached, at which point T=630R. Find the air mass that enters, the work, and heat transfer.

Open to: $P_2 = 60\ lbf/in^2$

$h_i = 366.13$

$$m_1 = \frac{P_1V_1}{RT_1} = \frac{45 \times 9 \times 144}{53.34 \times 519.7}$$

$= 2.104$ lbm



$P = P_1$ until $V = V_{stop}$ then const. V

${}_1W_2 = \int PdV = P_1(V_{stop} - V_1) = 45 \times (36 - 9)\frac{144}{778} =$ **224.9 Btu**

$m_2 = P_2V_2/RT_2 = 60\times36\times144/53.34\times630 = 9.256$ lbm

${}_1Q_2 = m_2u_2 - m_1u_1 - m_i\,h_i + {}_1W_2$

$= 9.256\times107.62 - 2.104\times88.677 - 7.152\times266.13 + 224.9 =$ **-868.9 Btu**

6.102E A nitrogen line, 540 R, and 75 lbf/in.^{2}, is connected to a turbine that exhausts to a closed initially empty tank of 2000 ft^3, as shown in Fig. P6.52. The turbine operates to a tank pressure of 75 lbf/in.^{2}, at which point the temperature is 450 R. Assuming the entire process is adiabatic, determine the turbine work.

C.V. turbine & tank $\Rightarrow$ USUF

Conservation of mass: $m_i = m_2 = m$

1$^{\underline{st}}$ Law: $m_i h_i = m_2 u_2 + W_{CV}$; $W_{CV} = m(h_i - u_2)$

Inlet state: $P_i = 75$ lbf/in^2, $T_i = 540$ R, $h_i = 133.38$ Btu/lbm

Final state 2: $P_2 = 75$ lbf/in^2, $T_2 = 450$ R,

$u_2 = h_2 - P_2 v_2 = 79.04$ Btu/lbm

$m_2 = V/v_2 = 2000/2.289 = 873.74$ lbm

$W_{CV} = 873.74(133.38 - 79.04) =$ **47 479 Btu**

CHAPTER 7

The new problem set compared to the fourth edition chapter 6 old set.

New	Old	New	Old	New	Old
1	1	26	18	51	new
2	2	27	new	52	new
3	3	28	19	53	37
4	4	29	20	54	38
5	5	30	new	55	39
6	6	31	21	56	new
7	7	32	22	57	40
8	new	33	25	58	new
9	8	34	new	59	new
10	9	35	23	60	41
11	10	36	24	61	new
12	new	37	27	62	new
13	11	38	28	63	42
14	new	39	29	64	43
15	12	40	new	65	44
16	new	41	30	66	45
17	13	42	31	67	46
18	14	43	new	68	47
19	new	44	32	69	new
20	new	45	33	70	48
21	15	46	new	71	new
22	new	47	new	72	50
23	16	48	34	73	new
24	new	49	36		
25	17	50	26		

7.1 Calculate the thermal efficiency of the steam power plant cycle described in Problem 6.39.

Solution:

From solution to problem 6.39, $\dot{W}_{NET} = 24805 - 300 = 24505$ kW

Total $\dot{Q}_H = 13755 + 67072 = 80827$ kW

$$\Rightarrow \eta_{TH} = \dot{W}_{NET}/\dot{Q}_H = \frac{24505}{80827} = \mathbf{0.303}$$

7.2 Calculate the coefficient of performance of the R-12 heat pump cycle described in Problem 6.47.

Solution:

From solution to problem 6.47, $-\dot{W}_{IN} = 4.0$ kW; $-\dot{Q}_{COND} = 8.654$ kW

$$\Rightarrow \text{Heat pump:} \quad \beta' = \dot{Q}_H/\dot{W}_{IN} = \frac{8.654}{4.0} = \mathbf{2.164}$$

7.3 Prove that a cyclic device that violates the Kelvin–Planck statement of the second law also violates the Clausius statement of the second law.

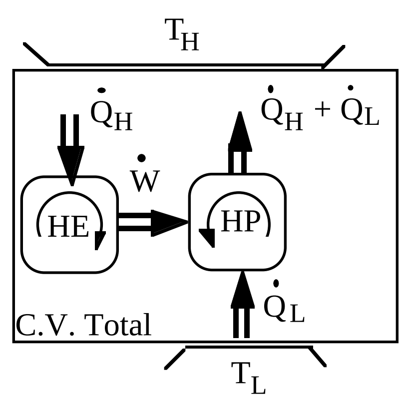
Solution: Proof very similar to the proof in section 7.2.

H.E. violating Kelvin receives Q_H from T_H and produces net $W = Q_H$.

This W input to H.P. receiving Q_L from T_L.

H.P. discharges $Q_H + Q_L$ to T_H . Net Q to T_H is : $-Q_H + Q_H + Q_L = Q_L$.

H.E. + H.P. together transfers Q_L from T_L to T_H with no W thus violates Clausius.



7.4 Discuss the factors that would make the power plant cycle described in Problem 6.39 an irreversible cycle.

Solution:

General discussion, but here are a few of the most significant factors.

1. Combustion process that generates the hot source of energy.
2. Heat transfer over finite temperature difference in boiler.
3. Flow resistance and friction in turbine results in less work out.
4. Flow friction and heat loss to/from ambient in all pipings.

7.5 Discuss the factors that would make the heat pump described in Problem 6.47 an irreversible cycle.

Solution:

General discussion but here are a few of the most significant factors.

1. Unwanted heat transfer in the compressor.
2. Pressure loss (back flow leak) in compressor
3. Heat transfer and pressure drop in line 1 => 2.
4. Pressure drop in all lines.
5. Throttling process 3 => 4.

7.6 Calculate the thermal efficiency of a Carnot-cycle heat engine operating between reservoirs at 500°C and 40°C. Compare the result with that of Problem 7.1.

Solution:

T_H = 500°C = 773.2 K; T_L = 40°C = 313.2 K

$$\text{Carnot:} \quad \eta_{TH} = \frac{T_H - T_L}{T_H} = \frac{773.2 - 313.2}{773.2} = \mathbf{0.595} \quad \text{(7.1 has : 0.3)}$$

7.7 Calculate the coefficient of performance of a Carnot-cycle heat pump operating between reservoirs at 0°C and 45°C. Compare the result with that of Problem 7.2.

Solution:

T_L = 0°C = 273.2 K; T_H = 45°C = 318.2 K

$$\text{Carnot:} \beta' = \frac{T_H}{T_H - T_L} = \frac{318.2}{45} = \mathbf{7.07} \quad \text{(7.2 has : 2.16)}$$

7.8 A car engine burns 5 kg fuel (equivalent to addition of Q_H) at 1500 K and rejects energy to the radiator and the exhaust at an average temperature of 750 K. If the fuel provides 40 000 kJ/kg what is the maximum amount of work the engine can provide?

Solution:

A heat engine $Q_H = 5 \times 40000 = 200\,000$ kJ

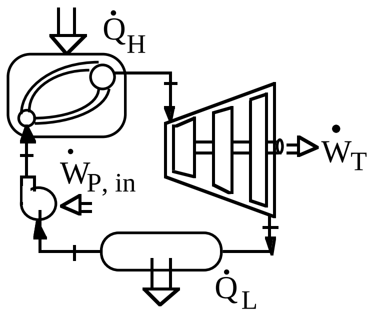
Assume a Carnot efficiency (maximum theoretical work)

$$\eta = 1 - T_L / T_H = 1 - 750/1500 = 0.5$$

$W = \eta\, Q_H = \mathbf{100\,000\ kJ}$

7.9 In a steam power plant 1 MW is added at 700°C in the boiler, 0.58 MW is taken out at 40°C in the condenser and the pump work is 0.02 MW. Find the plant thermal efficiency. Assuming the same pump work and heat transfer to the boiler is given, how much turbine power could be produced if the plant were running in a Carnot cycle?

Solution:



CV. Total: $\dot{Q}_H + \dot{W}_{P,in} = \dot{W}_T + \dot{Q}_L$

$\dot{W}_T = 1 + 0.002 - 0.58 = 0.44$ MW

$\eta_{TH} = (\dot{W}_T - \dot{W}_{P,in})/\dot{Q}_H = \mathbf{0.42}$

$\eta_{Carnot} = \dot{W}_{net}/\dot{Q}_H = 1 - T_L/T_H$

$$= 1 - \frac{313.15}{973.15} = 0.678$$

$$\dot{W}_T - \dot{W}_{P,in} = \eta_{Carnot}\dot{Q}_H = 0.678 \text{ MW} \quad \Rightarrow \quad \dot{W}_T = \mathbf{0.698\ MW}$$

7.10 At certain locations geothermal energy in undergound water is available and used as the energy source for a power plant. Consider a supply of saturated liquid water at 150°C. What is the maximum possible thermal efficiency of a cyclic heat engine using this source of energy with the ambient at 20°C? Would it be better to locate a source of saturated vapor at 150°C than use the saturated liquid at 150°C?

Solution:

$T_{MAX} = 150°C = 423.2 \text{ K} = T_H$; $T_{Min} = 20°C = 293.2 \text{ K} = T_L$

$$\eta_{TH\ MAX} = \frac{T_H - T_L}{T_H} = \frac{130}{423.2} = \mathbf{0.307}$$

Yes. Saturated vapor source at 150°C would remain at 150°C as it condenses to liquid, providing a large energy supply at that temperature.

7.11 Find the maximum coefficient of performance for the refrigerator in your kitchen, assuming it runs in a Carnot cycle.

Solution:

The refrigerator coefficient of performance is

$$\beta = Q_L/W = Q_L/(Q_H - Q_L) = T_L/(T_H - T_L)$$

Assuming $T_L \sim 0°C$, $T_H \sim 35°C$,

$$\beta \le 273.15/(35 - 0) = \mathbf{7.8}$$

Actual working fluid temperatures must be such that

$$T_L < T_{refrigerator} \quad \text{and} \quad T_H > T_{room}$$

7.12 An air-conditioner provides 1 kg/s of air at 15°C cooled from outside atmospheric air at 35°C. Estimate the amount of power needed to operate the air-conditioner. Clearly state all assumptions made.

Solution:

$$\dot{Q}_{air} = \dot{m}\,\Delta h \cong \dot{m}\,C_p\Delta T = 1 \times 1.004 \times 20 = 20 \text{ kW}$$

Assume Carnot cycle refrigerator

$$\beta = \frac{\dot{Q}_L}{\dot{W}} = \dot{Q}_L / (\dot{Q}_H - \dot{Q}_L) \cong \frac{T_L}{T_H - T_L} = \frac{273 + 15}{35 - 15} = 14.4$$

$$\dot{W} = \dot{Q}_L / \beta = 20.07 / 14.4 = \mathbf{1.39\ kW}$$

This estimate is the theoretical maximum performance. To do the required heat transfer $T_L \cong 5°C$ and $T_H = 45°C$ are more likely; secondly

$\beta < \beta_{carnot}$

7.13 A sales person selling refrigerators and deep freezers will guarantee a minimum coefficient of performance of 4.5 year round. How would you evaluate that? Are they all the same?

Solution:

Assume a high temperature of 35°C. If a freezer compartment is included $T_L \sim -20°C$ (deep freezer) and fluid temperature is then $T_L \sim -30°C$

$$\beta_{deep\ freezer} \le T_L/(T_H - T_L) = (273.15 - 30)/[35 - (-30)] = 3.74$$

A hot summer day may require a higher T_H to push Q_H out into the room, so even lower β.

Claim is possible for a refrigerator, but not for a deep freezer.

7.14 A car engine operates with a thermal efficiency of 35%. Assume the air-conditioner has a coefficient of performance that is one third of the theoretical maximum and it is mechanically pulled by the engine. How much fuel energy should you spend extra to remove 1 kJ at 15°C when the ambient is at 35°C?

Solution:

Maximum β for air-conditioner is for a Carnot cycle

$$\beta_{carnot} = \dot{Q}_L / \dot{W} = T_L / (T_H - T_L) = 288 / 20 = 14.4$$

$$\beta_{actual} = 14.4 / 3 = 4.8$$

$$W = Q_L / \beta = 1 / 4.8 = 0.2083$$

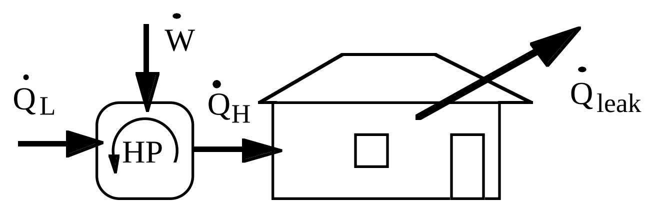
$$\Delta Q_{H,engine} = W / \eta_{eng} = 0.2083 / 0.35 = \mathbf{0.595\ kJ}$$

7.15 We propose to heat a house in the winter with a heat pump. The house is to be maintained at 20°C at all times. When the ambient temperature outside drops to −10°C, the rate at which heat is lost from the house is estimated to be 25 kW. What is the minimum electrical power required to drive the heat pump?

Solution:

Minimum power if we assume a Carnot cycle

$\dot{Q}_H = \dot{Q}_{leak} = 25$ kW



$$\beta' = \frac{\dot{Q}_H}{\dot{W}_{IN}} = \frac{T_H}{T_H - T_L} = \frac{293.2}{30} = 9.773 \quad \Rightarrow \quad \dot{W}_{IN} = \frac{25}{9.773} = \mathbf{2.56\ kW}$$

7.16 Electric solar cells can produce power with 15% efficiency. Assume a heat engine with a low temperature heat rejection at 30°C driving an electric generator with 80% efficiency. What should the effective high temperature in the heat engine be to have the same overall efficiency as the solar cells.

Solution:

$$W_{el} = Q_H \eta_{cell} = \eta_{gen} W_{eng} = \eta_{gen}\ \eta_{eng}\ Q_{Heng} \;\Rightarrow\; \eta_{cell} = \eta_{gen}\,\eta_{eng}$$

$$\eta_{eng} = \eta_{cell} / \eta_{gen} = 0.15 / 0.8 = 0.1875 = (1 - T_L / T_H) \;\Rightarrow$$

$$T_H = T_L / (1 - \eta_{eng}) = 303 / 0.8125 \cong 373\ \text{K} = \mathbf{100°C}$$

7.17 A cyclic machine, shown in Fig. P7.17, receives 325 kJ from a 1000 K energy reservoir. It rejects 125 kJ to a 400 K energy reservoir and the cycle produces 200 kJ of work as output. Is this cycle reversible, irreversible, or impossible?

Solution:

$$\eta_{Carnot} = 1 - \frac{T_L}{T_H} = 1 - 400/1000 = 0.6$$

$$\eta_{eng} = W/Q_H = 200/325 = 0.615 \; > \; \eta_{Carnot}$$

This is **impossible.**

7.18 A household freezer operates in a room at 20°C. Heat must be transferred from the cold space at a rate of 2 kW to maintain its temperature at –30°C. What is the theoretically smallest (power) motor required to operate this freezer?

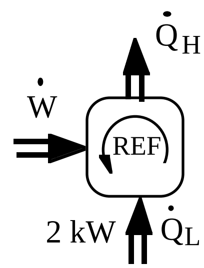
Solution:

Assume a Carnot cycle between T_L = -30°C and T_H = 20°C:

$$\beta = \dot{Q}_L/\dot{W}_{in} = T_L/(T_H - T_L)$$

$$= (273.15 - 30)/[20 - (-30)] = 4.86$$

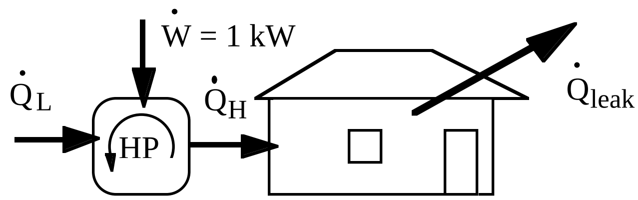
$$\dot{W}_{in} = \dot{Q}_L/\beta = 2/4.86 = \mathbf{0.41\ kW}$$



This is the theoretical minimum power input. Any actual machine requires a larger input.

7.19 A heat pump has a coefficient of performance that is 50% of the theoretical maximum. It maintains a house at 20°C, which leaks energy of 0.6 kW per degree temperature difference to the ambient. For a maximum of 1.0 kW power input find the minimum outside temperature for which the heat pump is a sufficient heat source.

Solution:



C.V. House. For constant 20°C the heat pump must provide $\dot{Q}_{leak} = 0.6\ \Delta T$

$$\dot{Q}_H = \dot{Q}_{leak} = 0.6\ (T_H - T_L) = \beta\ \dot{W}$$

C.V. Heat pump. Definition of the coefficient of performance and the fact that the maximum is for a Carnot heat pump.

$$\beta = \dot{Q}_H / \dot{W} = \dot{Q}_H / (\dot{Q}_H - \dot{Q}_L) = 0.5\ \beta_{carnot} = 0.5 \times T_H / (T_H - T_L)$$

Substitute into the first equation to get

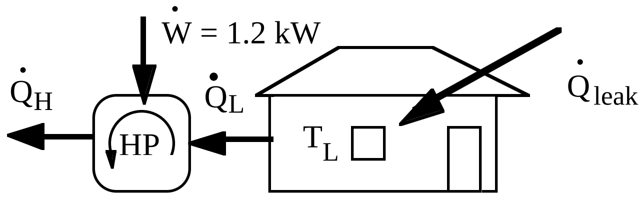
$$0.6\ (T_H - T_L) = [\ 0.5 \times T_H / (T_H - T_L)\ ]\ 1 \quad =>$$

$$(T_H - T_L)^2 = (0.5 / 0.6)\ T_H \times 1 = 0.5 / 0.6 \times 293.15 = 244.29$$

$$T_H - T_L = 15.63 \ \ => T_L = 20 - 15.63 = \mathbf{4.4}\ °\mathbf{C}$$

7.20 A heat pump cools a house at 20°C with a maximum of 1.2 kW power input. The house gains 0.6 kW per degree temperature difference to the ambient and the heat pump coefficient of performance is 60% of the theoretical maximum. Find the maximum outside temperature for which the heat pump provides sufficient cooling.

Solution:



Here:

$T_L = T_{house}$

$T_H = T_{amb}$

In this setup the low temperature space is the house and the high temperature space is the ambient. The heat pump must remove the gain or leak heat transfer to keep it at a constant temperature.

$\dot{Q}_{leak} = 0.6\,(T_{amb} - T_{house}) = \dot{Q}_L$ which must be removed by the heat pump.

$$\beta' = \dot{Q}_H / \dot{W} = 1 + \dot{Q}_L / \dot{W} = 0.6\,\beta'_{carnot} = 0.6\,T_{amb} / (T_{amb} - T_{house})$$

Substitute in for $\dot{Q}_L$ and multiply with $(T_{amb} - T_{house})$:

$$(T_{amb} - T_{house}) + 0.6\,(T_{amb} - T_{house})^2 / \dot{W} = 0.6\,T_{amb}$$

Since $T_{house} = 293.15$ K and $\dot{W} = 1.2$ kW it follows

$$T_{amb}^2 - 585.5\,T_{amb} + 85350.6 = 0$$

Solving => T_{amb} = **311.51 K = 38.36 °C**

7.21 Differences in surface water and deep water temperature can be utilized for power generation. It is proposed to construct a cyclic heat engine that will operate near Hawaii, where the ocean temperature is 20°C near the surface and 5°C at some depth. What is the possible thermal efficiency of such a heat engine?

Solution:

$T_H = 20°C = 293.2$ K; $T_L = 5°C = 278.2$ K

$$\eta_{TH\,MAX} = \frac{T_H - T_L}{T_H} = \frac{293.2 - 278.2}{293.2} = \mathbf{0.051}$$

7.22 A thermal storage is made with a rock (granite) bed of 2 m^3 which is heated to 400 K using solar energy. A heat engine receives a Q_H from the bed and rejects heat to the ambient at 290 K. The rock bed therefore cools down and as it reaches 290 K the process stops. Find the energy the rock bed can give out. What is the heat engine efficiency at the beginning of the process and what is it at the end of the process?

Solution:

Assume the whole setup is reversible and that the heat engine operates in a Carnot cycle. The total change in the energy of the rock bed is

$u_2 - u_1 = q = C\ \Delta T = 0.89\ (400 - 290) = 97.9$ kJ/kg

$m = \rho V = 2750 \times 2 = 5500$ kg , $Q = mq = 5500 \times 97.9 =$ **538 450 kJ**

To get the efficiency use the CARNOT as

$\eta = 1 - T_o/T_H = 1 - 290/400 =$ **0.275** at the beginning of process

$\eta = 1 - T_o/T_H = 1 - 290/290 =$ **0.0** at the end of process

7.23 An inventor has developed a refrigeration unit that maintains the cold space at –10°C, while operating in a 25°C room. A coefficient of performance of 8.5 is claimed. How do you evaluate this?

Solution:

$\beta_{Carnot} = Q_L/W_{in} = T_L/(T_H-T_L) = 263.15/[25 - (-10)] = 7.52$

$8.5 > \beta_{Carnot} \Rightarrow$ **impossible claim**

7.24 A steel bottle V = 0.1 m^3 contains R-134a at 20°C, 200 kPa. It is placed in a deep freezer where it is cooled to -20°C. The deep freezer sits in a room with ambient temperature of 20°C and has an inside temperature of -20°C. Find the amount of energy the freezer must remove from the R-134a and the extra amount of work input to the freezer to do the process.

Solution:

C.V. R-134a out to the -20 °C space.

Energy equation: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process : V = Const $\Rightarrow$ $v_2 = v_1$ $\Rightarrow$ ${}_1W_2 = 0$

Table B.5.2: $v_1 = 0.11436$, $u_1 = 418.145 - 200 \times 0.11436 = 395.273$

$m = V/ v_1 = 0.87443$ kg

State 2: $v_2 = v_1 < v_g = 0.14649$ Table B.5.1 => 2 phase

=> $x_2 = (0.11436 - 0.000738)/0.14576 = 0.77957$

$u_2 = 173.65 + 0.77957*192.85 = 323.99$ kJ/kg

${}_1Q_2 = m(u_2 - u_1) =$ **- 62.334 kJ**

Assume Carnot cycle

$\beta = Q_L / W_{in} = T_L/(T_H-T_L) = 253.15 / [\ 20 - (-20)] = 6.33$

$W_{in} = Q_L / \beta = 62.334 / 6.33 =$ **9.85 kJ**

7.25 A certain solar-energy collector produces a maximum temperature of 100°C. The energy is used in a cyclic heat engine that operates in a 10°C environment. What is the maximum thermal efficiency? What is it, if the collector is redesigned to focus the incoming light to produce a maximum temperature of 300°C?

Solution:

For T_H = 100°C = 373.2 K & T_L = 283.2 K

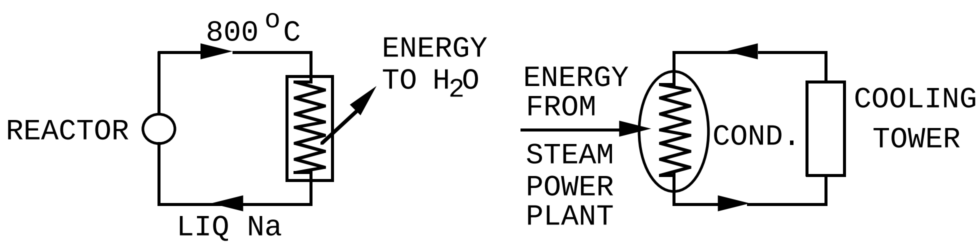
$$\eta_{TH\ MAX} = \frac{T_H - T_L}{T_H} = \frac{90}{373.2} = \mathbf{0.241}$$

For T_H = 300°C = 573.2 K & T_L = 283.2 K

$$\eta_{TH\ MAX} = \frac{T_H - T_L}{T_H} = \frac{290}{573.2} = \mathbf{0.506}$$

7.26 Liquid sodium leaves a nuclear reactor at 800°C and is used as the energy souce in a steam power plant. The condenser cooling water comes from a cooling tower at 15°C. Determine the maximum thermal efficiency of the power plant. Is it misleading to use the temperatures given to calculate this value?

Solution:



T_H = 800°C = 1073.2 K, T_L = 15°C = 288.2 K

$$\eta_{TH\ MAX} = \frac{T_H - T_L}{T_H} = \frac{1073.2 - 288.2}{1073.2} = \mathbf{0.731}$$

It might be misleading to use 800°C as the value for T_H, since there is not a supply of energy available at a constant temperature of 800°C (liquid Na is cooled to a lower temperature in the heat exchanger).

⇒ The Na cannot be used to boil H_2O at 800°C.

Similarly, the H_2O leaves the cooling tower and enters the condenser at 15°C, and leaves the condenser at some higher temperature.

⇒ The water does not provide for condensing steam at a constant temperature of 15°C.

7.27 A 4L jug of milk at 25°C is placed in your refrigerator where it is cooled down to 5°C. The high temperature in the Carnot refrigeration cycle is 45°C and the properties of milk are the same as for liquid water. Find the amount of energy that must be removed from the milk and the additional work needed to drive the refrigerator.

C.V milk + out to the 5 °C refrigerator space

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process : P = constant = 1 atm => ${}_1W_2 = Pm\,(v_2 - v_1)$

State 1: Table B.1.1, $v_1 \cong v_f = 0.001003\ m^3/kg$, $h_1 \cong h_f = 104.87$ kJ/kg

$m_2 = m_1 = V_1/v_1 = 0.004 / 0.001003 =$ **3.988 kg**

State 2: Table B.1.1, $h_2 \cong h_f = 20.98$ kJ/kg

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(u_2 - u_1) + Pm\,(v_2 - v_1) = m(h_2 - h_1)$$

$${}_1Q_2 = 3.998\ (20.98 - 104.87) = -3.988 \times 83.89 = \mathbf{-\ 334.55\ kJ}$$

C.V. Refrigeration cycle $T_L = 5$ °C ; $T_H = 45$ °C, assume Carnot

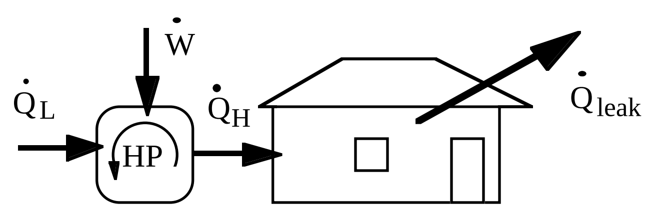
Ideal : $\beta = Q_L / W = Q_L / (Q_H - Q_L) = T_L / (T_H - T_L)$

$= 278.15 / 40 = \mathbf{6.954}$

$W = Q_L / \beta = 334.55 / 6.954 = \mathbf{48.1\ kJ}$

7.28 A house is heated by a heat pump driven by an electric motor using the outside as the low-temperature reservoir. The house loses energy directly proportional to the temperature difference as $\dot{Q}_{loss} = K(T_H - T_L)$. Determine the minimum electric power to drive the heat pump as a function of the two temperatures.

Solution:
Coefficient of performance less than or equal to Carnot heat pump.



$$\beta_{H,P} = \dot{Q}_H/\dot{W}_{in} \le T_H/(T_H - T_L)\ ; \qquad \dot{Q}_H = K(T_H - T_L)$$

$$\dot{W}_{in} = \dot{Q}_H/\beta \ \ge\ K(T_H - T_L) \times (T_H - T_L)/T_H = K(T_H - T_L)^2/T_H$$

7.29 A house is heated by an electric heat pump using the outside as the low-temperature reservoir. For several different winter outdoor temperatures, estimate the percent savings in electricity if the house is kept at 20°C instead of 24°C. Assume that the house is losing energy to the outside as described in the previous problem.

Solution:

Heat Pump $\dot{Q}_{loss} \propto (T_H - T_L)$

$$\text{Max Perf.} \quad \frac{\dot{Q}_H}{\dot{W}_{IN}} = \frac{T_H}{T_H - T_L} = \frac{K(T_H - T_L)}{\dot{W}_{IN}}, \quad \dot{W}_{IN} = \frac{K(T_H - T_L)^2}{T_H}$$

A: T_{H_A} = 24°C = 297.2 K B: T_{H_B} = 20°C = 293.2 K

T_L,°C	$\dot{W}_{IN_A}/K$	$\dot{W}_{IN_B}/K$	% saving
-20	6.514	5.457	16.2 %
-10	3.890	3.070	21.1 %
0	1.938	1.364	29.6 %
10	0.659	0.341	48.3 %

7.30 An air-conditioner with a power input of 1.2 kW is working as a refrigerator (β = 3) or as a heat pump (β' = 4). It maintains an office at 20°C year round which exchanges 0.5 kW per degree temperature difference with the atmosphere. Find the maximum and minimum outside temperature for which this unit is sufficient.

Solution:

Analyse the unit in heat pump mode

Replacement heat transfer equals the loss: $\dot{Q} = 0.5\ (T_H - T_{amb})$

$\dot{W} = \dot{Q}_H / \beta' = 0.5\ (T_H - T_{amb}) / 4$

$T_H - T_{amb} = 4\ \dot{W} / 0.5 = 9.6$

Heat pump mode: Minumum T_{amb} = 20 - 9.6 = **10.4 °C**

The unit as a refrigerator must cool with rate: $\dot{Q} = 0.5\ (T_{amb} - T_{house})$

$\dot{W} = \dot{Q}_L / \beta = 0.5\ (T_{amb} - T_{house}) / 3$

$T_{amb} - T_{house} = 3\ \dot{W} / 0.5 = 7.2$

Refrigerator mode: Maximum T_{amb} = 20 + 7.2 = **27.2 °C**

7.31 A house is cooled by an electric heat pump using the outside as the high-temperature reservoir. For several different summer outdoor temperatures, estimate the percent savings in electricity if the house is kept at 25°C instead of 20°C. Assume that the house is gaining energy from the outside directly proportional to the temperature difference.

Solution:

Air-conditioner (Refrigerator) $\dot{Q}_{LEAK} \propto (T_H - T_L)$

Max Perf. $\dfrac{\dot{Q}_L}{\dot{W}_{IN}} = \dfrac{T_L}{T_H - T_L} = \dfrac{K(T_H - T_L)}{\dot{W}_{IN}}$, $\dot{W}_{IN} = \dfrac{K(T_H - T_L)^2}{T_L}$

A: T_{L_A} = 20°C = 293.2 K B: T_{L_B} = 25°C = 298.2 K

T_H,°C	$\dot{W}_{IN_A}/K$	$\dot{W}_{IN_B}/K$	% saving
45	2.132	1.341	37.1 %
40	1.364	0.755	44.6 %
35	0.767	0.335	56.3 %

7.32 Helium has the lowest normal boiling point of any of the elements at 4.2 K. At this temperature the enthalpy of evaporation is 83.3 kJ/kmol. A Carnot refrigeration cycle is analyzed for the production of 1 kmol of liquid helium at 4.2 K from saturated vapor at the same temperature. What is the work input to the refrigerator and the coefficient of performance for the cycle with an ambient at 300 K?

Solution:

For the Carnot cycle the ratio of the heat transfers is the ratio of temperatures

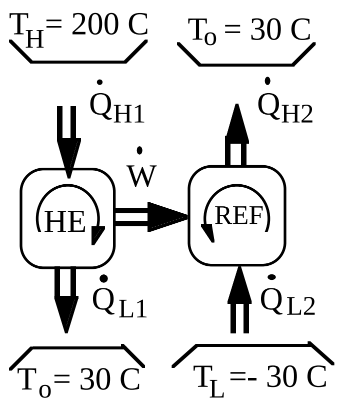
$$Q_H = Q_L \times \frac{T_H}{T_L} = 83.3 \times \frac{300}{4.2} = 5950 \text{ kJ}$$

$$W_{IN} = Q_H - Q_L = 5950 - 83.3 = \mathbf{5886.7\ kJ}$$

$$\beta = \frac{Q_L}{W_{IN}} = \frac{83.3}{5886.7} = \mathbf{0.0142} \qquad \left[= \frac{T_L}{T_H - T_L} \right]$$

7.33 We wish to produce refrigeration at −30°C. A reservoir, shown in Fig. P7.33, is available at 200°C and the ambient temperature is 30°C. Thus, work can be done by a cyclic heat engine operating between the 200°C reservoir and the ambient. This work is used to drive the refrigerator. Determine the ratio of the heat transferred from the 200°C reservoir to the heat transferred from the −30°C reservoir, assuming all processes are reversible.

Solution: Equate the work from the heat engine to the refrigerator.



$$W = Q_{H1}\left(\frac{T_H - T_0}{T_H}\right)$$

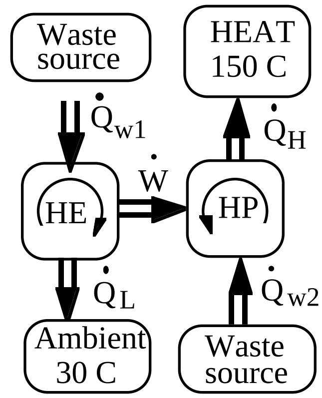
also

$$W = Q_{L2}\left(\frac{T_0 - T_L}{T_L}\right)$$

$$\frac{Q_{H1}}{Q_{L2}} = \left(\frac{T_o - T_L}{T_L}\right)\left(\frac{T_H}{T_H - T_o}\right) = \left(\frac{60}{243.2}\right)\left(\frac{473.2}{170}\right) = \mathbf{0.687}$$

7.34 A combination of a heat engine driving a heat pump (similar to Fig. P7.33) takes waste energy at 50°C as a source Q_{w1} to the heat engine rejecting heat at 30°C. The remainder Q_{w2} goes into the heat pump that delivers a Q_H at 150°C. If the total waste energy is 5 MW find the rate of energy delivered at the high temperature.

Solution:



Waste supply: $\dot Q_{W1} + \dot Q_{W2} = 5$ MW

Heat Engine:

$$\dot W = \eta\, \dot Q_{W1} = (1 - T_{L1} / T_{H1})\, \dot Q_{W1}$$

Heat pump:

$$\dot W = \dot Q_H / \beta_{HP} = \dot Q_{W2} / \beta'$$
$$= \dot Q_{W2} / [T_{H1} / (T_H - T_{H1})]$$

Equate the two work terms:

$$(1 - T_{L1} / T_{H1})\, \dot Q_{W1} = \dot Q_{W2} \times (T_H - T_{H1}) / T_{H1}$$

Substitute $\dot Q_{W1} = 5 \text{ MW} - \dot Q_{W2}$

$$(1 - 303.15/323.15)(5 - \dot Q_{W2}) = \dot Q_{W2} \times (150 - 50) / 323.15$$

$20\,(5 - \dot Q_{W2}) = \dot Q_{W2} \times 100 \quad => \quad \dot Q_{W2} = 0.8333$ MW

$\dot Q_{W1} = 5 - 0.8333 = 4.1667$ MW

$\dot W = \eta\, \dot Q_{W1} = 0.06189 \times 4.1667 = 0.258$ MW

$\dot Q_H = \dot Q_{W2} + \dot W =$ **1.09 MW**

(For the heat pump $\beta' = 423.15 / 100 = 4.23$)

7.35 A temperature of about 0.01 K can be achieved by magnetic cooling, (magnetic work was discussed in Problems 4.41 and 4.42). In this process a strong magnetic field is imposed on a paramagnetic salt, maintained at 1 K by transfer of energy to liquid helium boiling at low pressure. The salt is then thermally isolated from the helium, the magnetic field is removed, and the salt temperature drops. Assume that 1 mJ is removed at an average temperature of 0.1 K to the helium by a Carnot-cycle heat pump. Find the work input to the heat pump and the coefficient of performance with an ambient at 300 K.

Solution:

$$\beta = \dot{Q}_L/\dot{W}_{IN} = \frac{T_L}{T_H - T_L} = \frac{0.1}{299.9} = \mathbf{0.00033}$$

$$\dot{W}_{IN} = \frac{1\times10^{-3}}{0.00033} = \mathbf{3\ J}$$

7.36 The lowest temperature that has been achieved is about 1×10^{-6} K. To achieve this an additional stage of cooling is required beyond that described in the previous problem, namely nuclear cooling. This process is similar to magnetic cooling, but it involves the magnetic moment associated with the nucleus rather than that associated with certain ions in the paramagnetic salt. Suppose that 10 μJ is to be removed from a specimen at an average temperature of 10^{-5} K (ten microjoules is about the potential energy loss of a pin dropping 3 mm). Find the work input to a Carnot heat pump and its coefficient of performance to do this assuming the ambient is at 300 K.

Solution:

$$Q_L = 10\ \mu J = 10\times10^{-6}\ J \quad \text{at} \quad T_L = 10^{-5}\ K$$

$$\Rightarrow Q_H = Q_L \times \frac{T_H}{T_L} = 10\times10^{-6} \times \frac{300}{10^{-5}} = 300\ J$$

$$W_{in} = Q_H - Q_L = 300 - 10\times10^{-6} \cong \mathbf{300\ J}$$

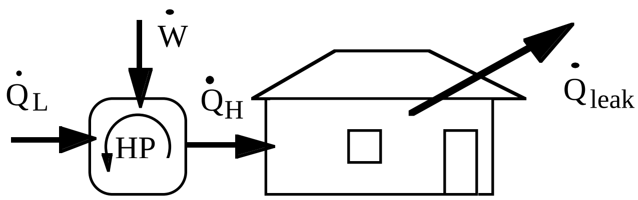
$$\beta = \frac{Q_L}{W_{in}} = \frac{10\times10^{-6}}{300} = \mathbf{3.33\times10^{-8}}$$

7.37 A heat pump heats a house in the winter and then reverses to cool it in the summer. The interior temperature should be 20°C in the winter and 25°C in the summer. Heat transfer through the walls and ceilings is estimated to be 2400 kJ per hour per degree temperature difference between the inside and outside.
a. If the winter outside temperature is 0°C, what is the minimum power required to drive the heat pump?
b.For the same power as in part (a), what is the maximum outside summer temperature for which the house can be maintained at 25°C?

Solution:

a) Winter:

House is T_H and ambient is at T_L



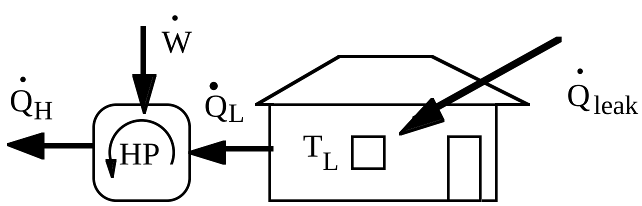
T_H = 20°C = 293.2 K , T_L = 0°C = 273.2 K and

$$\dot{Q}_H = 2400(20 - 0) \text{ kJ/h}$$

$$\beta' = \dot{Q}_H/\dot{W}_{IN} = \frac{2400(20 - 0)}{\dot{W}_{IN}} = \frac{T_H}{T_H - T_L} = \frac{293.2}{20}$$

$$\Rightarrow \dot{W}_{IN} = 3275 \text{ kJ/h} = \mathbf{0.91\ kW} \quad \text{(For Carnot cycle)}$$

b)



Summer:

$T_L = T_{house}$

$T_H = T_{amb}$

T_L = 25°C = 298.2 K, $\dot{W}_{IN}$ = 3275 kJ/h and

$$\dot{Q}_L = 2400(T_H - 298.2) \text{ kJ/h}$$

$$\beta = \frac{\dot{Q}_L}{\dot{W}_{IN}} = \frac{2400(T_H - 298.2)}{3275} = \frac{T_L}{T_H - T_L} = \frac{298.2}{T_H - 298.2}$$

$$\text{or,} \quad (T_H - 298.2)^2 = \frac{298.2 \times 3275}{2400} = 406.92$$

$$T_H = 318.4 \text{ K} = \mathbf{45.2°C}$$

7.38 It is proposed to build a 1000-MW electric power plant with steam as the working fluid. The condensers are to be cooled with river water (see Fig. P7.38). The maximum steam temperature is 550°C, and the pressure in the condensers will be 10 kPa. Estimate the temperature rise of the river downstream from the power plant.

Solution:

$$\dot{W}_{NET} = 10^6 \text{ kW}, \quad T_H = 550°\text{C} = 823.3 \text{ K}$$

$$P_{COND} = 10 \text{ kPa} \rightarrow T_L = T_G \text{ (P = 10 kPa)} = 45.8°\text{C} = 319 \text{ K}$$

$$\eta_{TH\ CARNOT} = \frac{T_H - T_L}{T_H} = \frac{823.2 - 319}{823.2} = 0.6125$$

$$\Rightarrow \dot{Q}_{L\ MIN} = 10^6\left(\frac{1 - 0.6125}{0.6125}\right) = 0.6327\times10^6 \text{ kW}$$

$$\text{But } \dot{m}_{H_2O} = \frac{60 \times 8 \times 10/60}{0.001} = 80000 \text{ kg/s}$$

$$\Rightarrow \Delta T_{H_2O\ MIN} = \dot{Q}_{MIN}/\dot{m}_{H_2O}C_{P\ LIQ\ H_2O} = \frac{0.6327\times10^6}{80000 \times 4.184} = \mathbf{1.9°C}$$

7.39 Two different fuels can be used in a heat engine, operating between the fuel-burning temperature and a low temperature of 350 K. Fuel A burns at 2500 K delivering 52000 kJ/kg and costs \$1.75 per kilogram. Fuel B burns at 1700 K, delivering 40000 kJ/kg and costs \$1.50 per kilogram. Which fuel would you buy and why?

Solution:

$$\text{Fuel A:} \quad \eta_{TH,A} = 1 - T_L/T_H = 1 - \frac{350}{2500} = 0.86$$

$$W_A = \eta_{TH,A} \times Q_A = 0.86 \times 52000 = 44720 \text{ kJ/kg}$$

$$W_A/\$_A = 44720/1.75 = 25554 \text{ kJ/\$}$$

$$\text{Fuel B:} \quad \eta_{TH,B} = 1 - T_L/T_H = 1 - \frac{350}{1700} = 0.794$$

$$W_B = \eta_{TH,B} \times Q_B = 0.794 \times 40000 = 31760 \text{ kJ/kg}$$

$$W_B/\$_B = 31760/1.5 = 21173 \text{ kJ/\$}$$

Select fuel A for more work per dollar.

7.40 A refrigerator uses a power input of 2.5 kW to cool a 5°C space with the high temperature in the cycle as 50°C. The Q_H is pushed to the ambient air at 35°C in a heat exchanger where the transfer coefficient is 50 W/m^2K. Find the required minimum heat transfer area.

Solution:

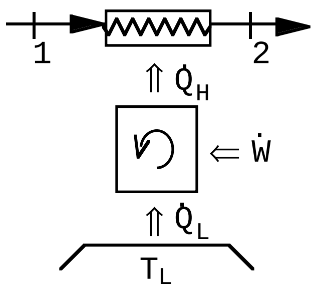
$$\dot{W} = 2.5 \text{ kW} = \dot{Q}_H / \beta_{HP}$$

$$\dot{Q}_H = \dot{W} \times \beta_{HP} = 2.5 \times [323 / (50 - 5)] = 17.95 \text{ kW} = h\, A\, \Delta T$$

$$A = \dot{Q}_H / h\,\Delta T = 17.95 / 50 \times 10^{-3} \times 15 = \mathbf{23.9\ m^2}$$

7.41 Refrigerant-12 at 95°C, $x = 0.1$ flowing at 2 kg/s is brought to saturated vapor in a constant-pressure heat exchanger. The energy is supplied by a heat pump with a low temperature of 10°C. Find the required power input to the heat pump.

Solution:



Assume Carnot heat pump

$$\beta' = \dot{Q}_H/\dot{W} = T_H/(T_H - T_L)$$

$T_H = 368.2$, $T_L = 283.2$, => $\beta' = 4.332$

Table B.3.1: $h_1 = 147.23$, $h_2 = 211.73$

$$\dot{Q}_H = \dot{m}_{R\text{-}12}(h_2 - h_1) = 129.0 \text{ kW}$$

$$\dot{W} = \dot{Q}_H/\beta = 129.0/4.332 = \mathbf{29.8\ kW}$$

7.42 A furnace, shown in Fig. P7.42, can deliver heat, Q_{H1} at T_{H1} and it is proposed to use this to drive a heat engine with a rejection at T_{atm} instead of direct room heating. The heat engine drives a heat pump that delivers Q_{H2} at T_{room} using the atmosphere as the cold reservoir. Find the ratio Q_{H2}/Q_{H1} as a function of the temperatures. Is this a better set-up than direct room heating from the furnace?

Solution:

C.V.: Heat Eng.: $\dot{W}_{HE} = \eta\dot{Q}_{H1}$ where $\eta = 1 - T_{atm}/T_{H1}$

C.V.: Heat Pump: $\dot{W}_{HP} = \dot{Q}_{H2}/\beta'$ where $\beta' = T_{rm}/(T_{rm} - T_{atm})$

Work from heat engine goes into heat pump so we have

$$\dot{Q}_{H2} = \beta'\, \dot{W}_{HP} = \beta'\, \eta\, \dot{Q}_{H1}$$

and we may substitute T's for β', η. If furnace is used directly $\dot{Q}_{H2} = \dot{Q}_{H1}$, so if $\beta'\eta > 1$ this proposed setup is better. Is it? For $T_{H1} > T_{atm}$ formula shows that it is good for Carnot cycles. In actual devices it depends wether $\beta'\eta > 1$ is obtained.

7.43 A heat engine has a solar collector receiving 0.2 kW per square meter inside which a transfer media is heated to 450 K. The collected energy powers a heat engine which rejects heat at 40 C. If the heat engine should deliver 2.5 kW what is the minimum size (area) solar collector?

Solution:

$$T_H = 450 \text{ K} \qquad T_L = 40\ ^oC = 313.15 \text{ K}$$

$$\eta_{HE} = 1 - T_L / T_H = 1 - 313.15 / 450 = 0.304$$

$$\dot W = \eta\, \dot Q_H \quad => \quad \dot Q_H = \dot W / \eta = 2.5 / 0.304 = 8.224 \text{ kW}$$

$$\dot Q_H = 0.2\ A \quad => \quad A = \dot Q_H / 0.2 = \mathbf{41\ m^2}$$

7.44 In a cryogenic experiment you need to keep a container at −125°C although it gains 100 W due to heat transfer. What is the smallest motor you would need for a heat pump absorbing heat from the container and rejecting heat to the room at 20°C?

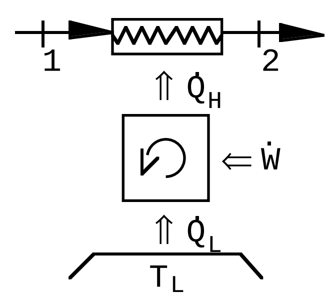
Solution:

$$\beta'_{HP} = \dot Q_H / \dot W = \frac{T_H}{T_H - T_L} = \frac{293.15}{20 - (-125)} = 2.022 = 1 + \dot Q_L / \dot W$$

$$=> \qquad \dot W = \dot Q_L/(\beta' - 1) = 100/1.022 = \mathbf{97.8\ W}$$

7.45 Sixty kilograms per hour of water runs through a heat exchanger, entering as saturated liquid at 200 kPa and leaving as saturated vapor. The heat is supplied by a Carnot heat pump operating from a low-temperature reservoir at 16°C. Find the rate of work into the heat pump.

Solution:



C.V. Heat exchanger

$$\dot m_1 = \dot m_2 ; \qquad \dot m_1 h_1 + \dot Q_H = \dot m_1 h_2$$

Table B.1.2: $h_1 = 504.7, \quad h_2 = 2706.7$

$$T_H = T_{sat}(P) = 120.93 + 273.15 = 394.08$$

$$\dot Q_H = = \frac{1}{60}(2706.7 - 504.7) = 36.7 \text{ kW}$$

Assume a Carnot heat pump.

$$\beta' = \dot Q_H/\dot W = T_H / (T_H - T_L) = 394.08 / 104.93 = 3.76$$

$$\dot W = \dot Q_H/\beta' = 36.7/3.76 = \mathbf{9.76\ kW}$$

7.46 Air in a rigid 1 m^3 box is at 300 K, 200 kPa. It is heated to 600 K by heat transfer from a reversible heat pump that receives energy from the ambient at 300 K besides the work input. Use constant specific heat at 300 K. Since the coefficient of performance changes write $dQ = m_{air} C_v dT$ and find dW. Integrate dW with temperature to find the required heat pump work.

Solution:

$$\beta = Q_H / W = Q_H / (Q_H - Q_L) \cong T_H / (T_H - T_L)$$

$$m_{air} = P_1V_1 / RT_1 = 200 \times 1 / 0.287 \times 300 = 2.322 \text{ kg}$$

$$dQ_H = m_{air} C_v dT_H = \beta\, dW \cong [T_H / (T_H - T_L)]\, dW$$

$$=> dW = m_{air} C_v [T_H / (T_H - T_L)]\, dT_H$$

$$_1W_2 = \int m_{air} C_v (1- T_L / T)\, dT = m_{air} C_v \int (1 - T_L / T)\, dT$$

$$= m_{air} C_v [T_2 - T_1 - T_L \ln (T_2 / T_1)]$$

$$= 2.322 \times 0.7165 [600 - 300 - 300 \ln (600/300)] = \mathbf{153.1\ kJ}$$

7.47 Consider the rock bed thermal storage in Problem 7.22. Use the specific heat so you can write dQ_H in terms of dTrock and find the expression for dW out of the heat engine. Integrate this expression over temperature and find the total heat engine work output.

Solution:

$$dW = \eta dQ_H = - (1 - T_o / T_{rock})\, mC\, dT_{rock}$$

$$m = 2 \times 2750 = 5500 \text{ kg}$$

$$_1W_2 = \int - (1 - T_o / T_{rock})\, mC\, dT_{rock} = - mC [T_2 - T_1 - T_o \ln (T_2 / T_1)]$$

$$= - 5500 \times 0.89 [290 - 400 - 290 \ln (290/400)] = \mathbf{81945\ kJ}$$

7.48 A Carnot heat engine, shown in Fig. P7.48, receives energy from a reservoir at T_{res} through a heat exchanger where the heat transferred is proportional to the temperature difference as $\dot{Q}_H = K(T_{res} - T_H)$. It rejects heat at a given low temperature T_L. To design the heat engine for maximum work output show that the high temperature, T_H. in the cycle should be selected as $T_H = \sqrt{T_{res}T_L}$

Solution:

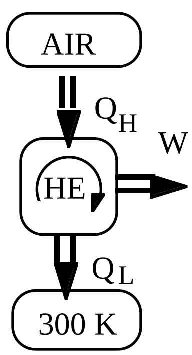
$$W = \eta_{TH} Q_H = \frac{T_H - T_L}{T_H} \times K(T_{res} - T_H) \;; \quad \text{maximize } W(T_H) \Rightarrow \frac{\delta W}{\delta T_H} = \emptyset$$

$$\frac{\delta W}{\delta T_H} = K(T_{res} - T_H)T_L T_H^{-2} - K(1 - T_L/T_H) = \emptyset$$

$$\Rightarrow \mathbf{T_H = \sqrt{T_{res} T_L}}$$

7.49 A 10-m^3 tank of air at 500 kPa, 600 K acts as the high-temperature reservoir for a Carnot heat engine that rejects heat at 300 K. A temperature difference of 25°C between the air tank and the Carnot cycle high temperature is needed to transfer the heat. The heat engine runs until the air temperature has dropped to 400 K and then stops. Assume constant specific heat capacities for air and find how much work is given out by the heat engine.

Solution:



$$T_H = T_{air} - 25°C \quad T_L = 300 \text{ K}$$

$$m_{air} = \frac{P_1 V}{RT_1} = \frac{500 \times 10}{0.287 \times 600} = 29.04 \text{ kg}$$

$$dW = \eta dQ_H = \left(1 - \frac{T_L}{T_{air} - 25}\right) dQ_H$$

$$dQ_H = -m_{air} du = -m_{air} C_v dT_{air}$$

$$W = \int dW = -m_{air} C_v \int \left[1 - \frac{T_L}{T_a - 25}\right] dT_a = -m_{air} C_v \left[T_{a2} - T_{a1} - T_L \ln \frac{T_{a2} - 25}{T_{a1} - 25}\right]$$

$$= -29.04 \times 0.717 \times \left[400 - 600 - 300 \ln \frac{375}{575}\right] = \mathbf{1494.3 \text{ kJ}}$$

7.50 Consider a Carnot cycle heat engine operating in outer space. Heat can be rejected from this engine only by thermal radiation, which is proportional to the radiator area and the fourth power of absolute temperature, $Q_{rad} \sim KAT^4$. Show that for a given engine work output and given T_H, the radiator area will be minimum when the ratio $T_L/T_H = 3/4$.

Solution:

$$W_{NET} = Q_H\left(\frac{T_H - T_L}{T_H}\right) = Q_L\left(\frac{T_H - T_L}{T_L}\right); \qquad \text{also} \quad Q_L = KAT_L^4$$

$$\frac{W_{NET}}{KT_H^4} = \frac{AT_L^4}{T_H^4}\left(\frac{T_H}{T_L} - 1\right) = A\left[\left(\frac{T_L}{T_H}\right)^3 - \left(\frac{T_L}{T_H}\right)^4\right] = \text{const}$$

Differentiating,

$$dA\left[\left(\frac{T_L}{T_H}\right)^3 - \left(\frac{T_L}{T_H}\right)^4\right] + A\left[3\left(\frac{T_L}{T_H}\right)^2 - 4\left(\frac{T_L}{T_H}\right)^3\right] d\left(\frac{T_L}{T_H}\right) = 0$$

$$\frac{dA}{d(T_L/T_H)} = - A\left[3\left(\frac{T_L}{T_H}\right)^2 - 4\left(\frac{T_L}{T_H}\right)^3\right] / \left[\left(\frac{T_L}{T_H}\right)^3 - \left(\frac{T_L}{T_H}\right)^4\right] = 0$$

$$\frac{T_L}{T_H} = \frac{3}{4} \text{ for min. A} \begin{cases} \text{Check 2nd deriv. to prove} \\ \text{it is min. A not max. A} \end{cases}$$

7.51 Air in a piston/cylinder goes through a Carnot cycle with the P-v diagram shown in Fig. 7.24. The high and low temperatures are 600 K and 300 K respectively. The heat added at the high temperature is 250 kJ/kg and the lowest pressure in the cycle is 75 kPa. Find the specific volume and pressure at all 4 states in the cycle assuming constant specific heats at 300 K..

Solution:

q_H = 250 kJ/kg , T_H = 600 K, T_L = 300 K, P_3 = 75 kPa

C_v = 0.717 ; R = 0.287

1: 600 K , 2: 600 K, 3: 75 kPa, 300 K 4: 300 K

$v_3 = RT_3 / P_3 = 0.287 \times 300 / 75 = 1.148\ m^3/kg$

$2 \rightarrow 3$ Eq.7.11 & C_v = const $=> C_v \ln (T_L / T_H) + R \ln (v_3/v_2) = 0$

$=> \ln (v_3/v_2) = - (C_v / R) \ln (T_L / T_H)$

$= - (0.7165/0.287) \ln (300/600) = 1.73045$

$=> v_2 = v_3 / \exp (1.73045) = 1.148/5.6432 = 0.2034\ m^3/kg$

$1 \rightarrow 2$ $q_H = RT_H \ln (v_2 / v_1)$

$\ln (v_2 / v_1) = q_H /RT_H = 250/0.287 \times 600 = 1.4518$

$v_1 = v_2 / \exp (1.4518) = 0.04763\ m^3/kg$

$v_4 = v_1 \times v_3 / v_2 = 0.04763 \times 1.148/0.2034 = 0.2688$

$P_1 = RT_1 / v_1 = 0.287 \times 600/0.04763 = 3615$ kPa

$P_2 = RT_2 / v_2 = 0.287 \times 600/0.2034 = 846.6$ kPa

$P_4 = RT_4 / v_4 = 0.287 \times 300/0.2688 = 320$ kPa

7.52 Hydrogen gas is used in a Carnot cycle having an efficiency of 60% with a low temperature of 300 K. During the heat rejection the pressure changes from 90 kPa to 120 kPa. Find the high and low temperature heat transfer and the net cycle work per unit mass hydrogen.

Solution:

$\eta = 0.6 = 1 - T_L / T_H \qquad => T_H = T_L /(1 - 0.6) = 750$ K

$v_3 / v_4 = (RT_3 / P_3) / (RT_4 / P_4) = P_4 / P_3 = 120 / 90 = 1.333$

$q_L = RT_L \ln (v_3/v_4) = 355.95$ kJ/kg ; $\quad R = 4.1243$

$q_H = q_L / (1 - 0.6) = 889.9$ kJ/kg ; $\quad w = q_H - q_L =$ **533.9 kJ/kg**

7.53 Obtain information from manufacturers of heat pumps for domestic use. Make a listing of the coefficient of performance and compare those to corresponding Carnot cycle devices operating between the same temperature reservoirs.

Solution:

Discussion

English Unit Problems.

7.54E Calculate the thermal efficiency of the steam power plant cycle described in Problem 6.91.

Solution:

From solution to problem 6.91,

$\dot{W}_{NET} = 33000 - 400 = 32600 \text{ hp} = 8.3\times10^7 \text{ Btu/h}$

$\dot{Q}_{H,tot} = 4.75\times10^7 + 2.291\times10^8 = 2.766\times10^8$; $\quad \eta = \dfrac{\dot{W}}{\dot{Q}_H} = \mathbf{0.30}$

7.55E Calculate the thermal efficiency of a Carnot-cycle heat engine operating between reservoirs at 920 F and 110 F. Compare the result with that of Problem 7.54.

Solution:

$T_H = 920 \text{ F}, \quad T_L = 110 \text{ F}$

$\eta_{Carnot} = 1 - \dfrac{T_L}{T_H} = 1 - \dfrac{110 + 459.67}{920 + 459.67} = \mathbf{0.587}$ (about twice 7.54: 0.3)

7.56E A car engine burns 10 lbm of fuel (equivalent to addition of QH) at 2600 R and rejects energy to the radiator and the exhaust at an average temperature of 1300 R. If the fuel provides 17 200 Btu/lbm what is the maximum amount of work the engine can provide?

Solution:

A heat engine $\quad Q_H = 10 \times 17200 = 170\ 200 \text{ Btu}$

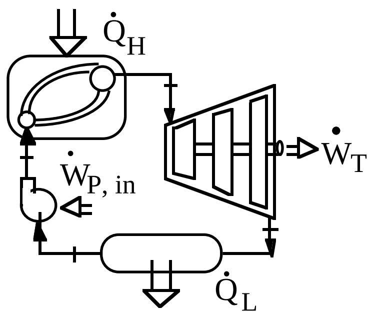
Assume a Carnot efficiency (maximum theoretical work)

$\eta = 1 - T_L/T_H = 1 - 1300/2600 = 0.5$

$W = \eta\ Q_H = 0.5 \times 170\ 200 = \mathbf{85\ 100\ Btu}$

7.57E In a steam power plant 1000 Btu/s is added at 1200 F in the boiler, 580 Btu/s is taken out at 100 F in the condenser and the pump work is 20 Btu/s. Find the plant thermal efficiency. Assume the same pump work and heat transfer to the boiler as given, how much turbine power could be produced if the plant were running in a Carnot cycle?

Solution:



C.V. Total: $\dot{Q}_H + \dot{W}_{P,in} = \dot{W}_T + \dot{Q}_L$

$\Rightarrow \dot{W}_T = 1000 + 20 - 580 = 440$ Btu/s

$\eta_{TH} = (\dot{W}_T - \dot{W}_{P,in})/\dot{Q}_H = 420/1000 = \mathbf{0.42}$

$\eta_{carnot} = \dot{W}_{net}/\,\dot{Q}_H = 1 - T_L/T_H$

$$= 1 - \frac{100 + 459.67}{1200 + 459.67} = 0.663$$

$$\dot{W}_T - \dot{W}_{P,in} = \eta_{carnot}\dot{Q}_H = 663 \text{ Btu/s} \quad => \quad \dot{W}_T = \mathbf{683\ \frac{Btu}{s}}$$

7.58E An air-conditioner provides 1 lbm/s of air at 60 F cooled from outside atmospheric air at 95 F. Estimate the amount of power needed to operate the air-conditioner. Clearly state all assumptions made.

Solution:

$\dot{Q}_{air} = \dot{m}\,\Delta h \cong \dot{m}\,C_p\,\Delta T = 1 \times 0.24 \times (95 - 60) = 8.4$ Btu/s

Assume Carnot cycle refrigerator

$\beta = (60 + 459.67) / (95 - 60) = 14.8$

$\dot{W} = \dot{Q}_L / \beta = 8.4 / 14.8 =$ **0.57 Btu/s**

This estimate is the theoretical maximum performance. To do the required heat transfer $T_L \approx 40$ F and $T_H \approx$ **110 F** are more likely; secondly $\beta < \beta_{carnot}$

7.59E A car engine operates with a thermal efficiency of 35%. Assume the air-conditioner has a coefficient of performance that is one third of the theoretical maximum and it is mechanically pulled by the engine. How much fuel energy should you spend extra to remove 1 Btu at 60 F when the ambient is at 95 F?

Solution:

$\beta = T_L / (T_H - T_L) = (60 + 459.67) / (95 - 60) = 14.8$

$\beta_{actual} = \beta / 3 = 4.93$

$W = Q_L / \beta = 1 / 4.93 = 0.203$ Btu

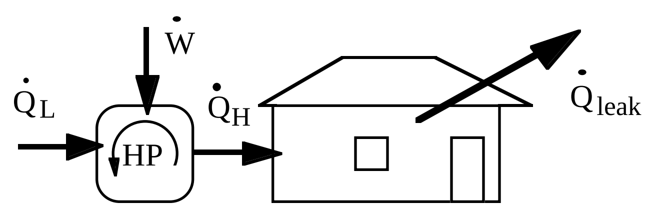
$\Delta Q_{Hengine} = W / \eta = 0.203 / 0.35 =$ **0.58 Btu**

7.60E We propose to heat a house in the winter with a heat pump. The house is to be maintained at 68 F at all times. When the ambient temperature outside drops to 15 F, the rate at which heat is lost from the house is estimated to be 80000 Btu/h. What is the minimum electrical power required to drive the heat pump?

Solution:

Minimum power if we assume a Carnot cycle

$\dot{Q}_H = \dot{Q}_{leak} = 80\ 000$ Btu/h

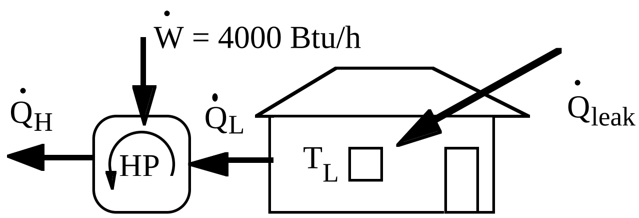


$$\beta' = \frac{\dot{Q}_H}{\dot{W}_{IN}} = \frac{T_H}{T_H - T_L} = \frac{527.7}{53} = 9.957$$

$\Rightarrow \dot{W}_{IN} = 80\ 000 / 9.957 = 8035$ Btu/h = **2.355 kW**

7.61E A heat pump cools a house at 70 F with a maximum of 4000 Btu/h power input. The house gains 2000 Btu/h per degree temperature difference to the ambient and the heat pump coefficient of performance is 60% of the theoretical maximum. Find the maximum outside temperature for which the heat pump provides sufficient cooling.

Solution:



Here:
$T_L = T_{house}$
$T_H = T_{amb}$

In this setup the low temperature space is the house and the high temperature space is the ambient. The heat pump must remove the gain or leak heat transfer to keep it at a constant temperature.

$\dot{Q}_{leak} = 2000\ (T_{amb} - T_{house}) = \dot{Q}_L$ which must be removed by the heat pump.

$$\beta' = \dot{Q}_H / \dot{W} = 1 + \dot{Q}_L / \dot{W} = 0.6\ \beta'_{carnot} = 0.6\ T_{amb} / (T_{amb} - T_{house})$$

Substitute in for $\dot{Q}_L$ and multiply with $(T_{amb} - T_{house})$:

$$(T_{amb} - T_{house}) + 2000\ (T_{amb} - T_{house})^2 / \dot{W} = 0.6\ T_{amb}$$

Since T_{house} = 529.7 R and $\dot{W}$ = 4000 Btu/h it follows

$$T_{amb}^2 - 1058.6\ T_{amb} + 279522.7 = 0$$

Solving => T_{amb} = **554.5 R = 94.8 F**

7.62E A thermal storage is made with a rock (granite) bed of 70 ft^3 which is heated to 720 R using solar energy. A heat engine receives a Q_H from the bed and rejects heat to the ambient at 520 R. The rock bed therefore cools down and as it reaches 520 R the process stops. Find the energy the rock bed can give out. What is the heat engine efficiency at the beginning of the process and what is it at the end of the process?

Solution:

$$u_2 - u_1 = q = C\ \Delta T = 0.21\ (720 - 520) = 42\ \text{Btu/lbm}$$

$$m = \rho V = 172 \times 70 = 12040\ \text{lbm}; \quad Q = mq = \mathbf{505\ 680\ Btu}$$

To get the efficiency assume a Carnot cycle device

$\eta = 1 - T_o / T_H = 1 - 520/720 = \mathbf{0.28}$ beginning

$\eta = 1 - T_o / T_H = 1 - 520/520 = \mathbf{0}$ end

7.63E An inventor has developed a refrigeration unit that maintains the cold space at 14 F, while operating in a 77 F room. A coefficient of performance of 8.5 is claimed. How do you evaluate this?

Solution:

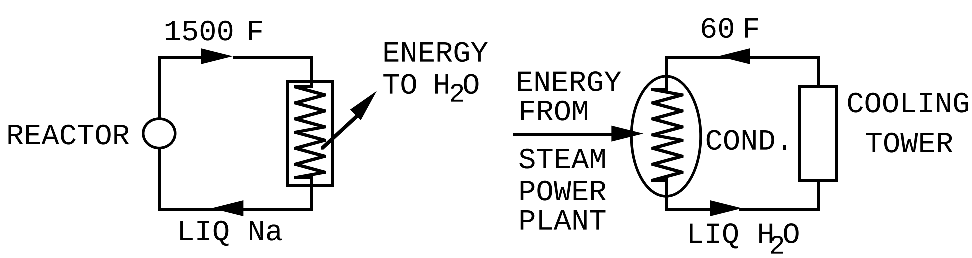
Assume Carnot cycle then

$$\beta = \frac{Q_L}{W_{in}} = \frac{T_L}{T_H - T_L} = \frac{14 + 459.67}{77 - 14} = 7.5$$

Claim is **impossible**

7.64E Liquid sodium leaves a nuclear reactor at 1500 F and is used as the energy source in a steam power plant. The condenser cooling water comes from a cooling tower at 60 F. Determine the maximum thermal efficiency of the power plant. Is it misleading to use the temperatures given to calculate this value?

Solution:



T_H = 1500 F = 1960 R, T_L = 60 F = 520 R

$$\eta_{TH\ MAX} = \frac{T_H - T_L}{T_H} = \frac{1960 - 520}{19860} = 0.735$$

It might be misleading to use 1500 F as the value for T_H, since there is not a supply of energy available at a constant temperature of 1500 F (liquid Na is cooled to a lower temperature in the heat exchanger).

⇒ The Na cannot be used to boil H_2O at 1500 F.

Similarly, the H_2O leaves the cooling tower and enters the condenser at 60 F, and leaves the condenser at some higher temperature.

⇒ The water does not provide for condensing steam at a constant temperature of 60 F.

7.65E A house is heated by an electric heat pump using the outside as the low-temperature reservoir. For several different winter outdoor temperatures, estimate the percent savings in electricity if the house is kept at 68 F instead of 75 F. Assume that the house is losing energy to the outside directly proportional to the temperature difference as $\dot{Q}_{loss} = K(T_H - T_L)$.

Solution:

Heat Pump $\dot{Q}_{LOSS} \propto (T_H - T_L)$

Max Perf. $\dfrac{\dot{Q}_H}{\dot{W}_{in}} = \dfrac{T_H}{T_H - T_L} = \dfrac{K(T_H - T_L)}{\dot{W}_{in}}, \qquad \dot{W}_{in} = \dfrac{K(T_H - T_L)^2}{T_H}$

A: T_{H_A} = 75 F = 534.7 R B: T_{H_B} = 68 F = 527.7 R

T_L, F	$\dot{W}_{IN_A}/K$	$\dot{W}_{IN_B}/K$	% saving
-10	13.512	11.529	14.7 %
10	7.902	6.375	19.3 %
30	3.787	2.736	27.8 %
50	1.169	0.614	47.5 %

7.66E A house is cooled by an electric heat pump using the outside as the high-temperature reservoir. For several different summer outdoor temperatures estimate the percent savings in electricity if the house is kept at 77 F instead of 68 F. Assume that the house is gaining energy from the outside directly proportional to the temperature difference.

Solution:

Air-conditioner (Refrigerator) $\dot{Q}_{LEAK} \propto (T_H - T_L)$

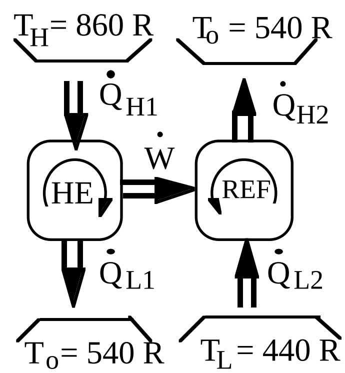
Max Perf. $\dfrac{\dot{Q}_L}{\dot{W}_{in}} = \dfrac{T_L}{T_H - T_L} = \dfrac{K(T_H - T_L)}{\dot{W}_{in}}, \quad \dot{W}_{in} = \dfrac{K(T_H - T_L)^2}{T_L}$

A: T_{L_A} = 68 F = 527.7 R B: T_{L_B} = 77 F = 536.7 R

T_H, F	$\dot{W}_{IN_A}/K$	$\dot{W}_{IN_B}/K$	% saving
115	4.186	2.691	35.7 %
105	2.594	1.461	43.7 %
95	1.381	0.604	56.3 %

7.67E We wish to produce refrigeration at –20 F. A reservoir is available at 400 F and the ambient temperature is 80 F, as shown in Fig. P7.33. Thus, work can be done by a cyclic heat engine operating between the 400 F reservoir and the ambient. This work is used to drive the refrigerator. Determine the ratio of the heat transferred from the 400 F reservoir to the heat transferred from the –20 F reservoir, assuming all processes are reversible.

Solution: Equate the work from the heat engine to the refrigerator.



$$W = Q_{H1}\left(\frac{T_H - T_O}{T_H}\right)$$

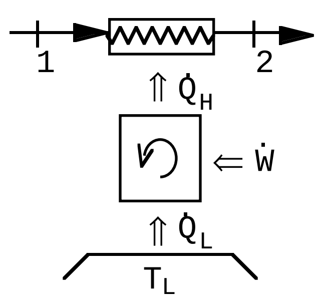
also

$$W = Q_{L2}\left(\frac{T_O - T_L}{T_L}\right)$$

$$\frac{Q_H}{Q_L} = \left(\frac{T_O - T_L}{T_L}\right)\left(\frac{T_H}{T_H - T_O}\right) = \frac{100}{440} \times \frac{860}{320} = 0.611$$

7.68E Refrigerant-22 at 180 F, *x* = 0.1 flowing at 4 lbm/s is brought to saturated vapor in a constant-pressure heat exchanger. The energy is supplied by a heat pump with a low temperature of 50 F. Find the required power input to the heat pump.

Solution:



Assume Carnot heat pump

$\beta' = \dot{Q}_H/\dot{W} = T_H/(T_H - T_L)$

$T_H = 640$, $T_L = 510$, $\beta' = 4.923$

Table C.10.1: $h_1 = 68.5$, $h_2 = 110.07$

$\dot{Q}_H = \dot{m}_{F12}(h_2 - h_1) = 166.3$ Btu/s

$\dot{W} = \dot{Q}_H/\beta = 166.3/4.923 =$ **33.8 Btu/s**

7.69E A heat engine has a solar collector receiving 600 Btu/h per square foot inside which a transfer media is heated to 800 R. The collected energy powers a heat engine which rejects heat at 100 F. If the heat engine should deliver 8500 Btu/h what is the minimum size (area) solar collector?

Solution:

$T_H = 800$ R $\qquad T_L = 100 + 459.67 = 560$ R

$\eta = 1 - T_L/\,T_H = 1 - 560/800 = 0.3$

$\dot{W} = \eta\dot{Q}_H \qquad => \quad \dot{Q}_H = \dot{W}\,/\eta = 8500/0.3 = 28333$ Btu/s

$\dot{Q}_H = 600$ A $\qquad => \quad$ A $= \dot{Q}_H\ /\ 600 =$ **47.2 ft²**

7.70E Six-hundred pound-mass per hour of water runs through a heat exchanger, entering as saturated liquid at 30 lbf/in.^{2} and leaving as saturated vapor. The heat is supplied by a Carnot heat pump operating from a low-temperature reservoir at 60 F. Find the rate of work into the heat pump.

Solution:

C.V. Heat exchanger

$\dot{m}_1 = \dot{m}_2\ ; \qquad \dot{m}_1h_1 + \dot{Q}_H = \dot{m}_1h_2$

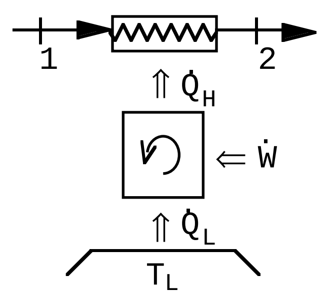


Table C.8.1: $\quad h_1 = 218.92 \qquad h_2 = 1164.3$

$T_H = T_{sat}(P) = 250.34$ F $= 710$ R

$\dot{Q}_H = \frac{1}{6}(1164.3 - 218.92) = 157.6$ Btu/s

Assume a Carnot heat pump.

$$\beta = \dot{Q}_H/\dot{W} = \frac{T_H}{T_H - T_L} = \frac{710}{190.34} = 3.73$$

$\dot{W} = \dot{Q}_H/\beta = 157.6/3.73 =$ **42.25 Btu/s**

7.71E Air in a rigid 40 ft^3 box is at 540 R, 30 lbf/in.^{2}. It is heated to 1100 R by heat transfer from a reversible heat pump that receives energy from the ambient at 540 R besides the work input. Use constant specific heat at 540 R. Since the coefficient of performance changes write $dQ = m_{air}\ C_v\ dT$ and find dW. Integrate dW with temperature to find the required heat pump work.

Solution:

$$\beta = Q_H / W = Q_H / (Q_H - Q_L) \cong T_H / (T_H - T_L)$$

$$m_{air} = P_1V_1 / RT_1 = (30 \times 40 \times 144) / (540 \times 53.34) = 6.0 \text{ lbm}$$

$$dQ_H = m_{air}\ C_v\ dT_H = \beta\ dW = \cong [T_H / (T_H - T_L)]\ dW$$

$$= > dW = m_{air}\ C_v\ [T_H / (T_H - T_L)]\ dT_H$$

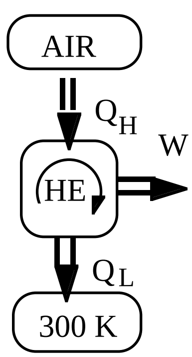
$${}_1W_2 = \int m_{air}\ C_v\ (\ 1- T_L\ / \ T\ )\ dT = m_{air}\ C_v \int (\ 1 - T_L\ / \ T\ )\ dT$$

$$= m_{air}\ C_v\ [T_2 - T_1 - T_L \ln{(T_2 / T_1)}]$$

$${}_1W_2 = 6.0 \times 0.171\ [1100 - 540 - \ln{(1100/540)}] = \mathbf{180.4\ Btu}$$

7.72E A 350-ft^3 tank of air at 80 lbf/in.^{2}, 1080 R acts as the high-temperature reservoir for a Carnot heat engine that rejects heat at 540 R. A temperature difference of 45 F between the air tank and the Carnot cycle high temperature is needed to transfer the heat. The heat engine runs until the air temperature has dropped to 700 R and then stops. Assume constant specific heat capacities for air and find how much work is given out by the heat engine.

Solution:



$$T_H = T_{air} - 45\ , \quad T_L = 540 \text{ R}$$

$$m_{air} = \frac{P_1V}{RT_1} = \frac{80 \times 350 \times 144}{53.34 \times 1080} = 69.991 \text{ lbm}$$

$$dW = \eta dQ_H = \left(1 - \frac{T_L}{T_{air} - 45}\right) dQ_H$$

$$dQ_H = -m_{air}du = -m_{air}C_v dT_{air}$$

$$W = \int dW = -m_{air}C_v \int \left[1 - \frac{T_L}{T_a\text{-}45}\right] dT_a = -m_{air}C_v \left[T_{a2}\text{-}T_{a1}\text{-}T_L \ln \frac{T_{a2}\text{-}45}{T_{a1}\text{-}45}\right]$$

$$= -69.991 \times 0.171 \times \left[700 - 1080 - 540 \ln \frac{655}{1035}\right] = \mathbf{1591\ Btu}$$

7.73E Air in a piston/cylinder goes through a Carnot cycle with the P-v diagram shown in Fig. 7.24. The high and low temperatures are 1200 R and 600 R respectively. The heat added at the high temperature is 100 Btu/lbm and the lowest pressure in the cycle is 10 lbf/in.^{2}. Find the specific volume and pressure at all 4 states in the cycle assuming constant specific heats at 80 F.

Solution:

q_H = 100 Btu/lbm T_H = 1200 R

T_L = 600 R P_3 = 10 lbf/in.^{2}

C_v = 0.171 ;   R = 53.34

1: 1200 R ,   2: 1200 R,   3: 10 psi, 600 R   4: 600 R

$v_3 = RT_3 / P_3 = 53.34 \times 600 /(10 \times 144) = 22.225$ ft^3/lbm

$2 \rightarrow 3$ Eq.7.11 & C_v = const $\Rightarrow C_v \ln (T_L / T_H) + R \ln (v_3/v_2) = 0$

$\Rightarrow \ln (v_3/v_2) = - (C_v / R) \ln (T_L / T_H)$

$= - (0.171/53.34) \ln (600/1200) = 1.7288$

$\Rightarrow v_2 = v_3 / \exp (1.7288) = 22.225/5.6339 = 3.9449$ ft^3/lbm

$1 \rightarrow 2$ $q_H = RT_H \ln (v_2 / v_1)$

$\ln (v_2 / v_1) = q_H /RT_H = 100 \times 778/(53.34 \times 1200) = 1.21547$

$v_1 = v_2 / \exp (1.21547) = 1.1699$ ft^3/lbm

$v_4 = v_1 \times v_3 / v_2 = 1.1699 \times 22.225/3.9449 = 6.591$

$P_1 = RT_1 / v_1 = 53.34 \times 1200/(1.1699 \times 144) = 379.9$ psia

$P_2 = RT_2 / v_2 = 53.34 \times 1200/(3.9449 \times 144) = 112.7$ psia

$P_4 = RT_4 / v_4 = 53.34 \times 600/(6.591 \times 144) = 33.7$ psia

CHAPTER 8

The correspondence between the new problem set and the previous 4th edition chapter 7 problem set.

New	Old	New	Old	New	Old
1	new	26	new	51	61
2	1	27	29	52	new
3	2	28	28	53	42
4	3	29	27	54	43
5	new	30	new	55	44
6	4	31	new	56	45
7	5	32	new	57	46
8	new	33	20	58	new
9	7	34	21	59	48
10	8	35	22	60	new
11	9	36	30	61	49
12	10	37	31	62	51
13	11	38	new	63	53
14	new	39	new	64	54
15	13	40	33	65	new
16	new	41	34	66	56
17	15	42	new	67	57
18	6	43	35	68	new
19	16	44	36	69	58
20	12	45	37	70	55
21	17	46	38	71	60
22	new	47	39	72	59
23	new	48	new	73	14
24	new	49	40	74	52
25	25	50	41	75	new

The problems that are labeled advanced are:

New	Old	New	Old	New	Old
76	23	79	47	82	50
77	26	80	new		
78	32	81	new		

The English unit problems are:

New	Old	New	Old	New	Old
83	new	95	134	107	new
84	122 mod	96	136	108	new
85	123	97	135	109	145
86	124	98	new	110	new
87	125	99	133	111	147
88	new	100	137	112	new
89	127	101	new	113	new
90	128	102	138		
91	130	103	139		
92	126	104	140		
93	129	105	141		
94	131	106	143		

8.1 Consider the steam power plant in Problem 7.9 and the heat engine in Problem 7.17. Show that these cycles satisfy the inequality of Clausius.

Solution:

Show Clausius: $\int dQ/T \leq 0$

For problem 7.9 we have :

$Q_H / T_H - Q_L / T_L = 1000/973.15 - 580/313.15$

$= 1.0276 - 1.852 = -0.825 < 0$ **OK**

For problem 7.17 we have:

$Q_H / T_H - Q_L / T_L = 325/1000 - 125/400$

$= 0.325 - 0.3125 = 0.0125 > 0$

This is impossible

8.2 Find the missing properties and give the phase of the substance

a. H2O s = 7.70 kJ/kg K, P = 25 kPa h = ? T = ? x = ?

b. H2O u = 3400 kJ/kg, P = 10 MPa T = ? x = ? s = ?

c. R-12 T = 0°C, P = 250 kPa s = ? x = ?

d. R-134a T = −10°C, x = 0.45 v = ? s = ?

e. NH3 T = 20°C, s = 5.50 kJ/kg K u = ? x = ?

a) Table B.1.1 $T = T_{sat}(P) = 64.97°C$

$$x = (s - s_f)/s_{fg} = \frac{7.70 - 0.893}{6.9383} = 0.981$$

$h = 271.9 + 0.981 \times 2346.3 = 2573.8$ kJ/kg

b) Table B.1.2 u > ug => Sup.vap Table B.1.3, x = undefined

$T \cong 682°C$, $s \cong 7.1223$ kJ/kg K

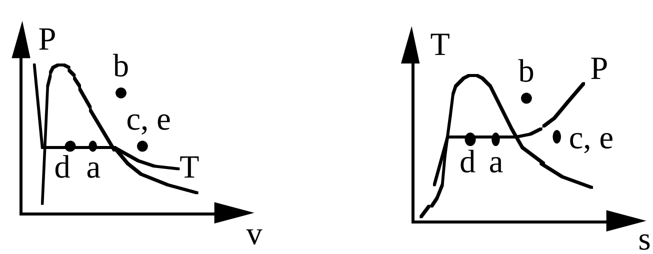
c) Table B.3.2, sup. vap., x = undefined, s = 0.7139 kJ/kg K

d) Table B.5.1 $v = v_f + xv_{fg} = 0.000755 + 0.45 \times 0.098454 = 0.04506\ m^3/kg$

$s = s_f + xs_{fg} = 0.9507 + 0.45 \times 0.7812 = 1.3022$ kJ/kg K

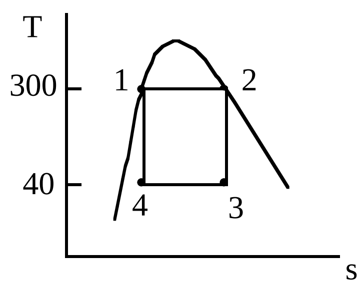
e) Table B.2.1, s > sg => Sup.vap. Table B.2.2, x = undefined

$u = h-Pv = 1492.8 - 439.18 \times 0.3100 = 1356.7$ kJ/kg



8.3 Consider a Carnot-cycle heat engine with water as the working fluid. The heat transfer to the water occurs at 300°C, during which process the water changes from saturated liquid to saturated vapor. The heat is rejected from the water at 40°C. Show the cycle on a *T–s* diagram and find the quality of the water at the beginning and end of the heat rejection process. Determine the net work output per kilogram of water and the cycle thermal efficiency.

From the definition of the Carnot cycle, two constant s and two constant T processes.



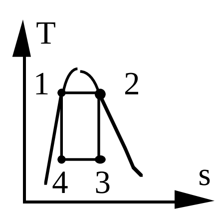
$s_3 = s_2 = 5.70438$
$= 0.57243 + x_3(7.68449)$
$x_3 = \mathbf{0.6678}$
$s_4 = s_1 = 3.25327$
$= 0.57243 + x_4(7.68449)$
$x_4 = \mathbf{0.3489}$

c) $\eta_{TH} = w_{NET}/q_H = (T_H - T_L)/T_H = 260/573.2 = \mathbf{0.4536}$

$q_H = T_H(s_2 - s_1) = 573.2(5.70438 - 3.25327) = 1405.0$ kJ/kg

$w_{NET} = \eta_{TH} \times q_H = \mathbf{637.3\ kJ/kg}$

8.4 In a Carnot engine with water as the working fluid, the high temperature is 250°C and as Q_H is received, the water changes from saturated liquid to saturated vapor. The water pressure at the low temperature is 100 kPa. Find T_L, the cycle thermal efficiency, the heat added per kilogram, and the entropy, *s*, at the beginning of the heat rejection process.



Constant T $\Rightarrow$ constant P from 1 to 2, Table B.1.1

$q_H = h_2 - h_1 = h_{fg} = \mathbf{1716.2\ kJ/kg}$

States 3 & 4 are two-phase, Table B.1.2

$\Rightarrow\ T_L = T_3 = T_4 = \text{Tsat}(P) = \mathbf{99.63°C}$

$$\eta_{cycle} = 1 - T_L/T_H = 1 - \frac{373}{273.15 + 250} = \mathbf{0.287}$$

Table B.1.1: $s_3 = s_2 = s_g(250°C) = \mathbf{6.073\ kJ/kg\ K}$

8.5 Water is used as the working fluid in a Carnot cycle heat engine, where it changes from saturated liquid to saturated vapor at 200°C as heat is added. Heat is rejected in a constant pressure process (also constant T) at 20 kPa. The heat engine powers a Carnot cycle refrigerator that operates between -15°C and +20°C. Find the heat added to the water per kg water. How much heat should be added to the water in the heat engine so the refrigerator can remove 1 kJ from the cold space?

Solution:

Carnot cycle:

$q_H = T_H (s_2 - s_1) = h_{fg} = 473.15 (4.1014) = \mathbf{1940\ kJ/kg}$

$T_L = T_{sat} (20\ kPa) = 60.06\ ^oC$

$\beta_{ref} = Q_L / W = T_L / (T_H - T_L) = (273 - 15) / (20 - (-15))$

$= 258 / 35 = 7.37$

$W = Q_L / \beta = 1 / 7.37 = 0.136$ kJ

$W = \eta_{HE}\ Q_{H\ H2O}$ $\qquad \eta_{HE} = 1 - 333/473 = 0.29$

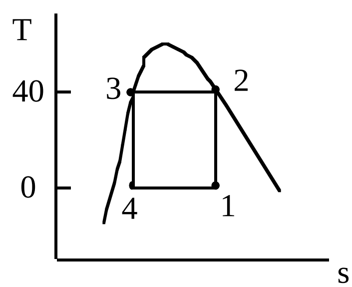
$Q_{H\ H2O} = 0.136 / 0.296 = \mathbf{0.46\ kJ}$

8.6 Consider a Carnot-cycle heat pump with R-22 as the working fluid. Heat is rejected from the R-22 at 40°C, during which process the R-22 changes from saturated vapor to saturated liquid. The heat is transferred to the R-22 at 0°C.

a. Show the cycle on a *T–s* diagram.

b. Find the quality of the R-22 at the beginning and end of the isothermal heat addition process at 0°C.

c. Determine the coefficient of performance for the cycle.

a) 

b) $s_4 = s_3 = 0.34170$ kJ/kg K

$= 0.17511 + x_4(0.7518)$

=> $x_4 = \mathbf{0.2216}$

$s_1 = s_2 = 0.87458$ kJ/kg K

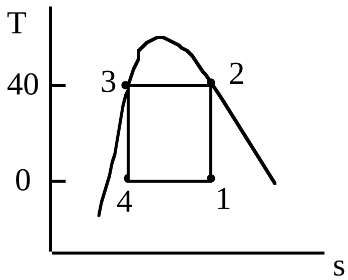
$= 0.17511 + x_1(0.7518)$

=> $x_1 = \mathbf{0.9304}$

c) $\beta' = q_H/w_{IN} = T_H/(T_H - T_L) = 313.2/40 = \mathbf{7.83}$

8.7 Do Problem 8.6 using refrigerant R-134a instead of R-22.

a)



b) $s_4 = s_3 = 1.1909$ kJ/kg K

$= 1.00 + x_4(0.7262)$

$\Rightarrow \quad x_4 = \mathbf{0.2629}$

$s_1 = s_2 = 1.7123$ kJ/kg K

$= 1.00 + x_1(0.7262)$

$\Rightarrow \quad x_1 = \mathbf{0.9809}$

c) $\beta' = q_H/w_{IN} = T_H/(T_H - T_L) = 313.2/40 = \mathbf{7.83}$

8.8 Water at 200 kPa, x = 1.0 is compressed in a piston/cylinder to 1 MPa, 250°C in a reversible process. Find the sign for the work and the sign for the heat transfer.

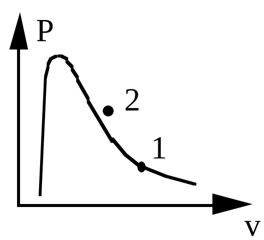
Solution:

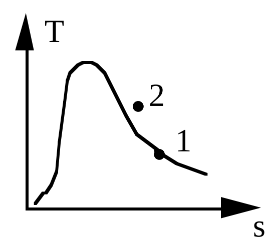
State 1: Table B.1.1: $v_1 = 0.8857$; $u_1 = 2529.5$ kJ/kg; $s_1 = 7.1271$ kJ/kg K

State 2: Table B.1.3: $v_2 = 0.23268$; $u_2 = 2709.9$ kJ/kg; $s_2 = 6.9246$ kJ/kg K

$v_2 < v_1 \quad \Rightarrow \quad {}_1w_2 = \int P\,dv \quad < 0$

$s_2 < s_1 \quad \Rightarrow \quad {}_1q_2 = \int T\,ds \quad < 0$





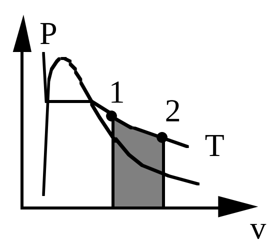
8.9 One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible isothermal process to 100 kPa. Find the work and heat transfer for this process.

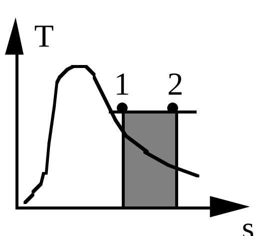
C.V.: NH_3 $\quad m_2 = m_1$; $\quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Rev.: ${}_1W_2 = \int PdV$

${}_1Q_2 = \int Tds = T(s_2 - s_1)$

State 1: $u_1 = 1391.3$; $s_1 = 5.265$





State 2: $u_2 = 1424.7$; $s_2 = 6.494$; $v_2 = 1.5658$; $h_2 = 1581.2$

${}_1Q_2 = 1(273 + 50)(6.494 - 5.265) = \mathbf{396.967\ kJ}$

${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) = \mathbf{363.75\ kJ}$

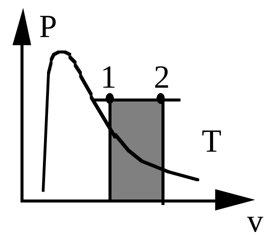
8.10 One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible isobaric process to 140°C. Find the work and heat transfer for this process.

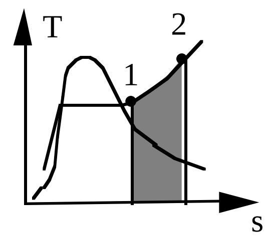
Control mass.

$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Process: P = constant

$\Rightarrow\ {}_1W_2 = mP(v_2 - v_1)$





State 1: $v_1 = 0.145\ m^3/kg$, Table B.2.2

$u_1 = h_1 - P_1v_1 = 1536.3 - 1000 \times 0.145 = 1391.3$ kJ/kg

State 2: $v_2 = 0.1955\ m^3/kg$, Table B.2.2

$u_2 = h_2 - P_2v_2 = 1762.2 - 1000 \times 0.1955 = 1566.7$ kJ/kg

${}_1W_2 = 1 \times 1000(0.1955 - 0.145) = \mathbf{50.5\ kJ}$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1 \times (1566.7 - 1391.3) + 50.5 = \mathbf{225.9\ kJ}$

8.11 One kilogram of ammonia in a piston/cylinder at 50°C, 1000 kPa is expanded in a reversible adiabatic process to 100 kPa. Find the work and heat transfer for this process.

Control mass: Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

Process: $\mathbf{{}_1Q_2 = \emptyset}$; ${}_1S_{2,gen} = \emptyset \ \Rightarrow\ s_2 = s_1 = 5.2654$ kJ/kg K

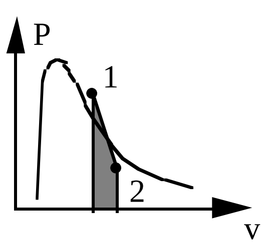
State 1: (P, T) Table B.2.2, $u_1 = h_1 - P_1v_1 = 1536.3 - 1000 \times 0.14499 = 1391.3$

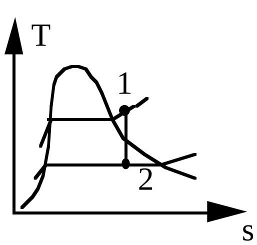
State 2: P_2 , $s_2 \ \Rightarrow$ 2 phase Table B.2.1

Interpolate: $s_{g2} = 5.8404$ kJ/kg K, $s_f = 0.1192$ kJ/kg K

$x_2 = (5.2654-0.1192)/5.7212 = 0.90$, $u_2 = 27.66 + 0.9 \times 1257.0 = 1158.9$

${}_1W_2 = 1 \times (1391.3 - 1158.9) = \mathbf{232.4\ kJ}$





8.12 A cylinder fitted with a piston contains ammonia at 50°C, 20% quality with a volume of 1 L. The ammonia expands slowly, and during this process heat is transferred to maintain a constant temperature. The process continues until all the liquid is gone. Determine the work and heat transfer for this process.

C.V. Ammonia in the cylinder.

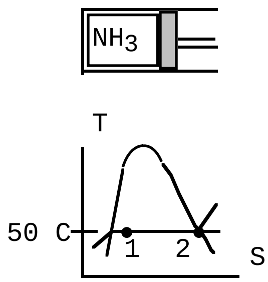


Table B.2.1: $T_1 = 50°C$, $x_1 = 0.20$, $V_1 = 1$ L

$v_1 = 0.001777 + 0.2 \times 0.06159 = 0.014095$

$s_1 = 1.5121 + 0.2 \times 3.2493 = 2.1620$

$m = V_1/v_1 = 0.001/0.014095 = 0.071$ kg

$v_2 = v_G = 0.06336$, $s_2 = s_G = 4.7613$

Process: T = constant to $x_2 = 1.0$, P = constant = 2.033 MPa

${}_1W_2 = \int PdV = Pm(v_2 - v_1) = 2033 \times 0.071 \times (0.06336 - 0.014095) = \mathbf{7.11\ kJ}$

${}_1Q_2 = \int TdS = Tm(s_2 - s_1) = 323.2 \times 0.071(4.7613 - 2.1620) = \mathbf{59.65\ kJ}$

or ${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = m(h_2 - h_1)$

$h_1 = 421.48 + 0.2 \times 1050.01 = 631.48$, $h_2 = 1471.49$

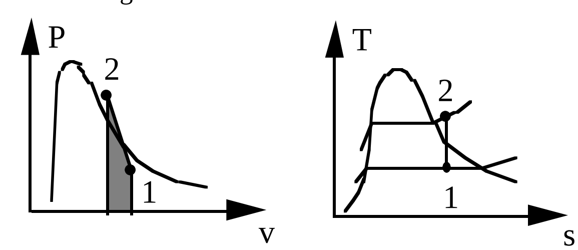
${}_1Q_2 = 0.071(1471.49 - 631.48) = \mathbf{59.65\ kJ}$

8.13 An insulated cylinder fitted with a piston contains 0.1 kg of water at 100°C, 90% quality. The piston is moved, compressing the water until it reaches a pressure of 1.2 MPa. How much work is required in the process?

C.V. Water in cylinder.

Energy Eq.: ${}_1Q_2 = 0 = m(u_2 - u_1) + {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = 0 + 0$ (assume reversible)



State 1: 100°C, $x_1 = 0.90$:

Table B.1.1,

$s_1 = 1.3068 + 0.90 \times 6.048$

$= 6.7500$ kJ/kg K

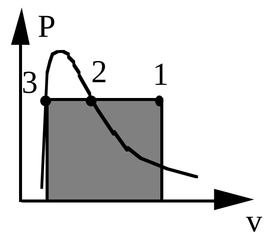
$u_1 = 418.91 + 0.9 \times 2087.58 = 2297.7$ kJ/kg

$$\left.\begin{array}{l} s_2 = s_1 = 6.7500 \\ P_2 = 1.2 \text{ MPa} \end{array}\right\} \Rightarrow \left\{\begin{array}{l} T_2 = 232.3°C \\ u_2 = 2672.9 \end{array}\right.$$

${}_1W_2 = -0.1(2672.9 - 2297.7) = \mathbf{-37.5\ kJ}$

8.14 A cylinder fitted with a frictionless piston contains water. A constant hydraulic pressure on the back face of the piston maintains a cylinder pressure of 10 MPa. Initially, the water is at 700°C, and the volume is 100 L. The water is now cooled and condensed to saturated liquid. The heat released during this process is the Q supply to a cyclic heat engine that in turn rejects heat to the ambient at 30°C. If the overall process is reversible, what is the net work output of the heat engine?

C.V.: H_2O, 1‡3, this is a control mass:

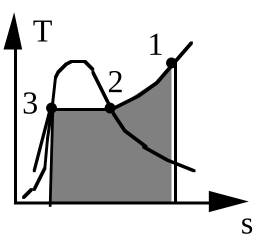


Continuity Eq.: $m_1 = m_3 = m$

Energy Eq.: $m(u_3-u_1) = {}_1Q_3 - {}_1W_3$;

Process: P = C => ${}_1W_3 = \int P\, dV = Pm(v_3-v_1)$

State 1: 700°C, 10 MPa, V_1 = 100 L Table B.1.4



$v_1 = 0.04358\ m^3/kg$ => $m = m_1 = V_1/v_1 = 2.295$ kg

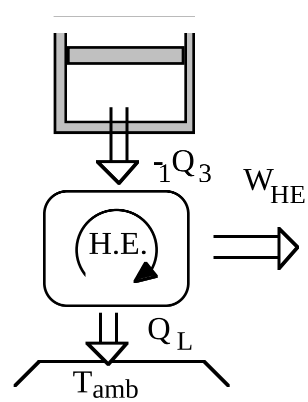
h_1 = 3870.5 kJ/kg, s_1 = 7.1687 kJ/kg K

State 3: $P_3 = P_1$ = 10 MPa, $x_3 = 0$ Table B.1.2

$h_3 = h_f$ = 1407.5 kJ/Kg, $s_3 = s_f$ = 3.3595 kJ/Kg K

${}_1Q_3 = m(u_3-u_1) + Pm(v_3 - v_1) = m(h_3 - h_1)$

$= -5652.6$ kJ



Heat transfer to the heat engine:

$Q_H = -{}_1Q_3$ = 5652.6 kJ

Take control volume as total water and heat engine.

Process: Rev., $\Delta S_{net} = 0$; $T_L = 30^oC$

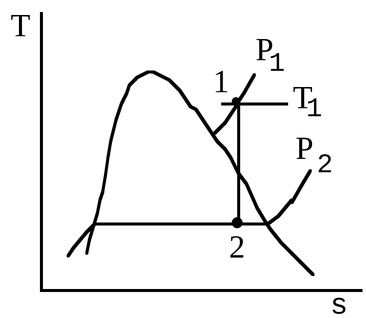
2^{nd} Law: $\Delta S_{net} = m(s_3 - s_1) - Q_{cv}/T_L$;

$Q_{cv} = T_o\, m(s_3 - s_1) = -2650.6$ kJ

=> $Q_L = -Q_{cv}$ = 2650.6 kJ

$W_{net} = W_{HE} = Q_H - Q_L$ = **3002 kJ**

8.15 One kilogram of water at 300°C expands against a piston in a cylinder until it reaches ambient pressure, 100 kPa, at which point the water has a quality of 90%. It may be assumed that the expansion is reversible and adiabatic. What was the initial pressure in the cylinder and how much work is done by the water?



C.V. Water. Process: Rev., Q = 0

$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = -\, {}_1W_2$

$m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = 0 + 0$

=> $s_2 = s_1$

$P_2 = 100$ kPa, $x_2 = 0.90$ =>

$s_2 = 1.3026 + 0.9 \times 6.0568 = 6.7537$

$u_2 = 417.36 + 0.9 \times 2088.7 = 2297.2$

a) At $T_1 = 300°C$, $s_1 = 6.7537$ $\Rightarrow$ $P_1 =$ **2.048 MPa,** $u_1 = 2771.5$ kJ/kg

b) ${}_1W_2 = m(u_1 - u_2) = 1(2771.5 - 2297.2) =$ **474.3 kJ**

8.16 A piston/cylinder has 2 kg ammonia at 50°C, 100 kPa which is compressed to 1000 kPa. The process happens so slowly that the temperature is constant. Find the heat transfer and work for the process assuming it to be reversible.

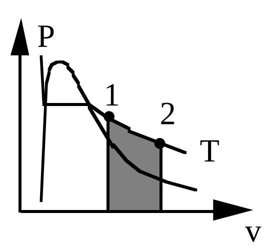
CV : NH_3 Control Mass

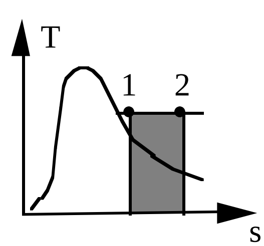
Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$; Entropy: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen}$

Process: T = constant and assume reversible process ${}_1S_{2\,gen} = 0$

1: (T,P), v = 1.5658, $u_1 = 1581.2 - 100 \times 1.5668 = 1424.62$, $s_1 = 6.4943$

2: (T,P), v = 0.1450, $u_2 = 1536.3 - 1000 \times 0.145 = 1391.3$, $s_2 = 5.2654$





${}_1Q_2 = mT(s_2 - s_1) = 2 \times 323.15\ (5.2654 - 6.4943) =$ **-794.2 kJ**

${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) = -794.24 - 2(1391.3 - 1424.62) =$ **-727.6 kJ**

8.17 A heavily insulated cylinder/piston contains ammonia at 1200 kPa, 60°C. The piston is moved, expanding the ammonia in a reversible process until the temperature is −20°C. During the process 600 kJ of work is given out by the ammonia. What was the initial volume of the cylinder?

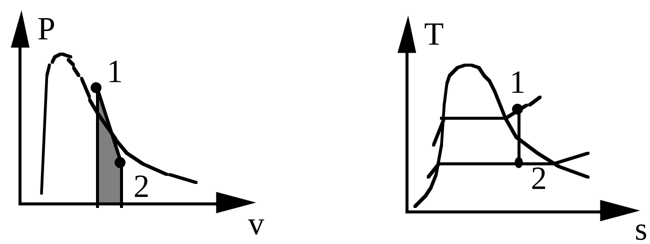
C.V. ammonia. Control mass with no heat transfer.

State 1: Table B.2.2 $v_1 = 0.1238$, $s_1 = 5.2357$ kJ/kg K

$$u_1 = h - Pv = 1553.3 - 1200\times0.1238 = 1404.9 \text{ kJ/kg}$$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen}$

Process: reversible (${}_1S_{2\,gen} = 0$) and adiabatic ($dQ = 0$) => $s_2 = s_1$



State 2: T_2, s_2 $\Rightarrow x_2 = (5.2357 - 0.3657)/5.2498 = 0.928$

$$u_2 = 88.76 + 0.928\times1210.7 = 1211.95$$

$${}_1Q_2 = 0 = m(u_2 - u_1) + {}_1W_2 = m(1211.95 - 1404.9) + 600$$

$$\Rightarrow m = 3.110 \text{ kg}$$

$V_1 = mv_1 = 3.11 \times 0.1238 =$ **$0.385\ m^3$**

8.18 A closed tank, $V = 10$ L, containing 5 kg of water initially at 25°C, is heated to 175°C by a heat pump that is receiving heat from the surroundings at 25°C. Assume that this process is reversible. Find the heat transfer to the water and the work input to the heat pump.

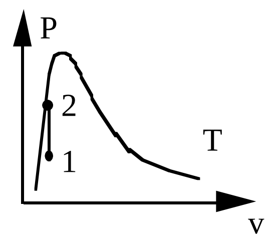
C.V.: Water from state 1 to state 2.

Process: constant volume (reversible isometric)

1: $v_1 = V/m = 0.002 \Rightarrow\ x_1 = (0.002 - 0.001003)/43.358 = 0.000023$

$u_1 = 104.86 + 0.000023\times2304.9 = 104.93$ kJ/kg

$s_1 = 0.3673 + 0.000023\times8.1905 = 0.36759$ kJ/kg K



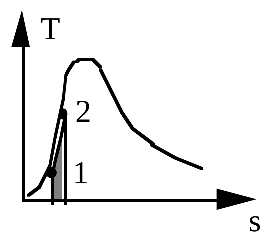
Continuity eq. (same mass) and V = C fixes v_2

2: T_2, $v_2 = v_1 \Rightarrow$

$x_2 = (0.002-0.001121)/0.21568 = 0.004075$

$u_2 = 740.16 + 0.004075\times1840.03 = 747.67$ kJ/kg

$s_2 = 2.0909 + 0.004075\times4.5347 = 2.1094$ kJ/kg K



Energy eq. has W = 0, thus provides heat transfer as

$${}_1Q_2 = m(u_2 - u_1) = \mathbf{3213.7\ kJ}$$

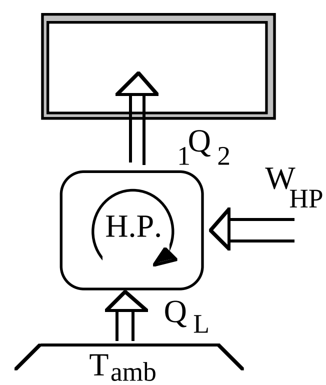
Entropy equation for the total control volume gives for a reversible process:

$$m(s_2 - s_1) = Q_L/T_0$$

$$\Rightarrow\ Q_L = mT_0(s_2 - s_1) = 2596.6\ \text{kJ}$$

and then the energy equation for the heat pump gives

$$W_{HP} = {}_1Q_2 - Q_L = \mathbf{617.1\ kJ}$$

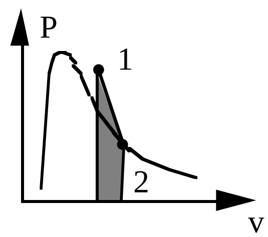


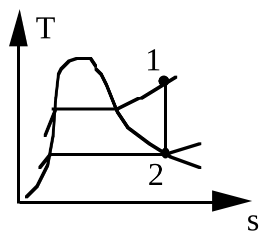
8.19 A rigid, insulated vessel contains superheated vapor steam at 3 MPa, 400°C. A valve on the vessel is opened, allowing steam to escape. The overall process is irreversible, but the steam remaining inside the vessel goes through a reversible adiabatic expansion. Determine the fraction of steam that has escaped, when the final state inside is saturated vapor.

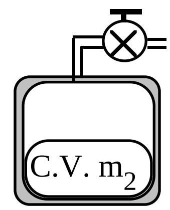
C.V.: steam remaining inside tank. Rev. & Adiabatic (inside only)

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen}$







Rev (${}_1S_{2\,gen} = 0$) Adiabatic (Q = 0) => $s_2 = s_1 = 6.9212 = s_G$ at T_2

$\Rightarrow T_2 = 141°C$, $v_2 = v_{G\ AT\ T_2} = 0.4972$

$$\frac{m_e}{m_1} = \frac{m_1 - m_2}{m_1} = 1 - \frac{m_2}{m_1} = 1 - \frac{v_1}{v_2} = 1 - \frac{0.09936}{0.4972} = \mathbf{0.80}$$

8.20 A cylinder containing R-134a at 10°C, 150 kPa, has an initial volume of 20 L. A piston compresses the R-134a in a reversible, isothermal process until it reaches the saturated vapor state. Calculate the required work and heat transfer to accomplish this process.

C.V. R-134a.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen}$

State 1: (T, P) Table B.5.2 $u_1 = 410.6 - 0.14828 \times 150 = 388.36$, $s_1 = 1.822$

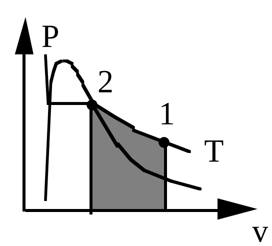
$m = V/v_1 = 0.02/0.148283 = 0.1349$ kg

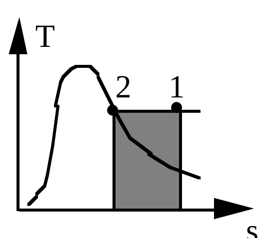
State 2: (10°C, sat. vapor)

$u_2 = 383.67$, $s_2 = 1.7218$

Process: T = constant, reversible

${}_1S_{2\,gen} = 0$ =>





$${}_1Q_2 = \int Tds = mT(s_2 - s_1) = 0.1349 \times 283.15 \times (1.7218 - 1.822) = \mathbf{-3.83\ kJ}$$

$${}_1W_2 = m(u_1 - u_2) + {}_1Q_2 = 0.1349 \times (388.36 - 383.67) - 3.83 = \mathbf{-3.197\ kJ}$$

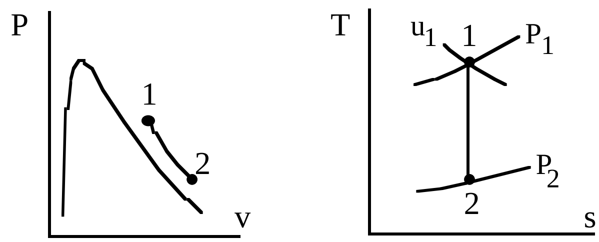
8.21 An insulated cylinder fitted with a piston contains 0.1 kg of superheated vapor steam. The steam expands to ambient pressure, 100 kPa, at which point the steam inside the cylinder is at 150°C. The steam does 50 kJ of work against the piston during the expansion. Verify that the initial pressure is 1.19 MPa and find the initial temperature.

C.V. Water in cylinder. Control mass insulated so no heat transfer Q = 0.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

Process: Q = 0 and assume reversible ${}_1S_{2\ gen} = 0$ => s = constant.



State 2: $P_2 = 100$ kPa , $T_2 = 150°C$: $u_2 = 2582.8$ kJ/kg

s = constant => $s_2 = 7.6134 = s_1$

${}_1W_2 = m(u_1 - u_2) = 50 = 0.1(u_1 - 2582.8)$ => $u_1 = 3082.8$ kJ/kg

Now state 1 given by (u, s) so look in Table B.1.3

For P = 1.0 MPa, u = 3082.8 => s = 7.6937 too high , T = 477°C

For P = 1.2 MPa, u = 3082.8 => s = 7.6048 too low , T = 476°C

By linear interpolation: P_1 = **1.18 MPa** T_1 = **476°C**

8.22 A heavily-insulated cylinder fitted with a frictionless piston contains ammonia at 6°C, 90% quality, at which point the volume is 200 L. The external force on the piston is now increased slowly, compressing the ammonia until its temperature reaches 50°C. How much work is done on the ammonia during this process?

Solution:

C.V. ammonia in cylinder, insulated so assume adiabatic $Q = 0$.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen}$

State 1: $T_1 = 6^oC$, $x_1 = 0.9$, $V_1 = 200$ L $= 0.2$ m^3

Table B.2.1 saturated vapor, $P_1 = P_g = 534$ kPa

$v_1 = v_f + x_1 v_{fg} = 0.21166$ m^3/kg,

$u_1 = u_f + x_1 u_{fg} = 207.414 + 0.9\times1115.3 = 1211.2$ kJ/kg

$s_1 = s_f + x_1 s_{fg} = 0.81166 + 0.9\times4.4425 = 4.810$ kJ/kg-K,

$m_1 = V_1/v_1 = 0.2 / 0.21166 = 0.945$ kg

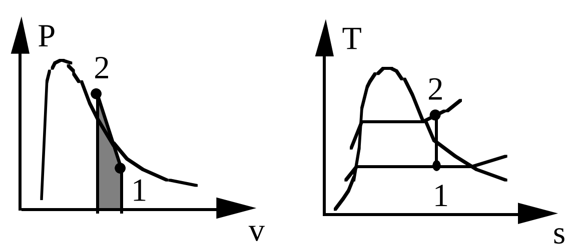
Process: 1‡2 Adiabatic ${}_1Q_2 = 0$ & Reversible ${}_1S_{2\,gen} = 0$ => $s_1 = s_2$

State 2: $T_2 = 50^oC$, $s_2 = s_1 = 4.810$ kJ/kg-K

superheated vapor, interpolate in Table B.2.2 => $P_2 = 1919$ kPa,

$v_2 = 0.0684$ m^3/kg, $h_2 = 1479.5$ kJ/kg

$u_2 = h_2 - P_2v_2 = 1479.5 - 1919\times0.0684 = 1348.2$ kJ/kg



Energy equation gives the work as

${}_1W_2 = m(u_1 - u_2) = 0.945\ (1211.2 - 1348.2) =$ **-129.4 kJ**

8.23 A piston/cylinder with constant loading of piston contains 1L water at 400 kPa, quality 15%. It has some stops mounted so the maximum possible volume is 11L. A reversible heat pump extracting heat from the ambient at 300 K, 100 kPa heats the water to 300°C. Find the total work and heat transfer for the water and the work input to the heat pump.

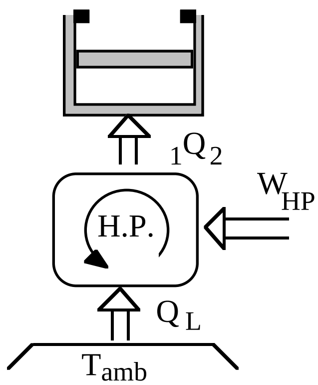
Solution: Take CV around the water and check possible P-V combinations.

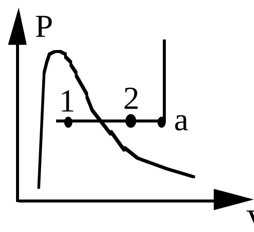
State 1: $v_1 = 0.001084 + 0.15\times 0.46138 = 0.07029$

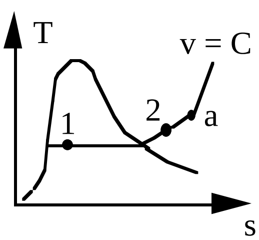
$u_1 = 604.29 + 0.15 \times 1949.26 = 896.68$ kJ/kg

$s_1 = 1.7766 + 0.15 \times 5.1193 = 2.5445$ kJ/kg K

$m_1 = V_1/v_1 = 0.001/0.07029 = 0.0142$ kg







State a: $v = 11\ v_1 = 0.77319$, 400 kPa => Sup. vap. $T_a = 400^oC > T_2$

State 2: Since $T_2 < T_a$ then piston is not at stops but floating so $P_2 = 400$ kPa.

(T,P) => $v_2 = 0.65484$ => $V_2 = (v_2/v_1) \times V_1 = 9.316$ L

$_1W_2 = \int P\,dV = P(V_2 - V_1) = 400\ (9.316 - 1) \times 0.001 =$ **3.33 kJ**

$_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.0142\ (2804.8 - 896.68) + 3.33 =$ **30.43 kJ**

Take CV as water plus the heat pump out to the ambient.

$m(s_2 - s_1) = Q_L/T_o$ =>

$Q_L = mT_o\ (s_2 - s_1) = 300\times 0.0142\ (7.5661 - 2.5445) = 21.39$ kJ

$W_{HP} = {}_1Q_2 - Q_L =$ **9.04 kJ**

8.24 A piston/cylinder contains 2 kg water at 200°C, 10 MPa. The piston is slowly moved to expand the water in an isothermal process to a pressure of 200 kPa. Any heat transfer takes place with an ambient at 200°C and the whole process may be assumed reversible. Sketch the process in a P-V diagram and calculate both the heat transfer and the total work.

Solution:

C.V. Water.

Energy: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

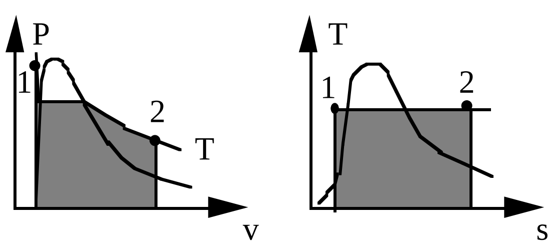
Entropy $m(s_2 - s_1) = {}_1Q_2 / T$

State 1: Table B.1.4 : $v_1 = 0.001148$, $u_1 = 844.49$, $s_1 = 2.3178$,

$V_1 = mv_1 = 0.0023\ m^3$

State 2: Table B.1.3 : $v_2 = 1.08034$, $s_2 = 7.5066$, $u_2 = 2654.4$

$V_2 = mv_2 = 2.1607\ m^3$,

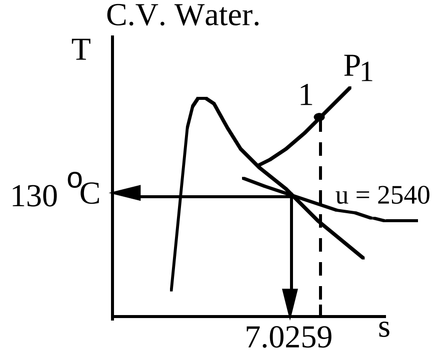


${}_1Q_2 = mT(s_2 - s_1) = 2 \times 473.15\ (7.5066 - 2.3178) =$ **4910 kJ**

${}_1W_2 = {}_1Q_2 - m(u_2 - u_1) =$ **1290.3 kJ**

8.25 An insulated cylinder/piston has an initial volume of 0.15 m^3 and contains steam at 400 kPa, 200°C. The steam is expanded adiabatically, and the work output is measured very carefully to be 30 kJ. It is claimed that the final state of the water is in the two-phase (liquid and vapor) region. What is your evaluation of the claim?

C.V. Water.



Energy Eq.:

$${}_1Q_2 = 0 = m(u_2 - u_1) + {}_1W_2$$

$$m = \frac{V_1}{v_1} = \frac{0.15}{0.5342} = 0.2808 \text{ kg}$$

$$\Rightarrow u_2 = 2646.8 - \frac{30}{0.2808} = 2540.0 \text{ kJ/kg}$$

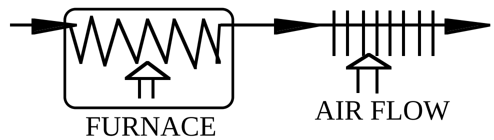
Entropy Eq.: $s_2 = s_1 = 7.1706$ kJ/kg K

State 2 given by (u, s) check Table B.1.1: s_G (at $u_G = 2540$) $= 7.0259 < s_1$

$\Rightarrow$ **State 2 must be in superheated vapor region.**

8.26 An amount of energy, say 1000 kJ, comes from a furnace at 800°C going into water vapor at 400°C, from which it goes to a solid metal at 200°C and then into some air at 70°C. For each location calculate the flux of *s* through a surface as (Q/T). What makes the flux larger and larger?

Solution:



T_1 => T_2 => T_3 => T_4

furnace vapor metal air

Flux of s: $F_s = Q/T$

$F_{s1} = 1000/1073.15 = 0.932$ kJ/K, $F_{s2} = 1000/673.15 = 1.486$ kJ/K

$F_{s3} = 1000/473.15 = 2.11$ kJ/K, $F_{s4} = 1000/343.15 = 2.91$ kJ/K

Q over ΔT is irreversible processes

8.27 An insulated cylinder/piston contains R-134a at 1 MPa, 50°C, with a volume of 100 L. The R-134a expands, moving the piston until the pressure in the cylinder has dropped to 100 kPa. It is claimed that the R-134a does 190 kJ of work against the piston during the process. Is that possible?

C.V. R-134a in cylinder. Insulated so assume Q = 0.

State 1: Table B.5.2, $v_1 = 0.02185$, $u_1 = 431.24 - 1000\times0.02185 = 409.4$,

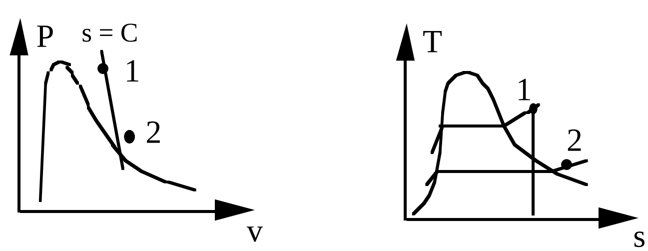
$s_1 = 1.7494$, $m = V_1/v_1 = 0.1/0.02185 = 4.577$ kg

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = \emptyset - 190 \Rightarrow u_2 = 367.89$ kJ/kg

State 2: P_2, u_2 $\Rightarrow$ Table B.5.2: $T_2 = -19.25$°C ; $s_2 = 1.7689$ kJ/kg K

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2,gen} = {}_1S_{2,gen} = 0.0893$ kJ/K

This is possible since ${}_1S_{2,gen} > \emptyset$



8.28 A piece of hot metal should be cooled rapidly (quenched) to 25°C, which requires removal of 1000 kJ from the metal. The cold space that absorbs the energy could be one of three possibilities: (1) Submerge the metal into a bath of liquid water and ice, thus melting the ice. (2) Let saturated liquid R-22 at −20°C absorb the energy so that it becomes saturated vapor. (3) Absorb the energy by vaporizing liquid nitrogen at 101.3 kPa pressure.

a. Calculate the change of entropy of the cooling media for each of the three cases.

b. Discuss the significance of the results.

a) Melting or boiling at const P & T

$_1Q_2 = m(u_2 - u_1) + Pm(v_2 - v_1) = m(h_2 - h_1)$

1) Ice melting at 0°C , Table B.1.5: $m = {_1Q_2}/h_{ig} = \frac{1000}{333.41} = 2.9993$ kg

$\Delta S_{H_2O} = 2.9993(1.221) = \mathbf{3.662\ kJ/K}$

2) R-22 boiling at -20°C, Table B.4.1: $m = {_1Q_2}/h_{fg} = \frac{1000}{220.327} = 4.539$ kg

$\Delta S_{R\text{-}22} = 4.539(0.8703) = \mathbf{3.950\ kJ/K}$

3) N_2 boiling at 101.3 kPa, Table B.6.1: $m = {_1Q_2}/h_{fg} = \frac{1000}{198.842} = 5.029$ kg

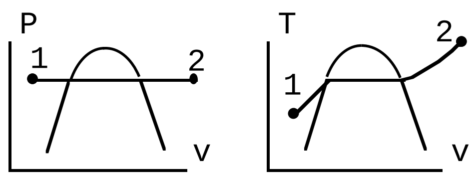
$\Delta S_{N_2} = 5.029(2.5708) = \mathbf{12.929\ kJ/K}$

b) The larger the ΔT through which the Q is transferred, the larger the ΔS.

8.29 A mass and atmosphere loaded piston/cylinder contains 2 kg of water at 5 MPa, 100°C. Heat is added from a reservoir at 700°C to the water until it reaches 700°C. Find the work, heat transfer, and total entropy production for the system and surroundings.

C.V. Water. Process: P = const. so $_1W_2 = P(V_2 - V_1)$

$U_2 - U_1 = {_1Q_2} - {_1W_2}$ or ${_1Q_2} = H_2 - H_1 = m(h_2 - h_1)$



B.1.4: $h_1 = 422.72$, $u_1 = 417.52$

$s_1 = 1.303$, $v_1 = 0.00104$

B.1.3: $h_2 = 3900.1$, $u_2 = 3457.6$

$s_2 = 7.5122$, $v_2 = 0.08849$

$_1Q_2 = 2(3900.1 - 422.72) = \mathbf{6954.76\ kJ}$

$_1W_2 = {_1Q_2} - m(u_2 - u_1) = \mathbf{874.6\ kJ}$

$m(s_2 - s_1) = \int dQ/T + {_1S_2}_{\,gen} = {_1Q_2}/T_{res} + {_1S_2}_{\,gen}$

${_1S_2}_{\,gen} = m(s_2\text{-}s_1) - {_1Q_2}/T_{res} = 2(7.5122 - 1.303) - 6954/973 = \mathbf{5.27\ kJ/K}$

8.30 A cylinder fitted with a movable piston contains water at 3 MPa, 50% quality, at which point the volume is 20 L. The water now expands to 1.2 MPa as a result of receiving 600 kJ of heat from a large source at 300°C. It is claimed that the water does 124 kJ of work during this process. Is this possible?

Solution:

C.V.: H_2O in Cylinder

State 1: 3 MPa, $x_1 = 0.5$, $V_1 = 20L = 0.02\ m^3$, Table B.1.2: $T_1 = 233.9^oC$

, $v_1 = v_f + x_1 v_{fg} = 0.001216 + 0.5\times0.06546 = 0.033948\ m^3/kg$

$u_1 = u_f + x_1 u_{fg} = 1804.5$ kJ/kg, $s_1 = s_f + x_1 s_{fg} = 4.4162$ kJ/kg-K

$m_1 = V_1/v_1 = 0.589$ kg

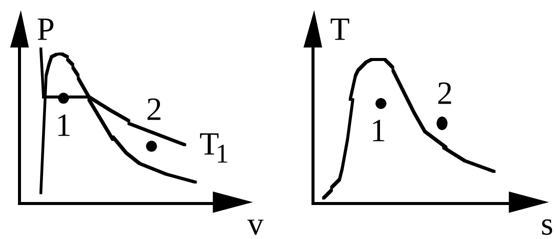
1^{st} Law: 1‡2, ${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$; ${}_1Q_2 = 600kJ$, ${}_1W_2 = 124$ kJ ?

solve for $u_2 = 1804.5 + (600 - 124)/0.589 = 2612.6$ kJ/kg

State 2:

$P_2 = 1.2$ MPa, $u_2 = 2612.6$ kJ/kg

$T_2 \cong 200^oC$, $s_2 = 6.5898$ kJ/kgK



$$2^{nd}\text{ Law: } \Delta S_{net} = m(s_2 - s_1) - \frac{Q_{cv}}{T_H}; \quad T_H = 300^oC, \quad Q_{CV} = {}_1Q_2$$

$\Delta S_{net} = 0.2335$ kJ/K $\geq$ 0; Process is possible

8.31 A 4 L jug of milk at 25°C is placed in your refrigerator where it is cooled down to the refrigerators inside constant temperature of 5°C. Assume the milk has the property of liquid water and find the entropy generated in the cooling process.

Solution:

C.V. Jug of milk. Control mass at constant pressure.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

State 1: Table B.1.1: $v_1 \cong v_f = 0.001003$, $h = h_f = 104.87$; $s = 0.3673$

State 2: Table B.1.1: $h = h_f = 20.98$, $s = s_f = 0.0761$

Process: P = constant = 101 kPa => ${}_1W_2 = mP(v_2 - v_1)$

$m = V/v_1 = 0.004 / 0.001003 = 3.988$ kg

${}_1Q_2 = m(h_2-h_1) = 3.988\ (20.98 - 104.87) = -3.988 \times 83.89 = -334.55$ kJ

$S_{gen} = 3.988\ (0.0761 - 0.3673) - (-334.55 / 278.15)$

$= -1.1613 + 1.2028 =$ **0.0415 kJ/K**

8.32 A piston/cylinder contains 1 kg water at 150 kPa, 20°C. The piston is loaded so pressure is linear in volume. Heat is added from a 600°C source until the water is at 1 MPa, 500°C. Find the heat transfer and the total change in entropy.

Solution:

CV H_2O $\quad$ 1 => 2 $\quad$ ${}_1Q_2$ & ${}_1W_2$

$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$; $\quad {}_1W_2 = \int P\, dV = \_\ (P_1 + P_2)(V_2 - V_1)$

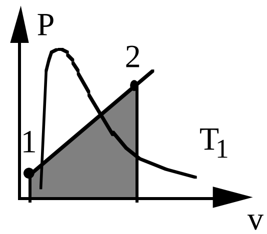
State 1: B.1.1 Compressed liq. use sat. liq. at same T: $v_1 = 0.001002$

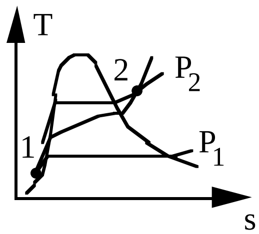
$u_1 = 83.94$; $s_1 = 0.2966$

State 2: Table B.1.3 sup. vap.

$v_2 = 0.35411$

$u_2 = 3124.3$; $s_2 = 7.7621$





${}_1W_2 = \_\ (1000 + 150)\ 1\ (0.35411 - 0.001002) = 203$ kJ

${}_1Q_2 = 1(3124.3 - 83.94) + 203 =$ **3243.4 kJ**

$m(s_2 - s_1) = 1(7.7621 - 0.2968) = 7.4655$

${}_1Q_2 / T_{source} = 3.7146$ kJ/K $\quad$ (for source $Q = -{}_1Q_2$)

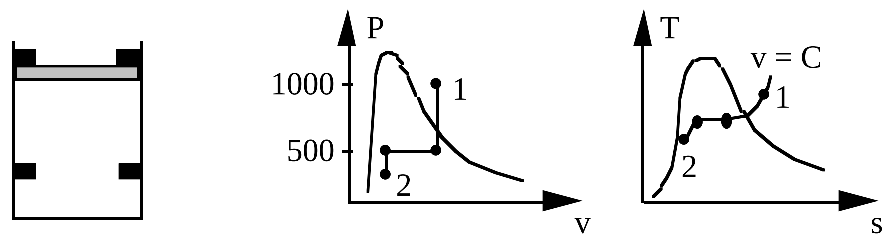
$\Delta S_{total} = \Delta S_{H2O} + \Delta S_{source} = 7.4655 - 3.7146 =$ **3.751 kJ/K**

8.33 Water in a piston/cylinder is at 1 MPa, 500°C. There are two stops, a lower one at which *V*min = 1 m^3 and an upper one at *V*max = 3 m^3. The piston is loaded with a mass and outside atmosphere such that it floats when the pressure is 500 kPa. This setup is now cooled to 100°C by rejecting heat to the surroundings at 20°C. Find the total entropy generated in the process.

C.V. Water.

Initial state: Table B.1.3: $v_1 = 0.35411$, $u_1 = 3124.3$, $s_1 = 7.7621$

$m = V/v_1 = 3/0.35411 = 8.472$ kg



Final state: 100°C and on line in P-V diagram.

Notice the following: $v_g(500 \text{ kPa}) = 0.3749 > v_1$, $v_1 = v_g(154°C)$

$T_{sat}(500 \text{ kPa}) = 152°C > T_2$, so now piston hits bottom.

State 2: $v_2 = v_{bot} = V_{bot}/m = 0.118$,

$x_2 = (0.118 - 0.001044)/1.67185 = 0.0699$,

$u_2 = 418.91 + 0.0699 \times 2087.58 = 564.98$ kJ/kg,

$s_2 = 1.3068 + 0.0699 \times 6.048 = 1.73$ kJ/kg K

${}_1W_2 = \int PdV = 500(V_2 - V_1) = -1000$ kJ $({}_1w_2 = -118)$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = -22683.4$ kJ $({}_1q_2 = -2677.5)$

Take C.V. total out to where we have 20°C:

$m(s_2 - s_1) = {}_1Q_2/T_0 + S_{gen} \Rightarrow$

$S_{gen} = m(s_2 - s_1) - {}_1Q_2/T_0 = 8.472\ (1.73 - 7.7621) + 22683 / 293.15$

= 26.27 kJ/K $(= \Delta S_{water} + \Delta S_{sur})$

8.34 Two tanks contain steam, and they are both connected to a piston/cylinder as shown in Fig. P8.34. Initially the piston is at the bottom and the mass of the piston is such that a pressure of 1.4 MPa below it will be able to lift it. Steam in A is 4 kg at 7 MPa, 700°C and B has 2 kg at 3 MPa, 350°C. The two valves are opened, and the water comes to a uniform state. Find the final temperature and the total entropy generation, assuming no heat transfer.

Control mass: All water $m_A + m_B$.

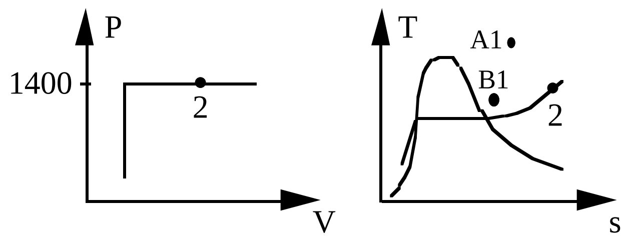
B.1.3: $v_{A1} = 0.06283$, $u_{A1} = 3448.5$, $s_{A1} = 7.3476$, $V_A = 0.2513\ m^3$

B.1.3: $v_{B1} = 0.09053$, $u_{B1} = 2843.7$, $s_{B1} = 6.7428$, $V_B = 0.1811\ m^3$

Continuity Eq.: $m_2 = m_A + m_B = 6$ kg

Energy Eq.: $m_2u_2 - m_Au_{A1} - m_Bu_{B1} = {}_1Q_2 - {}_1W_2 = -\,{}_1W_2$

Entropy Eq.: $m_2s_2 - m_As_{A1} - m_Bs_{B1} = {}_1S_{2\ gen}$



Assume $V_2 > V_A + V_B \Rightarrow P_2 = P_{lift}$, ${}_1W_2 = P_2(V_2 - V_A - V_B)$

Substitute into energy equation:

$$m_2h_2 = m_Au_{A1} + m_Bu_{B1} + P_2(V_A + V_B)$$

$$= 4 \times 3448.5 + 2 \times 2843.7 + 1400 \times 0.4324$$

State 2: $h_2 = 3347.8$ kJ/kg, $P_2 = 1400$ kPa, $v_2 = 0.2323$, $s_2 = 7.433$

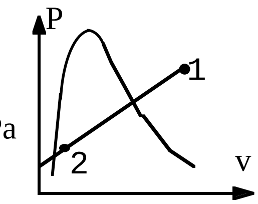
$\mathbf{T_2 = 441.9\ °C}$,

Check assumption: $V_2 = m_2v_2 = 1.394\ m^3 > V_A + V_B$ **OK.**

${}_1S_{2\ gen} = 6 \times 7.433 - 4 \times 7.3476 - 2 \times 6.7428 =$ **1.722 kJ/K**

8.35 A cylinder/piston contains 3 kg of water at 500 kPa, 600°C. The piston has a cross-sectional area of 0.1 m^2 and is restrained by a linear spring with spring constant 10 kN/m. The setup is allowed to cool down to room temperature due to heat transfer to the room at 20°C. Calculate the total (water and surroundings) change in entropy for the process.

State 1: Table B.1.3, $v_1 = 0.8041$, $u_1 = 3299.6$, $s_1 = 7.3522$



State 2: T_2 & on line in P-V diagram.

$$P = P_1 + (k_s/A^2_{cyl})(V - V_1)$$

Assume state 2 is two-phase, $P_2 = P_{sat}(T_2) = 2.339$ kPa

$v_2 = v_1 + (P_2 - P_1)A^2_{cyl}/mk_s$

$v_2 = 0.8041 + (2.339 - 500)0.01/(3 \times 10) = 0.6382 = v_f + x_2v_{fg}$

$x_2 = (0.6382 - 0.001002)/57.7887 = 0.011$, $u_2 = 109.46$, $s_2 = 0.3887$

$${}_1W_2 = \frac{1}{2}(P_1 + P_2)m \times (v_2 - v_1)$$

$$= \frac{1}{2}(500 + 2.339) \times 3 \times (0.6382 - 0.8041) = -125 \text{ kJ}$$

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 3(109.46 - 3299.6) - 125 = -9695.4$ kJ

$\Delta S_{tot} = S_{gen,tot} = m(s_2 - s_1) - {}_1Q_2/T_{room}$

$= 3(0.3887 - 7.3522) + 9695.4/293.15 =$ **12.18 kJ/K**

8.36 A cylinder/piston contains water at 200 kPa, 200°C with a volume of 20 L. The piston is moved slowly, compressing the water to a pressure of 800 kPa. The loading on the piston is such that the product *PV* is a constant. Assuming that the room temperature is 20°C, show that this process does not violate the second law.

C.V.: Water + cylinder out to room at 20°C

Process: PV = constant = Pmv $\Rightarrow$ $v_2 = P_1v_1/P_2$

$${}_1w_2 = \int Pdv = P_1v_1 \ln(v_2/v_1)$$

State 1: Table B.1.3, $v_1 = 1.0803$, $u_1 = 2654.4$, $s_1 = 7.5066$

State 2: P_2 , $v_2 = P_1v_1/P_2 = 200 \times 1.0803/800 = 0.2701$

Table B.1.3: $u_2 = 2655.0$ kJ/kg , $s_2 = 6.8822$ kJ/kg K

${}_1w_2 = 200 \times 1.0803 \ln(0.2701/1.0803) = -299.5$ kJ/kg

${}_1q_2 = u_2 - u_1 + {}_1w_2 = 2655.0 - 2654.4 - 299.5 = -298.9$

${}_1s_{s,gen} = s_2 - s_1 - {}_1q_2/T_{room} = 6.8822 - 7.5066 + 298.9/293.15$

$= 0.395$ kJ/kg K $> \emptyset$ **satisfy 2$^{\underline{nd}}$ law.**

8.37 One kilogram of ammonia (NH3) is contained in a spring-loaded piston/cylinder as saturated liquid at –20°C. Heat is added from a reservoir at 100°C until a final condition of 800 kPa, 70°C is reached. Find the work, heat transfer, and entropy generation, assuming the process is internally reversible.

C.V. = NH_3 Cont. $m_2 = m_1 = m$

Energy: $E_2 - E_1 = m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy: $S_2 - S_1 = \int dQ/T + {}_1S_{2,gen}$

Process: ${}_1W_2 = \int PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(P_1 + P_2)m(v_2 - v_1)$

State 1: Table B.2.1

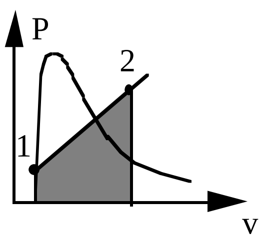
$P_1 = 190.08, \quad v_1 = 0.001504$

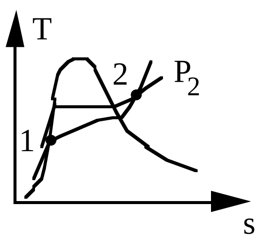
$u_1 = 88.76, \quad s_1 = 0.3657$

State 2: Table B.2.2 sup. vap.

$v_2 = 0.199, \quad s_2 = 5.5513$

$u_2 = 1597.5 - 800 \times 0.199 = 1438.3$





${}_1W_2 = \frac{1}{2}(190.08 + 800)1(0.1990 - 0.001504) =$ **97.768 kJ**

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 1(1438.3 - 88.76) + 97.768 =$ **1447.3 kJ**

$S_{gen} = m(s_2 - s_1) - {}_1Q_2/T_{res} = 1(5.5513 - 0.3657) - \frac{1447.3}{373.15} =$ **1.307 kJ/K**

8.38 A piston/cylinder has a piston loaded so pressure is linear with volume and it contains 2 kg water at 100°C, quality 10%. Heat is added from a 700°C energy reservoir so a final state of 500°C, 1 MPa is reached. Find the specific work and heat transfer for the water and the total entropy generation for the process.

Solution:

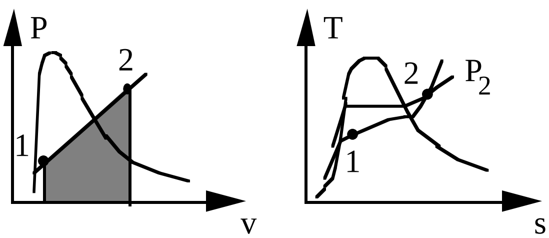
Take CV water which is a control mass.

From energy equation we get

$$q = u_2 - u_1 + w$$

Process: pressure is linearly dependent on volume. The work is the area below curve:

$w = \_ (P_1 + P_2)(v_2 - v_1)$



State 1: Table B.1.1

$v_1 = 0.001044 + 0.1 \times 1.67186$

$= 0.16823,$

$u_1 = 627.67$, $s_1 = 1.9116$

State 2: Table B.1.3

$v_2 = 0.35411$, $u_2 = 3124.3$, $s_2 = 7.7621$

For 2[nd] law take CV out to reservoir so T is the reservoir temperature

$$s_2 - s_1 = q / T_{res} + s_{gen}$$

$w = 0.5\ (101.3 + 1000)\ (0.35411 - 0.16823) =$ **102.35 kJ/kg**

$q = 3124.3 - 627.67 + 102.35 =$ **2599 kJ/kg**

$s_{gen} = 7.7621 - 1.9116 - 2599/973.15 =$ **3.18 kJ/kg K**

8.39 An insulated cylinder fitted with a frictionless piston contains saturated vapor R-12 at ambient temperature, 20°C. The initial volume is 10 L. The R-12 is now expanded to a temperature of -30°C. The insulation is then removed from the cylinder, allowing it to warm at constant pressure to ambient temperature. Calculate the net work and the net entropy change for the overall process.

C.V.: R-12

State 1: $T_1 = 20^oC$, $V_1 = 10\ L = 0.01\ m^3$, Sat. Vapor ‡ $x_1 = 1.0$

$P_1 = P_g = 567$ kPa, $v_1 = v_g = 0.03078\ m^3/kg$, $m_1 = V_1/v_1 = 0.325$ kg

$u_1 = u_g = 178.32$ kJ/kg, $s_1 = s_g = 0.68841$ kJ/kg-K

State 2: $T_2 = -30^oC$

Assume 1‡2 Adiabatic & Reversible: $s_2 = s_1 = 0.68841$ kJ/kg-K

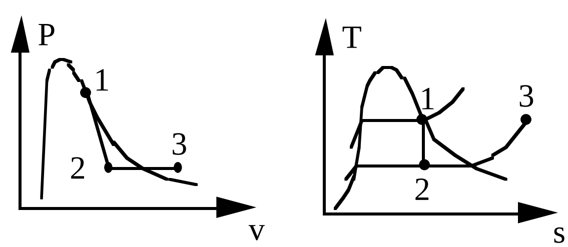
$s_2 = s_f + x_2 s_{fg}$; => $x_2 = 0.95789$, $P_2 = P_g = 100.4$ kPa

$v_2 = v_f + x_2 v_{fg} = 0.15269\ m^3/kg$, $h_2 = h_f + x_2 h_{fg} = 167.23$

$u_2 = h_2 - P_2 v_2 = 151.96$ kJ/kg

State 3: $T_3 = 20^oC$, $P_3 = P_2 = 100.41$ kPa

$v_3 = 0.19728\ m^3/kg$, $h_3 = 203.86$ kJ/kg, $s_3 = 0.82812$ kJ/kg-K



1^{st} Law: 1‡2, ${}_1Q_2 = m(u_2 - u_1) + {}_1W_2$; ${}_1Q_2 = 0$

${}_1W_2 = m(u_1 - u_2) = 8.57$ kJ

2‡3: Process: P = constant => ${}_2W_3 = \int Pm\ dv = Pm(v_3 - v_2) = 1.45$ kJ

$W_{TOT} = {}_1W_2 + {}_2W_3 = 8.57 + 1.45 =$ **10.02 kJ**

b) 2^{nd} Law: 1‡3, $\Delta S_{net} = m(s_3 - s_1) - Q_{CV}/T_o$; $T_o = 20^oC$

$Q_{CV} = {}_1Q_2 + {}_2Q_3$; ${}_1Q_2 = 0$

1^{st} Law: 2‡3 ${}_2Q_3 = m(u_3 - u_2) + {}_2W_3$; ${}_2W_3 = Pm(v_3 - v_2)$

${}_2Q_3 = m(u_3 - u_2) + Pm(v_3 - v_2) = m(h_3 - h_2) = 11.90$ kJ

$\Delta S_{net} =$ **0.0048 kJ/K**

8.40 A foundry form box with 25 kg of 200°C hot sand is dumped into a bucket with 50 L water at 15°C. Assuming no heat transfer with the surroundings and no boiling away of liquid water, calculate the net entropy change for the process.

C.V. Sand and water, constant pressure process

$$m_{sand}(u_2 - u_1)_{sand} + m_{H_2O}(u_2 - u_1)_{H_2O} = -P(V_2 - V_1)$$

$$\Rightarrow \; m_{sand}\Delta h_{sand} + m_{H_2O}\Delta h_{H_2O} = 0$$

For this problem we could also have said that the work is nearly zero as the solid sand and the liquid water will not change volume to any measurable extent. Now we get changes in u's instead of h's. For these phases $C_V = C_P = C$

$$25 \times 0.8 \times (T_2 - 200) + (50 \times 10^{-3}/0.001001) \times 4.184 \times (T_2 - 15) = 0$$

$$T_2 = 31.2°C$$

$$\Delta S = 25 \times 0.8 \ln\left(\frac{304.3}{473.15}\right) + 49.95 \times 4.184 \ln\left(\frac{304.3}{288.15}\right) = \mathbf{2.57\ kJ/K}$$

8.41 A large slab of concrete, 5 × 8 × 0.3 m, is used as a thermal storage mass in a solar-heated house. If the slab cools overnight from 23°C to 18°C in an 18°C house, what is the net entropy change associated with this process?

C.V.: Control mass concrete. $V = 5 \times 8 \times 0.3 = 12\ m^3$

$$m = \rho V = 2300 \times 12 = 27600\ kg$$

$${}_1Q_2 = mC\Delta T = 27600 \times 0.65(-5) = -89700\ kJ$$

$$\Delta S_{SYST} = mC \ln\frac{T_2}{T_1} = 27600 \times 0.65 \ln\frac{291.2}{296.2} = -305.4\ kJ/K$$

$$\Delta S_{SURR} = -{}_1Q_2/T_0 = +89700/291.2 = +308.0\ kJ/K$$

$$\Delta S_{NET} = -305.4 + 308.0 = \mathbf{+2.6\ kJ/K}$$

8.42 Find the total work the heat engine can give out as it receives energy from the rock bed as described in Problem 7.22. Hint: write the entropy balance equation for the control volume that is the combination of the rock bed and the heat engine.

To get the work I must integrate over the process or do the 2nd law for a control volume around the whole setup out to T_o

$$(S_2 - S_1)_{rock} = -Q_L/T_o = mC \ln(T_2/T_1) = 5400 \times 1.017 \ln(290/400)$$
$$= -1776.07$$

$$Q_L = -T_o(S_2 - S_1)_{rock} = -290\ (-1776.07) = 512\ 161\ kJ$$

$$W = Q - Q_L = 604098 - 512161 = \mathbf{91937\ kJ}$$

8.43 Liquid lead initially at 500°C is poured into a form so that it holds 2 kg. It then cools at constant pressure down to room temperature of 20°C as heat is transferred to the room. The melting point of lead is 327°C and the enthalpy change between the phases, h_{if} , is 24.6 kJ/kg. The specific heat is 0.138 kJ/kg K for the solid and 0.155 kJ/kg K for the liquid. Calculate the net entropy change for this process.

C.V. Lead, constant pressure process

$$m_{Pb}(u_2 - u_1)_{Pb} = {}_1Q_2 - P(V_2 - V_1)$$

$${}_1Q_2 = m_{Pb}(h_2 - h_1) = m_{Pb}(h_2 - h_{327,sol} - h_{if} + h_{327,f} - h_{500})$$

$$= 2 \times (0.138 \times (20 - 327) - 24.6 + 0.155 \times (327 - 500))$$

$$= -84.732 - 49.2 - 53.63 = -187.56 \text{ kJ}$$

$$\Delta S_{CV} = m_{Pb}\left[C_{p\ sol}\ln(T_2/600) - (h_{if}/600) + C_{P\ liq}\ln(600/T_1)\right]$$

$$= 2 \times \left[0.138 \ln \frac{293.15}{600} - \frac{24.6}{600} + 0.155 \ln \frac{600}{773.15}\right] = -0.358 \text{ kJ/K}$$

$$\Delta S_{SUR} = -{}_1Q_2/T_0 = 187.56/293.15 = 0.64 \text{ kJ/K}$$

$$\Delta S_{net} = \Delta S_{CV} + \Delta S_{SUR} = \mathbf{0.282\ kJ/K}$$

8.44 A hollow steel sphere with a 0.5-m inside diameter and a 2-mm thick wall contains water at 2 MPa, 250°C. The system (steel plus water) cools to the ambient temperature, 30°C. Calculate the net entropy change of the system and surroundings for this process.

C.V.: Steel + water. This is a control mass.

$$m_{STEEL} = (\rho V)_{STEEL} = 8050 \times (\pi/6)\left[(0.504)^3 - (0.5)^3\right] = 12.746 \text{ kg}$$

$$\Delta U_{STEEL} = (mC)_{STEEL}(T_2 - T_1) = 12.746 \times 0.48(30 - 250) = -1346 \text{ kJ}$$

$$V_{H2O} = (\pi/6)(0.5)^3, \quad m = V/v = 6.545\times10^{-2}/0.11144 = 0.587 \text{ kg}$$

$$v_2 = v_1 = 0.11144 = 0.001004 + x_2 \times 32.889 \;\Rightarrow\; x_2 = 3.358\times10^{-3}$$

$$u_2 = 125.78 + 3.358\times10^{-3} \times 2290.8 = 133.5$$

$$s_2 = 0.4639 + 3.358\times10^{-3} \times 8.0164 = 0.4638$$

$$\Delta U_{H_2O} = m_{H_2O}(u_2 - u_1)_{H_2O} = 0.587(133.5 - 2679.6) = -1494.6$$

$${}_1Q_2 = -1346 + (-1494.6) = -2840.6$$

$$\Delta S_{TOT} = \Delta S_{STEEL} + \Delta S_{H_2O} = 12.746 \times 0.48 \ln (303.15 / 523.15)$$

$$+ 0.587(0.4638 - 6.545) = \mathbf{-6.908\ kJ/K}$$

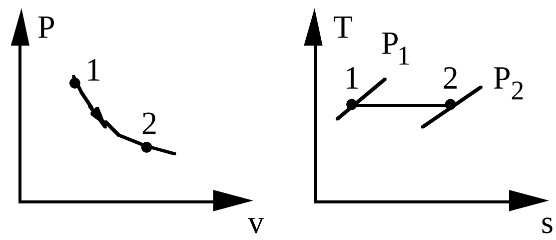
$$\Delta S_{SURR} = -{}_1Q_2/T_0 = +2840.6/303.2 = \mathbf{+9.370\ kJ/K}$$

$$\Delta S_{NET} = -6.908 + 9.370 = \mathbf{+2.462\ kJ/K}$$

8.45 A mass of 1 kg of air contained in a cylinder at 1.5 MPa, 1000 K, expands in a reversible isothermal process to a volume 10 times larger. Calculate the heat transfer during the process and the change of entropy of the air.

C.V. Air, control mass.

$m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = \emptyset$ (T = constant so ideal gas => $u_2 = u_1$)



$${}_1Q_2 = {}_1W_2 = \int PdV = P_1V_1 \ln (V_2/V_1) = mRT_1 \ln (V_2/V_1)$$

$$= 1 \times 0.287 \times 1000 \ln (10) = \mathbf{660.84\ kJ}$$

$$\Delta S_{air} = m(s_2 - s_1) = {}_1Q_2/T = 660.84/1000 = \mathbf{0.661\ kJ/K}$$

8.46 A mass of 1 kg of air contained in a cylinder at 1.5 MPa, 1000 K, expands in a reversible adiabatic process to 100 kPa. Calculate the final temperature and the work done during the process, using

a. Constant specific heat, value from Table A.5

b. The ideal gas tables, Table A.7

C.V. Air.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

Process: ${}_1Q_2 = 0$, ${}_1S_{2\ gen} = 0$ => $s_2 = s_1$

a) Use constant Cp from Table A.5, which gives the power relations.

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 1000\left(\frac{0.1}{1.5}\right)^{0.286} = \mathbf{460.9\ K}$$

$${}_1W_2 = -(U_2 - U_1) = mC_{Vo}(T_1 - T_2)$$

$$= 1 \times 0.717(1000 - 460.9) = \mathbf{386.5\ kJ}$$

b) Use the tabulated reduced pressure function that includes variable heat capacity from A.7

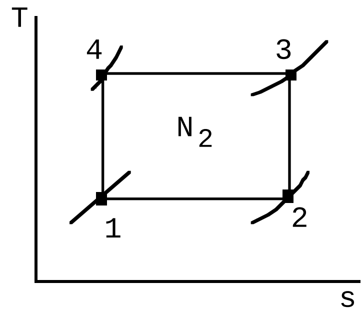
$$P_{r2} = P_{r1}\ \ P_2/P_1 = 91.65 \times \frac{0.1}{1.5} = 6.11 \quad T_2 = \mathbf{486\ K}$$

$${}_1W_2 = m(u_1 - u_2) = 1(759.2 - 349.4) = \mathbf{409.8\ kJ}$$

8.47 Consider a Carnot-cycle heat pump having 1 kg of nitrogen gas in a cylinder/piston arrangement. This heat pump operates between reservoirs at 300 K and 400 K. At the beginning of the low-temperature heat addition, the pressure is 1 MPa. During this processs the volume triples. Analyze each of the four processes in the cycle and determine

a. The pressure, volume, and temperature at each point

b. The work and heat transfer for each process



$T_1 = T_2 = \mathbf{300\ K}$, $T_3 = T_4 = \mathbf{400\ K}$,

$P_1 = \mathbf{1\ MPa}$, $V_2 = 3 \times V_1$

a) $P_2V_2 = P_1V_1 \Rightarrow P_2 = P_1/3 = \mathbf{0.3333\ MPa}$

$$V_1 = \frac{mRT_1}{P_1} = \frac{1 \times 0.2968 \times 300}{1000} = \mathbf{0.08904\ m^3}$$

$V_2 = \mathbf{0.26712\ m^3}$

$$P_3 = P_2(T_3/T_2)^{\frac{k}{k-1}} = 0.3333\left(\frac{400}{300}\right)^{3.5} = \mathbf{0.9123\ MPa}$$

$$V_3 = V_2 \times \frac{P_2}{P_3} \times \frac{T_3}{T_2} = 0.26712 \times \frac{0.3333}{0.9123} \times \frac{400}{300} = \mathbf{0.1302\ m^3}$$

$$P_4 = P_1(T_3/T_1)^{\frac{k}{k-1}} = 1\left(\frac{400}{300}\right)^{3.5} = \mathbf{2.73707\ MPa}$$

$$V_4 = V_1 \times \frac{P_1}{P_4} \times \frac{T_4}{T_1} = 0.08904 \times \frac{1}{2.737} \times \frac{400}{300} = \mathbf{0.04337\ m^3}$$

b) ${}_1W_2 = {}_1Q_2 = mRT_1 \ln(P_1/P_2)$

$= 1 \times 0.2968 \times 300 \ln(1/0.333) = \mathbf{97.82\ kJ}$

${}_3W_4 = {}_3Q_4 = mRT_3 \ln(P_3/P_4)$

$= 1 \times 0.2968 \times 400 \ln(0.9123/2.737) = \mathbf{-130.43\ kJ}$

${}_2W_3 = -mC_{V0}(T_3 - T_2) = -1 \times 0.7448(400 - 300) = \mathbf{-74.48\ kJ}$

${}_4W_1 = -mC_{V0}(T_1 - T_4) = -1 \times 0.7448(300 - 400) = \mathbf{+74.48\ kJ}$

${}_2Q_3 = \mathbf{0}$, ${}_4Q_1 = \mathbf{0}$

8.48 A rigid tank contains 2 kg of air at 200 kPa and ambient temperature, 20°C. An electric current now passes through a resistor inside the tank. After a total of 100 kJ of electrical work has crossed the boundary, the air temperature inside is 80°C. Is this possible?

Solution:

C.V.: Air in Tank; Ideal gas, $R = 0.287$ kJ/kg-K, $C_v = 0.717$ kJ/kg-K

1^{st} Law: 1‡2, $\quad {}_1Q_2 = m(u_2 - u_1) + {}_1W_2$, $\quad {}_1W_2 = -100$ kJ

State 1: $T_1 = 20^oC$, $P_1 = 200$ kPa, $\quad m_1 = 2$ kg

State 2: $T_2 = 80^oC$

Assume Constant Specific Heat

$${}_1Q_2 = mC_v(T_2 - T_1) + {}_1W_2 = -14.0 \text{ kJ}$$

2^{nd} Law: 1‡2, $\Delta S_{net} = m(s_2 - s_1) - Q_{cv}/T_o$, $\quad Q_{CV} = {}_1Q_2$

$$s_2 - s_1 = Cv \ \ln (T_2/T_1) + R\ln \frac{v_2}{v_1} \quad ; v_2 = v_1, \quad \ln \frac{v_2}{v_1} = 0$$

$$s_2 - s_1 = C_v\ln (T_2/T_1) = 0.1335 \text{ kJ/kg-K}$$

$\Delta S_{net} = 0.3156$ kJ/kg-K ≥ 0, Process is Possible

Note: $P_2 = P_1 \dfrac{T_2}{T_1}$, $\quad s_2 - s_1 = C_p \ln\dfrac{T_2}{T_1} - R \ln \dfrac{P_2}{P_1}$, Results in the same answer

8.49 A handheld pump for a bicycle has a volume of 25 cm^3 when fully extended. You now press the plunger (piston) in while holding your thumb over the exit hole so that an air pressure of 300 kPa is obtained. The outside atmosphere is at P_0, T_0. Consider two cases: (1) it is done quickly (~1 s), and (2) it is done very slowly (~1 h).

a. State assumptions about the process for each case.

b. Find the final volume and temperature for both cases.

C.V. Air in pump. Assume that both cases result in a reversible process.

Case I) Quickly means no time for heat transfer

$Q = \emptyset$, so a reversible adiabatic compression.

$$u_2 - u_1 = -{}_1w_2 \quad s_2 = s_1 = \emptyset$$

$$\Rightarrow P_{r2} = P_{r1} \times P_2/P_1 = 1.0907 \times (300/100) = 3.2721$$

$$T_2 = 407.5 \text{ K} \quad V_2 = P_1V_1T_2/T_1P_2 = 11.39 \text{ cm}^3$$

Case II) Slowly, time for heat transfer so $T = T_0$.

The process is then a reversible isothermal compression.

$$T_2 = T_0 = 298 \text{ K} \quad V_2 = V_1P_1/P_2 = 8.44 \text{ cm}^3$$

8.50 An insulated cylinder/piston contains carbon dioxide gas at 120 kPa, 400 K. The gas is compressed to 2.5 MPa in a reversible adiabatic process. Calculate the final temperature and the work per unit mass, assuming
a. Variable specific heat, Table A.8
b. Constant specific heat, value from Table A.5
c. Constant specific heat, value at an intermediate temperature from Table A.6

a) Table A.8 for CO_2

$$\bar{s}_2 - \bar{s}_1 = \bar{s}^o_{T2} - \bar{s}^o_{T1} - \bar{R}\ln(P_2/P_1)$$

$$\bar{s}^o_{T2} = 225.314 + 8.3145 \ln(2.5/0.12) = 250.561$$

$T_2 = \mathbf{697.3\ K}$

$$_1w_2 = -(u_2 - u_1) = -\left((\bar{h}_2-\bar{h}_1)-\bar{R}(T_2-T_1)\right)/M$$

$$= -[(17620 - 4003) - 8.3144(697.3 - 400)]/44.01 = \mathbf{-253.2\ kJ/kg}$$

b) $T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 400\left(\frac{2.5}{0.12}\right)^{0.224} = \mathbf{789.7\ K}$

$$_1w_2 = -C_{Vo}(T_2-T_1) = -0.6529(789.7-400) = \mathbf{-254.4\ kJ/kg}$$

c) For $T_2 \sim 700$ K, $T_{AVE} \sim 550$ K

From Eq. in Table A.6, $\bar{C}_{P_{AVE}} = 46.0244$

$$\bar{C}_{V0_{AVE}} = \bar{C}_{P0_{AVE}} - \bar{R} = 37.71, \quad k = \bar{C}_{P0}/\bar{C}_{V0} = 1.2205$$

$$T_2 = 400\left(\frac{2.5}{0.12}\right)^{0.1807} = \mathbf{692.4\ K}$$

$$_1w_2 = -\frac{37.71}{44.01}(692.4 - 400) = \mathbf{-250.5\ kJ/kg}$$

8.51 Consider a small air pistol with a cylinder volume of 1 cm^3 at 250 kPa, 27°C. The bullet acts as a piston initially held by a trigger. The bullet is released so the air expands in an adiabatic process. If the pressure should be 100 kPa as the bullet leaves the cylinder find the final volume and the work done by the air.

C.V. Air. Assume a reversible, adiabatic process.

$$P_{r2} = P_{r1}\ P_2/P_1 = 1.1165\times110/2500 = 0.4466 \quad \Rightarrow \quad T_2 = \mathbf{230.9\ K}$$

$$V_2 = V_1\ P_1\ T_2/P_2\ T_1 = 1 \times 250 \times 230.9/100 \times 300 = \mathbf{1.92\ cm^3}$$

$$_1W_2 = \frac{1}{1 - k}(P_2V_2 - P_1V_1) = \frac{1}{1 - 1.4}(100 \times 1.92 - 250 \times 1)\times10^{-6} = \mathbf{0.145\ J}$$

8.52 A rigid storage tank of 1.5 m^3 contains 1 kg argon at 30°C. Heat is then transferred to the argon from a furnace operating at 1300°C until the specific entropy of the argon has increased by 0.343 kJ/kg K. Find the total heat transfer and the entropy generated in the process.

Solution:

C.V. Argon. Control mass. R = 0.20813, m = 1 kg

Energy Eq.: $m (u_2 - u_1) = m C_v (T_2 - T_1) = {}_1Q_2$

Process: V = constant => $v_2 = v_1$

State 1: $P_1 = mRT/V = 42.063$ kPa

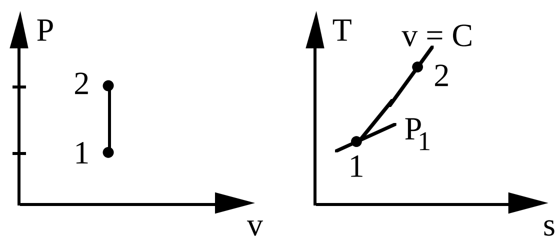
State 2: $s_2 = s_1 + 0.343$,

$$s_2 - s_1 = C_p \ln (T_2 / T_1) - R \ln (T_2 / T_1) = C_v \ln (T_2 / T_1)$$

$\ln (T_2 / T_1) = (s_2 - s_1)/ C_v = 0.343/0.312 = 1.0986$

$Pv = RT$ => $(P_2 / P_1) (v_2 / v_1) = T_2 / T_1 = P_2 / P_1$

$T_2 = 2.7 \times T_1 = 818.3$, $P_2 = 2.7 \times P_1 = 113.57$



${}_1Q_2 = 1 \times 0.3122 (818.3 - 303.15) = 160.8$ kJ

$m(s_2 - s_1) = \int {}_1Q_2/T_{res} + {}_1S_{2\ gen\ tot}$

${}_1S_{2\ gen\ tot} = 1 \times 0.31 - 160.8 / (1300 + 273) = 0.208$ kJ/K

8.53 A piston/cylinder, shown in Fig. P8.53, contains air at 1380 K, 15 MPa, with V_1 = 10 cm^3, A_{cyl} = 5 cm^2. The piston is released, and just before the piston exits the end of the cylinder the pressure inside is 200 kPa. If the cylinder is insulated, what is its length? How much work is done by the air inside?

C.V. Air, Cylinder is insulated so adiabatic, Q = 0., assume reversible.

Continuity Eq.: $m_2 = m_1 = m$,

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = 0 + 0$

State 1: Table A.7: u_1 = 1095.2 kJ/kg, P_{r1} = 340.53 , v_{r1} = 2.7024

$$m = P_1V_1/RT_1 = \frac{15000 \times 10\times10^{-6}}{0.287 \times 1380} = 0.000379 \text{ kg}$$

State 2: P_2 and from Entropy eq.: $s_2 = s_1$

$\Rightarrow$ $P_{r2} = P_{r1}P_2/P_1 = 340.53\times200/15000 = 4.5404$

T_2 = 447 K, u_2 = 320.85 kJ/kg, v_{r2} = 65.67

$\Rightarrow$ $V_2 = V_1v_{r2}/v_{r1} = 10 \times 65.67 / 2.7024 =$ **243 cm³** $\Rightarrow$ $L_2 =$ **48.6 cm**

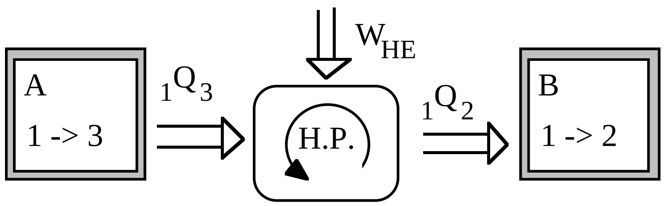
$\Rightarrow$ ${}_1w_2 = u_1 - u_2 = 774.4$ kJ/kg, ${}_1W_2 = m\ {}_1w_2 =$ **0.2935 kJ**

8.54 Two rigid tanks each contain 10 kg N_2 gas at 1000 K, 500 kPa. They are now thermally connected to a reversible heat pump, which heats one and cools the other with no heat transfer to the surroundings. When one tank is heated to 1500 K the process stops. Find the final (*P*, *T*) in both tanks and the work input to the heat pump, assuming constant heat capacities.

Control volume of hot tank B, process = constant volume & mass

$U_2 - U_1 \cong mC_v(T_2 - T_1) = {}_1Q_2 = 10 \times 0.7448 \times 500 = 3724$ kJ

$P_2 = P_1T_2/T_1 = 1.5(P_1) =$ **750 kPa**



State: 1 = initial,
2 = final hot
3 = final cold

To fix temperature in cold tank, C.V.: total

$(S_2 - S_1)_{tot} = 0 = m_{hot}(s_2 - s_1) + m_{cold}(s_3 - s_1)$

$C_{p,hot} \ln(T_2 / T_1) – R \ln(P_2 / P_1) + C_{p,cold}\ln(T_3 / T_1) – R \ln(P_3 / P_1) = \emptyset$

$P_3 = P_1T_3/T_1$ and $P_2 = P_1T_2/T_1$

Now everything is in terms of T and $C_p = C_v + R$, so

$C_{v,hot}\ln(T_2/T_1) + C_{v,cold}\ln(T_3/T_1) = 0$

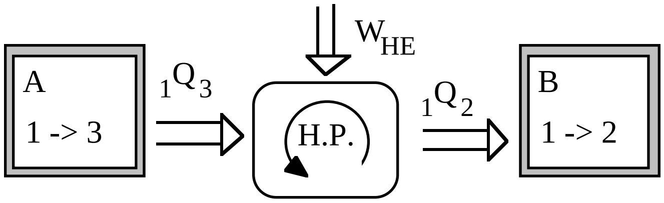
same C_v: $T_3 = T_1(T_1/T_2) =$ **667 K**, $P_3 =$ **333 kPa**

$Q_{cold} = - {}_1Q_3 = mC_v(T_3 - T_1) = -2480$,

$W_{HP} = {}_1Q_2 + Q_{cold} = {}_1Q_2 - {}_1Q_3 =$ **1244 kJ**

8.55 Repeat the previous problem, but with variable heat capacities.

C.V. Hot tank B. Constant volume and mass



State: 1 = initial,
2 = final hot
3 = final cold

$P_2 = P_1T_2/T_1 = 500 \times 1500/1000 =$ **750 kPa**

$_1Q_2 = U_2 - U_1 = m(u_2 - u_1) = 10 \times (38405 - 21463)/28.013$

$+ 10 \times 0.2968 \times (1000 - 1500) = 4563.9$ kJ

C.V. Total. Entropy Eq.: $(S_2 - S_1)_{tot} = 0 = m(s_2 - s_1)_{hot} + m(s_3 - s_1)_{cold}$

$s^o_{T_2} - s^o_{T_1} - R\ln(P_2/P_1) + s^o_{T_3} - s^o_{T_1} - R\ln(P_3/P_1) = \emptyset$

$P_3 = P_1T_3/T_1$, $\bar{s}^o_{T_1} = 228.171$, $\bar{s}^o_{T_2} = 241.881$

$\bar{s}^o_{T_3} - \bar{R}\ln(T_3/T_1) = 2\bar{s}^o_{T_1} + \bar{R}\ln(P_2/P_1) - \bar{s}^o_{T_2} = 217.83$

Trial and error on T_3 : 600 K => LHS = 216.42,

700 K => LHS = 219.83 so now $T_3 =$ **642 K**, $P_3 =$ **321 kPa**

$-{}_1Q_3 = U_3 - U_1 = m(u_3 - u_1) = m(h_3 - h_1 - RT_3 + RT_1)$

$= 10 \times [(10172 - 21463)/28.013 + 0.2968(1000 - 642)] = -2968$ kJ

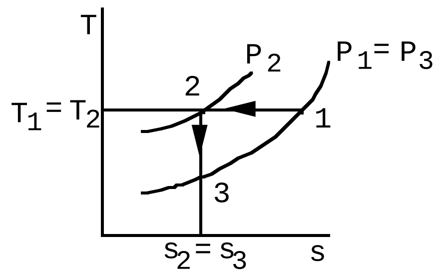
$W_{H.P.} = {}_1Q_2 - {}_1Q_3 =$ **1596 kJ**

8.56 We wish to obtain a supply of cold helium gas by applying the following technique. Helium contained in a cylinder at ambient conditions, 100 kPa, 20°C, is compressed in a reversible isothermal process to 600 kPa, after which the gas is expanded back to 100 kPa in a reversible adiabatic process.

a. Show the process on a *T–s* diagram.

b. Calculate the final temperature and the net work per kilogram of helium.

c. If a diatomic gas, such as nitrogen or oxygen, is used instead, would the final temperature be higher, lower, or the same?

a) 

c) Diatomic gas:

$k < 1.67$ (probably 1.40)

$\Rightarrow T_3 > 143.2$ K

$\Rightarrow$ **Higher**

b) $_1w_2 = -RT_1 \ln(P_2/P_1) = -2.0771 \times 293.15 \times \ln(600/100) = \mathbf{-1091.0\ kJ/kg}$

$$T_3 = T_2(P_3/P_2)^{\frac{k-1}{k}} = 293.15\ (100/600)^{0.4} = \mathbf{143.15\ K}$$

$$_2w_3 = C_{Vo}(T_2 - T_3) = 3.116\ (293.15 - 143.15) = +467.4 \text{ kJ/kg}$$

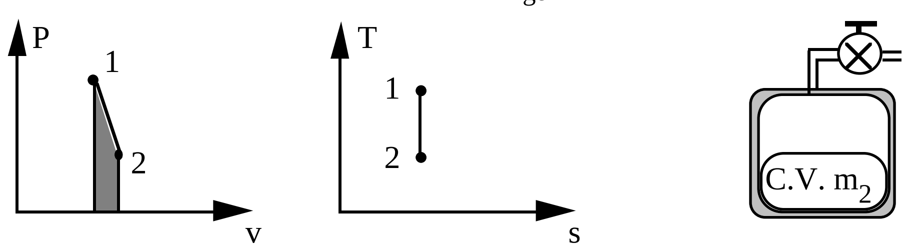
$$w_{NET} = -1091.0 + 467.4 = \mathbf{-623.6\ kJ/kg}$$

8.57 A 1-m^3 insulated, rigid tank contains air at 800 kPa, 25°C. A valve on the tank is opened, and the pressure inside quickly drops to 150 kPa, at which point the valve is closed. Assuming that the air remaining inside has undergone a reversible adiabatic expansion, calculate the mass withdrawn during the process.

C.V.: Air remaining inside tank, m_2.

Cont.Eq.: $m_2 = m$; Energy Eq.: $m(u_2 - u_1) = {_1Q_2} - {_1W_2}$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {_1S_2}_{\text{ gen}} = 0 + 0$



$$s_2 = s_1 \rightarrow T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 298.2(150/800)^{0.286} = \mathbf{184.8\ K}$$

$$m_1 = P_1V/RT_1 = (800 \times 1)/(0.287 \times 298.2) = 9.35 \text{ kg}$$

$$m_2 = P_2V/RT_2 = (150 \times 1)/(0.287 \times 184.8) = 2.83 \text{ kg}$$

$$m_e = m_1 - m_2 = \mathbf{6.52\ kg}$$

8.58 An uninsulated cylinder fitted with a piston contains air at 500 kPa, 200°C, at which point the volume is 10 L. The external force on the piston is now varied in such a manner that the air expands to 150 kPa, 25 L volume. It is claimed that in this process the air produces 70% of the work that would have resulted from a reversible, adiabatic expansion from the same initial pressure and temperature to the same final pressure. Room temperature is 20°C.

a) What is the amount of work claimed?

b) Is this claim possible?

Solution:

C.V.: Air; R = 0.287 kJ/kg-K, C_p = 1.004 kJ/kg K, C_v = 0.717 kJ/kg K

State 1: $T_1 = 200^oC$, P_1 = 500 kPa, V_1 = 10 L = 0.01 m^3;

$$m_1 = V_1/v_1 = P_1V_1/RT_1 = 0.0368 \text{ kg}$$

State 2: P_2 = 150 kPa, V_2 = 25 L = 0.025 m^3

η_s = 70%; Actual Work is 70% of Isentropic Work

a) Assume Reversible and Adiabatic Process; $s_1 = s_{2s}$

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 473.15\ (150 / 500) = 335.4 \text{ K}$$

1^{st} Law: ${}_1Q_{2s} = m(u_{2s} - u_1) + {}_1W_{2s}$; ${}_1Q_{2s} = 0$

Assume constant specific heat

${}_1W_{2\,s} = mC_v(T_1 - T_{2s}) = 3.63$ kJ

${}_1W_{2\,ac} = 0.7\times{}_1W_{2\,s}$ = **2.54 kJ**

b) Use Ideal Gas Law; $T_{2\,ac} = T_1P_2V_2 / P_1V_1 = 354.9$ K

1^{st} Law: ${}_1Q_{2\,ac} = mC_v(T_{2\,ac} - T_1) + {}_1W_{2\,ac} = -0.58$ kJ

2^{nd} Law: $\Delta S_{net} = m(s_2 - s_1) - \dfrac{Q_{CV}}{T_o}$; $Q_{CV} = {}_1Q_{2\,ac}$, $T_o = 20^oC$

$$s_2 - s_1 = Cp \ln\frac{T_2}{T_1} - R \ln\frac{P_2}{P_1} = 0.0569 \text{ kJ/kg-K}$$

ΔS_{net} = 0.00406 kJ/K $\geq$ 0 ; **Process is Possible**

8.59 A rigid container with volume 200 L is divided into two equal volumes by a partition. Both sides contain nitrogen, one side is at 2 MPa, 200°C, and the other at 200 kPa, 100°C. The partition ruptures, and the nitrogen comes to a uniform state at 70°C. Assume the temperature of the surroundings is 20°C, determine the work done and the net entropy change for the process.

C.V. : A + B no change in volume. $\mathbf{{}_1W_2 = 0}$

$m_{A1} = P_{A1}V_{A1}/RT_{A1} = (2000 \times 0.1)/(0.2968 \times 473.2) = 1.424 \text{ kg}$

$m_{B1} = P_{B1}V_{B1}/RT_{B1} = (200 \times 0.1)/(0.2968 \times 373.2) = 0.1806 \text{ kg}$

$P_2 = m_{TOT}RT_2/V_{TOT} = (1.6046 \times 0.2968 \times 343.2)/0.2 = 817 \text{ kPa}$

$$\Delta S_{SYST} = 1.424\left[1.0416 \ln\frac{343.2}{473.2} - 0.2968 \ln\frac{817}{2000}\right]$$

$$+ 0.1806\left[1.0416 \ln\frac{343.2}{373.2} - 0.2968 \ln\frac{817}{200}\right] = -0.1893 \text{ kJ/K}$$

${}_1Q_2 = \Delta\, {}_1U_2 = 1.424 \times 0.7448(70 - 200) + 0.1806 \times 0.7448(70 - 100)$

$= -141.9 \text{ kJ}$

$\Delta S_{SURR} = -\,{}_1Q_2/T_0 = 141.9/293.2 = +0.4840 \text{ kJ/K}$

$\Delta S_{NET} = -0.1893 + 0.4840 = \mathbf{+0.2947 \text{ kJ/K}}$

8.60 Nitrogen at 600 kPa, 127°C is in a 0.5 m^3 insulated tank connected to a pipe with a valve to a second insulated initially empty tank of volume 0.5 m^3. The valve is opened and the nitrogen fills both tanks. Find the final pressure and temperature and the entropy generation this process causes. Why is the process irreversible?

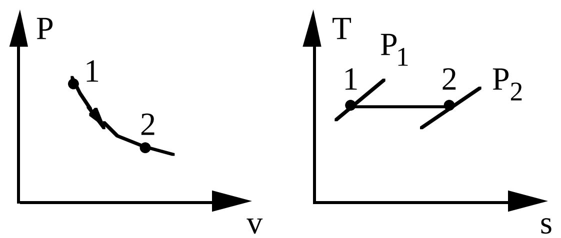
CV Both tanks + pipe + valve Insulated : Q = 0 Rigid: W = 0

$$m(u_2 - u_1) = 0 - 0 \qquad => \quad u_2 = u_1 = u_{a1}$$

$$m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = {}_1S_{2\,gen} \qquad (dQ = 0)$$

1: P_1 , T_1 , V_a => $m = PV/RT = (600 \times 0.5)/\ (0.2968 \times 400) = 2.527$

2: $V_2 = V_a + V_b$; uniform state $v_2 = V_2 / m$; $u_2 = u_{a1}$



Ideal gas u (T) => $u_2 = u_{a1}$ => $T_2 = T_{a1}$ = **400 K**

$P_2 = mR\,T_2 / V_2 = (V_1 /\ V_2)\ P_1 =$ _ $\times 600$ = **300 kPa**

$S_{gen} = m(s_2 - s_1) = m[s_{T2} - s_{T1} - R \ln(P_2 / P_1)]$

$= m\ [0 -\ R \ln (P_2 / P_1)] = -2.527 \times 0.2968 \ln$ _ = **0.52 kJ/K**

Irreversible due to unrestrained expansion in valve P ↓ but no work out.

If not a uniform final state then flow until $P_{2b} = P_{2a}$ and valve is closed.
Assume no Q between A, B

Cont.: $m_{a2} + m_{b2} = m_{a1}$;

Energy Eq.: $m_{a2}\,u_{a2} + m_{b2}\,u_{b2} = m_{a1}u_{a1}$

Entropy Eq.: $m_{a2}\,s_{a2} + m_{b2}\,s_{b2} - m_{a1}s_{a1} = 0 + S_{gen}$

Now we must assume m_{a2} went through rev adiabatic expansion

1) $V_2 = m_{a2}\,v_{a2} + m_{b2}\,v_{b2}$; 2) $P_{b2} = P_{a2}$;

3) $s_{a2} = s_{a1}$; 4) Energy equations

4 Eqs and 4 unknowns : P_2 , T_{a2} , T_{b2} , $x = m_{a2} / m_{a1}$

$V_2 / m_{a1} = x\, v_{a2} + (1 - x)\, v_{b2} = x \times (R\, T_{a2} / P_2) + (1 - x)\, (R\, T_{b2} / P_2)$

$m_{a2}\, (u_{a2} - u_{a1}) + m_{b2}\, (u_{b2} - u_{a1}) = 0$

$x\, C_v\, (T_{a2} - T_{a1}) + (1 - x)\, (T_{b2} - T_{a1})\, C_v = 0$

$x\, T_{a2} + (1 - x) T_{b2} = T_{a1}$

$P_2\, V_2 / m_{a1} R = x\, T_{a2} + (1 - x)\, T_{b2} = T_{a1})$

$P_2 = m_{a1} R\, T_{a1} / V_2 = m_{a1} R\, T_{a1} / 2V_{a1} = \_\, P_{a1}$ = **300 kPa**

$s_{a2} = s_{a1}$ => $T_{a2} = T_{a1}\, (P_2 / P_{a1})^{k-1 / k} = 400 \times (1/2)^{0.2857}$ = **328.1 K**

Now we have final state in A

$v_{a2} = R\, T_{a2} / P_2 = 0.3246$; $m_{a2} = V_a / v_{a2} = 1.54$ kg

$x = m_{a2} / m_{a1} = 0.60942$ $\quad m_{b2} = m_{a1} - m_{a2} = 0.987$ kg

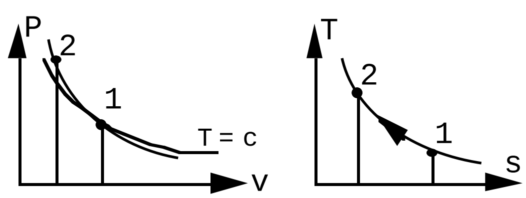
Substitute into energy equation

$T_{b2} = (T_{a1} - x\, T_{a2}) / (1 - x)$ = **512.2 K**

$S_{gen} = m_{b2}\, (s_{b2} - s_{a1}) = m_{b2}\, [C_p \ln (T_{b2} / T_{a1}) - R \ln (P_2 / P_{a1})]$

$= 0.987\, [1.0416 \ln (512.2/400) - 0.2968 \ln (1/2)]$ = **0.4572 kJ/K**

8.61 Neon at 400 kPa, 20°C is brought to 100°C in a polytropic process with *n* = 1.4. Give the sign for the heat transfer and work terms and explain.



Neon Table A.5

$k = \gamma = 1.667$ so $n < k$

$C_v = 0.618$, $R = 0.412$

From figures: v goes down so work in (W < 0);

s goes down so Q out (Q < 0)

We can also calculate the actual specific work and heat transfer terms as:

${}_1w_2 = (R/(1-n))(T_2 - T_1) = -82.39$ kJ/kg

$u_2 - u_1 = C_2(T_2 - T_1) = 49.432$, $\quad {}_1q_2 = \Delta u + {}_1w_2 = -32.958$

$_1W_2$ Negative $\Rightarrow$ $_1Q_2$ Negative

8.62 A cylinder/piston contains carbon dioxide at 1 MPa, 300°C with a volume of 200 L. The total external force acting on the piston is proportional to V^3. This system is allowed to cool to room temperature, 20°C. What is the total entropy generation for the process?

$$m = P_1V_1/RT_1 = (1000 \times 0.2)/(0.18892 \times 573.2) = 1.847 \text{ kg}$$

Process: $P = CV^3$ or PV^{-3} = constant, polytropic with $n = -3$

$$\Rightarrow P_2 = P_1(T_2/T_1)^{\frac{n}{n-1}} = 1000(293.2/573.2)^{3/4} = 604.8 \text{ kPa}$$

$$V_2 = V_1(T_1/T_2)^{\frac{1}{n-1}} = 0.16914 \text{ m}^3$$

$${}_1W_2 = \int PdV = (P_2V_2 - P_1V_1)/(1-n)$$

$$= [604.8 \times 0.16914 - 1000 \times 0.2]/[1-(-3)] = -24.4 \text{ kJ}$$

$${}_1Q_2 = 1.847 \times 0.6529(20 - 300) - 24.4 = -362.1 \text{ kJ}$$

$$\Delta S_{SYST} = 1.847\left[0.8418 \ln\frac{293.2}{573.2} - 0.18892 \ln\frac{604.8}{1000}\right]$$

$$= 1.847[-0.4694] = -0.87 \text{ kJ/K}$$

$$\Delta S_{SURR} = +362.1/293.2 = +1.235 \text{ kJ/K}$$

$$\Delta S_{NET} = -0.87 + 1.235 = \mathbf{+0.365 \text{ kJ/K}}$$

8.63 A cylinder/piston contains 1 kg methane gas at 100 kPa, 20°C. The gas is compressed reversibly to a pressure of 800 kPa. Calculate the work required if the process is

a. Adiabatic
b. Isothermal
c. Polytropic, with exponent $n = 1.15$

a) $m = 1$ kg, s = const

$$T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 293.2\left(\frac{800}{100}\right)^{0.230} = 473.0 \text{ K}$$

$${}_1w_2 = -C_{V0}(T_2-T_1) = -1.7354(473.0-293.2) = \mathbf{-312.0 \text{ kJ}}$$

b) T = const => ${}_1w_2 = {}_1q_2 = T(s_2 - s_1) = -RT\ln(P_2/P_1)$

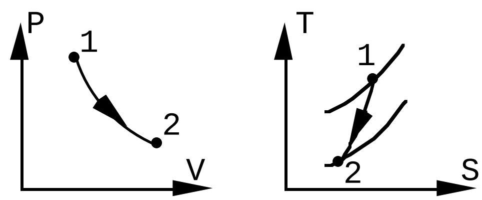
$$= -0.51835 \times 293.2 \ln(800/100) = \mathbf{-316.0 \text{ kJ}}$$

c) n = 1.15 $T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}} = 293.2\left(\frac{800}{100}\right)^{0.130} = 384.2 \text{ K}$

$${}_1w_2 = \int P\, dv = (P_2v_2 - P_1v_1)/(1-n) = R(T_2-T_1)/(1-n)$$

$$= \frac{0.51835(384.2 - 293.2)}{1 - 1.15} = \mathbf{-314.5 \text{ kJ}}$$

8.64 The power stroke in an internal combustion engine can be approximated with a polytropic expansion. Consider air in a cylinder volume of 0.2 L at 7 MPa, 1800 K. It now expands in a reversible polytropic process with exponent, $n = 1.5$, through a volume ratio of 8 : 1. Show this process on $P–v$ and $T–s$ diagrams, and calculate the work and heat transfer for the process.



$P_1 = 7$ MPa, $T_1 = 1800$ K,
$V_1 = 0.2$ L
Rev. $PV^{1.50} = \text{const}$,
$V_2/V_1 = 8$

$$m_1 = \frac{P_1V_1}{RT_1} = \frac{7000 \times 0.2 \times 10^{-3}}{0.287 \times 1800} = 2.71\times10^{-3} \text{ kg}$$

$$T_2 = T_1(V_1/V_2)^{n-1} = 1800(1/8)^{0.5} = 636.4 \text{ K}$$

$${}_1W_2 = \int PdV = mR(T_2\text{-}T_1)/(1\text{-}n)$$

$$= \frac{2.71\times10^{-3} \times 0.287(636.4 - 1800)}{1 - 1.5} = \mathbf{1.81\ kJ}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 2.71\times10^{-3} \times (463.05 - 1486.331) + 1.81 = \mathbf{-0.963\ kJ}$$

8.65 Helium in a piston/cylinder at 20°C, 100 kPa is brought to 400 K in a reversible polytropic process with exponent n = 1.25. You may assume helium is an ideal gas with constant specific heat. Find the final pressure and both the specific heat transfer and specific work.

Solution:

C.V. Helium

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 – u_1) = {}_1Q_2 – {}_1W_2$

Process $Pv^n = C$ & $Pv = RT$ => $Tv^{n-1} = C$

$T_1 = 293.15$, $T_2 = 400$ K, $C_v = 3.116$, $R = 2.0771$

$T_1v^{n-1} = T_2v^{n-1}$ => $v_2 / v_1 = (T_1 / T_2)^{1/n-1} = 0.2885$

$P_2 / P_1 = (v_1 / v_2)^n = 4.73$ => $P_2 =$ **473 kPa**

$${}_1w_2 = \int P\,dv = \int C\,v^{-n}\,dv = [\,C / (1\text{-}n)\,] \times (\,v_2^{1-n} - v_1^{1-n}\,)$$

$$= \frac{1}{1\text{-}n}(P_2\,v_2 - P_1\,v_1) = \frac{R}{1\text{-}n}(T_2 - T_1) = \mathbf{-887.7\ kJ/kg}$$

$${}_1q_2 = u_2 - u_1 + {}_1w_2 = C_v\,(T_2 - T_1) + -\,887.7 = \mathbf{-554.8\ kJ/kg}$$

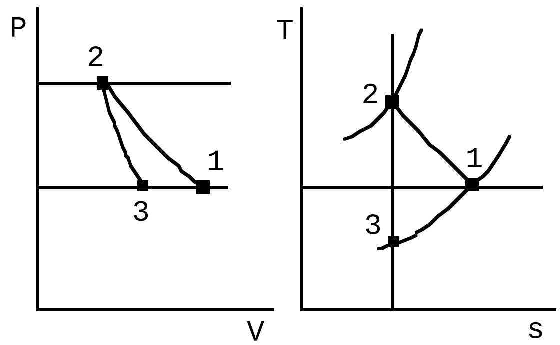
8.66 A cylinder/piston contains air at ambient conditions, 100 kPa and 20°C with a volume of 0.3 m3. The air is compressed to 800 kPa in a reversible polytropic process with exponent, *n* = 1.2, after which it is expanded back to 100 kPa in a reversible adiabatic process.

a. Show the two processes in *P–v* and *T–s* diagrams.

b. Determine the final temperature and the net work.

c. What is the potential refrigeration capacity (in kilojoules) of the air at the final state?

a)



$$m = P_1V_1/RT_1 = \frac{100 \times 0.3}{0.287 \times 293.2} = 0.3565 \text{ kg}$$

b) $T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}}$

$$= 293.2\left(\frac{800}{100}\right)^{0.167} = 414.9 \text{ K}$$

$$_1w_2 = \int_1^2 Pdv = \frac{P_2v_2\text{-}P_1v_1}{1\text{-}n} = \frac{R(T_2\text{-}T_1)}{1\text{-}n} = \frac{0.287(414.9\text{-}293.2)}{1\text{-}1.20} = -174.6 \text{ kJ/kg}$$

$$T_3 = T_2(P_3/P_2)^{\frac{k-1}{k}} = 414.9\left(\frac{100}{800}\right)^{0.286} = \mathbf{228.9\ K}$$

$_2w_3 = C_{V0}(T_2\text{-}T_3) = 0.717(414.9 - 228.9) = +133.3$ kJ/kg

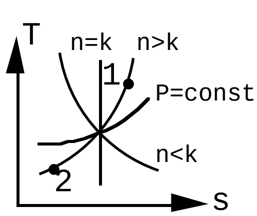
$w_{NET} = 0.3565(-174.6 + 133.3) =$ **-14.7 kJ**

c) Refrigeration: warm to T_0 at const P

$_3Q_1 = mC_{P0}(T_1 - T_3) = 0.3565 \times 1.004\ (293.2 - 228.9) =$ **23.0 kJ**

8.67 An ideal gas having a constant specific heat undergoes a reversible polytropic expansion with exponent, *n* = 1.4. If the gas is carbon dioxide will the heat transfer for this process be positive, negative, or zero?

Solution:



CO_2: k = 1.289 < n Since n > k and

$P_2 < P_1$ it follows that $s_2 < s_1$ and thus Q flows out.

$\mathbf{{}_1Q_2 < 0}$

8.68 A cylinder fitted with a piston contains 0.5 kg of R-134a at 60°C, with a quality of 50 percent. The R-134a now expands in an internally reversible polytropic process to ambient temperature, 20°C at which point the quality is 100 percent. Any heat transfer is with a constant-temperature source, which is at 60°C. Find the polytropic exponent n and show that this process satisfies the second law of thermodynamics.

Solution:

C.V.: R-134a, Internally Reversible, Polytropic Expansion: PV^n = Const.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

State 1: $T_1 = 60^oC$, $x_1 = 0.5$, Table B.5.1: $P_1 = P_g = 1681.8$ kPa,

$v_1 = v_f + x_1v_{fg} = 0.000951 + 0.5\times0.010511 = 0.006207\ m^3/kg$

$s_1 = s_f + x_1s_{fg} = 1.2857 + 0.5\times0.4182 = 1.4948$ kJ/kg K,

$u_1 = u_f + x_1u_{fg} = 286.19 + 0.5\times121.66 = 347.1$ kJ/kg

State 2: $T_2 = 20^oC$, $x_2 = 1.0$, $P_2 = P_g = 572.8$ kPa, Table B.5.1

$v_2 = v_g = 0.03606\ m^3/kg$, $s_2 = s_g = 1.7183$ kJ/kg-K

$u_2 = u_g = 389.19$ kJ/kg

Process: PV^n = Const. => $\frac{P_1}{P_2} = \left(\frac{v_2}{v_1}\right)^n$ => $n = \ln\frac{P_1}{P_2} / \ln\frac{v_2}{v_1}$ = **0.6122**

$${}_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1-n}$$

= 0.5(572.8 0.03606 - 1681.8 0.006207)/(1 - 0.6122) = 13.2 kJ

2^{nd} Law for C.V.: R-134a plus wall out to source:

$\Delta S_{net} = m(s_2 - s_1) - \frac{Q_H}{T_H}$; Check $\Delta S_{net} \geq 0$

$Q_H = {}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 34.2$ kJ

$\Delta S_{net} = 0.5(1.7183 - 1.4948) - 34.2/333.15 = 0.0092$ kJ/K,

$\Delta S_{net} > 0$ Process Satisfies 2^{nd} Law

8.69 A cylinder/piston contains 100 L of air at 110 kPa, 25°C. The air is compressed in a reversible polytropic process to a final state of 800 kPa, 200°C. Assume the heat transfer is with the ambient at 25°C and determine the polytropic exponent *n* and the final volume of the air. Find the work done by the air, the heat transfer and the total entropy generation for the process.

$$m = (P_1V_1)/(RT_1) = (110 \times 0.1)/(0.287 \times 298.15) = 0.1286 \text{ kg}$$

$$T_2/T_1 = (P_2/P_1)^{\frac{n-1}{n}} \quad \frac{473.15}{298.15} = \left(\frac{800}{110}\right)^{\frac{n-1}{n}} \Rightarrow \frac{n-1}{n} = 0.2328$$

$$\mathbf{n = 1.3034,}\ V_2 = V_1(P_1/P_2)^{\frac{1}{n}} = 0.1\left(\frac{110}{800}\right)^{0.7672} = \mathbf{0.02182\ m^3}$$

$$_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{800 \times 0.02182 - 110 \times 0.1}{1 - 1.3034} = \mathbf{-21.28\ kJ}$$

$$_1Q_2 = mC_v(T_2 - T_1) + {_1W_2}$$

$$= 0.1286 \times 0.7165 \times (200 - 25) - 21.28 = \mathbf{-5.155\ kJ}$$

$$s_2 - s_1 = C_{P0}\ln(T_2/T_1) - R\ln(P_2/P_1)$$

$$= 1.004 \ln\left(\frac{473.15}{298.15}\right) - 0.287 \ln\left(\frac{800}{110}\right) = -0.106 \frac{\text{kJ}}{\text{kg K}}$$

$$_1S_{2,gen} = m(s_2 - s_1) - {_1Q_2}/T_0$$

$$= 0.1286 \times (-0.106) + (5.155/298.15) = \mathbf{0.00366\ kJ/K}$$

8.70 A mass of 2 kg ethane gas at 500 kPa, 100°C, undergoes a reversible polytropic expansion with exponent, *n* = 1.3, to a final temperature of the ambient, 20°C. Calculate the total entropy generation for the process if the heat is exchanged with the ambient.

$$P_2 = P_1(T_2/T_1)^{\frac{n}{n-1}} = 500\left(\frac{293.2}{373.2}\right)^{4.333} = 175.8 \text{ kPa}$$

$$s_2 - s_1 = C_{P0}\ln(T_2/T_1) - R\ln(P_2/P_1)$$

$$= 1.7662 \ln(293.2/373.2) - 0.2765 \ln(175.8/500) = -0.1371 \text{ kJ/kg K}$$

$$_1w_2 = \int_1^2 PdV = \frac{P_2v_2 - P_1v_1}{1-n} = \frac{R(T_2 - T_1)}{1-n} = \frac{0.2765(293.2-373.2)}{1-1.30} = \mathbf{+73.7\ kJ/kg}$$

$$_1q_2 = C_{V0}(T_2 - T_1) + {_1w_2} = 1.4897(293.2 - 373.2) + 73.7 = -45.5 \text{ kJ/kg}$$

$$\Delta S_{SYST} = 2(-0.1371) = -0.2742 \text{ kJ/K}$$

$$\Delta S_{SURR} = -{_1Q_2}/T_0 = +2 \times 45.5/293.2 = +0.3104 \text{ kJ/K}$$

$$S_{gen} = \Delta S_{NET} = -0.2742 + 0.3104 = \mathbf{+0.0362\ kJ/K}$$

8.71 A cylinder/piston contains saturated vapor R-22 at 10°C; the volume is 10 L. The R-22 is compressed to 2 MPa, 60°C in a reversible (internally) polytropic process. If all the heat transfer during the process is with the ambient at 10°C, calculate the net entropy change.

1: $P_1 = 0.681$ MPa, $v_1 = 0.03471$, 2: $v_2 = 0.01214\ m^3/kg$

$m = V_1/v_1 = 0.01/0.03471 = 0.288$ kg

Since $Pv^n = \text{const}$, $\frac{2.0}{0.681} = \left(\frac{0.03471}{0.01214}\right)^n$ => $n = 1.0255$

$${}_1W_2 = \int PdV = m\frac{P_2v_2 - P_1v_1}{1-n} = 0.288\frac{2000 \times 0.01214 - 681 \times 0.03471}{1 - 1.0255}$$

$= -7.26$ kJ

${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 0.288(247.3 - 229.8) - 7.26 = -2.22$ kJ

$\Delta S_{SYST} = 0.288(0.8873 - 0.9129) = -0.00737$ kJ/K

$\Delta S_{SURR} = -{}_1Q_2/T_0 = +2.22/283.2 = +0.00784$ kJ/K

$S_{gen} = \Delta S_{NET} = -0.00737 + 0.00784 = \mathbf{+0.00047\ kJ/K}$

8.72 A closed, partly insulated cylinder divided by an insulated piston contains air in one side and water on the other, as shown in Fig. P8.59. There is no insulation on the end containing water. Each volume is initially 100 L, with the air at 40°C and the water at 90°C, quality 10%. Heat is slowly transferred to the water, until a final pressure of 500 kPa. Calculate the amount of heat transferred.

Let air = A, H_2O = B System: A only

$Q_A = 0$ & process slow $\Rightarrow S_{A2} = S_{A1} \rightarrow V_{A2} = V_{A1}(P_1/P_2)^{1/k}$

System: A + B $V_A + V_B = \text{const}$

$\Rightarrow V_{A1}(P_1/P_2)^{1/k} + m_B v_{BG\text{ at }P_2} = V_{TOTAL} = 0.2\ m^3$

$P_1 = P_{G\ 90°C} = 70.14$ kPa, $u_{B1} = 376.85 + 0.1 \times 2117.7 = 588.6$

$v_{B1} = 0.001036 + 0.10 \times 2.36 = 0.23704$ => $m_B = (0.1/0.23704) = 0.422$ kg

Substituting, $0.1(70.14/P_2)^{0.7143} + 0.422v_{BG\text{ at }P_2} = 0.2$

By trial and error, $P_2 =$ **453.3 kPa**, $u_{B2} = u_G = 2557.8$

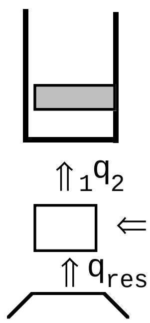
$m_A = P_1V_{A1}/R_AT_{A1} = 70.14 \times 0.1/0.287 \times 313.2 = 0.078$ kg

$$T_{A2} = T_{A1}(P_2/P_1)^{(k-1)/k} = 313.2\left(\frac{453.3}{70.14}\right)^{0.286} = 534.1\text{ K}$$

${}_1Q_2 = m_AC_{Vo}(T_{A2} - T_{A1}) + m_B(u_{B2} - u_{B1})$

$= 0.078 \times 0.7165(534.1 - 313.2) + 0.422(2557.8 - 588.6) = \mathbf{843.3\ kJ}$

8.73 A spring-loaded piston/cylinder, shown in Fig. P8.73, contains water at 100 kPa with *v* = 0.07237 m3/kg. The water is now heated to a pressure of 3 MPa by a reversible heat pump extracting *Q* from a reservoir at 300 K. It is known that the water will pass through saturated vapor at 1.5 MPa and that pressure varies linearly with volume. Find the final temperature, the heat transfer to the water and the work input to the heat pump.



C.V.: H_2O, 1→2

$m_1 = m_2 = m$, $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

$${}_1W_2 = \int_1^2 PdV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1)$$

1: 100 kPa, 0.07237 m^3/kg

 $\Rightarrow x_1 = 0.04213$ $u_1 = 505.36$ $s_1 = 1.5578$

2′: 1500 kPa, x = 1

 $\Rightarrow$ v = 0.13177 $\Rightarrow$ slope = 23569

2: $P_2 = P_1 + C(v_2 - v_1)$

 slope & $v_2 = 0.1954$

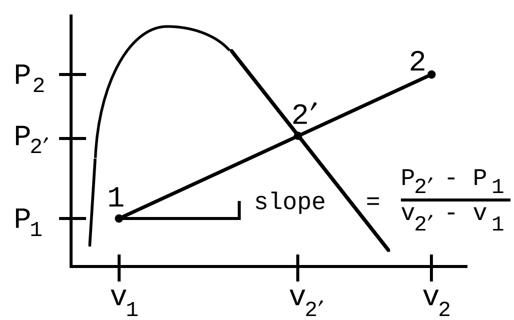
 $\Rightarrow$ **T_2 = 1000°C**, $u_2 = 4045.4$

 $s_2 = 8.4009$

$${}_1w_2 = \frac{1}{2}(P_1 + P_2)(v_2 - v_1)$$

 = 190.734 kJ/kg

${}_1q_2 = u_2 - u_1 + {}_1w_2 =$ **3730.7**



C.V.: H_2O + heat pump everything else reversible

$m_{H_2O}(u_2 - u_1) = Q_{res} - {}_1W_2 + W_{h.p.} \Rightarrow$ $w_{h.p.} = u_2 - u_1 + {}_1w_2 - q_{res}$

$w_{hp} = {}_1q_2 - q_{res} =$ **1677.8 kJ/kg**

$s_2 - s_1 = q_{res}/T_{res} \Rightarrow q_{res} = 300(8.4009 - 1.5578) = 2052.93$

8.74 A cylinder with a linear spring-loaded piston contains carbon dioxide gas at 2 MPa with a volume of 50 L. The device is of aluminum and has a mass of 4 kg. Everything (Al and gas) is initially at 200°C. By heat transfer the whole system cools to the ambient temperature of 25°C, at which point the gas pressure is 1.5 MPa. Find the total entropy generation for the process.

CO_2: $m = P_1V_1/RT_1 = 2000 \times 0.05/(0.18892 \times 473.2) = 1.1186$ kg

$V_2 = V_1(P_1/P_2)(T_2/T_1) = 0.05(2/1.5)(298.2/473.2) = 0.042\ m^3$

$${}_1W_{2\ CO_2} = \int PdV = \frac{P_1+P_2}{2}(V_2 - V_1) = \frac{2000+1500}{2}(0.042 - 0.050) = -14.0 \text{ kJ}$$

$${}_1Q_{2\ CO_2} = mC_{V0}(T_2-T_1) + {}_1W_2 = 1.1186 \times 0.6529(25-200)-14.0 = -141.81 \text{ kJ}$$

${}_1Q_{2\ Al} = mC(T_2 - T_1) = 4 \times 0.90(25 - 200) = -630$ kJ

System: CO_2 + Al

${}_1Q_2 = -141.81 - 630 = -771.81$ kJ

$\Delta S_{SYST} = m_{CO_2}(s_2 - s_1)_{CO_2} + m_{AL}(s_2 - s_1)_{AL}$

$$= 1.1186\left[0.8418 \ln\frac{298.2}{473.2} - 0.18892 \ln\frac{1.5}{2.0}\right] + 4 \times 0.9 \ln(298.2/473.2)$$

$$= -0.37407 - 1.6623 = -2.0364 \text{ kJ/K}$$

$\Delta S_{SURR} = -({}_1Q_2/T_0) = +(771.81/298.15) = +2.5887$ kJ/K

$\Delta S_{NET} = -2.0364 + 2.5887 =$ **+0.552 kJ/K**

8.75 A cylinder fitted with a piston contains air at 400 K, 1.0 MPa, at which point the volume is 100 L. The air now expands to a final state at 300 K, 200 kPa, and during the process the cylinder receives heat transfer from a heat source at 400 K. The work done by the air is 70% of what the work would have been for a reversible polytropic process between the same initial and final states. Calculate the heat transfer and the net entropy change for the process.

Solution:

C.V.: Air,

Table A.5: $R = 0.287$ kJ/kg K, $C_p = 1.004$ kJ/kg-K, $C_v = 0.717$ kJ/kg K

Actual ${}_1W_2$ is 70% of that if the process were Reversible and Polytropic.

State 1: (T, P), $V_1 = 100\text{ L} = 0.1\text{ m}^3$; $m_1 = P_1V_1/RT_1 = 0.871$ kg

State 2: $T_2 = 300\text{K}$, $P_2 = 200$ kPa

a) 1‡2 Assume Polytropic Reversible Process

$${}_1W_2 = \int P\,dV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{mR(T_2 - T_1)}{1 - n}$$

Find n: $$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)^{(n-1)/n} \quad => \quad \ln\frac{T_1}{T_2} = \frac{n-1}{n}\ln\frac{P_1}{P_2}$$

Solve for n; $n = 1.2177$

${}_1W_{2,rev} = 0.871\times0.287(300 - 400)/(1 - 1.2177) = 114.8$ kJ

${}_1W_{2,act} = 0.7\times{}_1W_{2,rev} = 80.4$ kJ

1st Law: 1‡2, ${}_1Q_2 = m(u_2 - u_1) + {}_1W_{2,act}$

Assume constant specific heat

${}_1Q_2 = mC_v(T_2 - T_1) + {}_1W_{2,act} =$ **18.0 kJ**

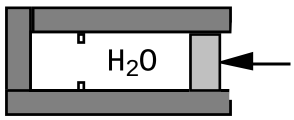
b) 2nd Law: 1‡2 $Q_H = {}_1Q_2$, $T_H = 400\text{K}$

$s_2 - s_1 = C_P \ln(T_2 / T_1) - R \ln(P_2 / P_1) = 0.1732$ kJ/kg-K

$$\Delta S_{net} = m(s_2 - s_1) - \frac{Q_H}{T_H} = 0.871\times0.1732 - 18/400 = \mathbf{0.1059\ kJ/K}$$

Advanced Problems

8.76 An insulated cylinder with a frictionless piston, shown in Fig. P8.76, contains water at ambient pressure, 100 kPa, a quality of 0.8 and the volume is 8 L. A force is now applied, slowly compressing the water until it reaches a set of stops, at which point the cylinder volume is 1 L. The insulation is then removed from the cylinder walls, and the water cools to ambient temperature, 20°C. Calculate the work and the heat transfer for the overall process.



$P_1 = 100$ kPa $x_1 = 0.80$ $V_1 = 8$ L

Slowly compress to stops, $V_2 = 1$ L

Insulation removed, cool to $T_3 = 20°C$

$u_1 = u_f + x_1 \times u_{fg} = 417.36 + 0.8 \times 2088.7 = 2088.3$ kJ/kg

Process 1→2: Rev., Q = 0

$\Rightarrow\ s_2 = s_1 = 1.3026 + 0.8 \times 6.0568 = 6.1480$

$v_1 = 0.001043 + 0.8 \times 1.6930 = 1.3554$

$v_2 = (1/8)v_1 = 0.16943$

s_2 & v_2 fix state 2, trial and error on P_2:

find x_2: $s_2 = s_f + x_2 \times s_{fg} = 6.1480$

find u_2: $u_2 = u_f + x_2 \times u_{fg}$

check v_2: $v_2 = v_f + x_2 \times (v_g - v_f) = 0.16943$

For 1.0 MPa, s = 6.1480: $u_2 = 2404.1$, $v_2 = 0.17538$

For 1.1 MPa, s = 6.1480: $u_2 = 2419.0$, $v_2 = 0.16117$

Interpolate to match v = 0.16943 => $P_2 = 1.04$ MPa, $u_2 = 2410.2$ kJ/kg

State 3: $T_3 = 20°C$, $v_3 = v_2 = 0.16943$

$v_3 = 0.001002 + x_3 \times 57.789 \Rightarrow x_3 = 0.0029145$

$u_3 = 83.95 + 0.0029145 \times 2319.0 = 90.71$

$m = V_1/v_1 = 0.008/1.3554 = 0.0059$ kg

${}_1W_3 = {}_1W_2 + {}_2W_3 = m(u_1 - u_2) = 0.0059(2088.3 - 2410.2)$

$=$ **-1.90 kJ** $({}_2W_3 = 0)$

${}_1Q_3 = {}_1Q_2 + {}_2Q_3 = m(u_3 - u_2) = 0.0059(90.71 - 2410.2)$

$=$ **-13.68 kJ** $({}_1Q_2 = 0)$

8.77 Consider the process shown in Fig. P8.77. The insulated tank A has a volume of 600 L, and contains steam at 1.4 MPa, 300°C. The uninsulated tank B has a volume of 300 L and contains steam at 200 kPa, 200°C. A valve connecting the two tanks is opened, and steam flows from A to B until the temperature in A reaches 250°C. The valve is closed. During the process heat is transferred from B to the surroundings at 25°C, such that the temperature in B remains at 200°C. It may be assumed that the steam remaining in A has undergone a reversible adiabatic expansion. Determine the final pressure in tank A, the final pressure and mass in tank B, and the net entropy change, system plus surroundings, for the process.

a) $m_{A1} = 0.6/0.18228 = 3.292$; $m_{B1} = 0.3/1.0803 = 0.278$ kg

$s_{A2} = s_{A1} = 6.9534$, $T_{A2} = 250°C$ => $P_{A2} =$ **949.5 kPa**

b) $m_{A2} = 0.6/0.2479 = 2.42$ kg

$m_{Ae} = m_{Bi} = 3.292 - 2.42 = 0.872$ kg => $m_{B2} = 0.278 + 0.872 =$ **1.15 kg**

$v_{B2} = 0.3/1.15 = 0.2609$, $T_{B2} = 200°C$ => $P_{B2} =$ **799.8 kPa**

c) $_1Q_2 = (m_{A2}u_{A2} + m_{B2}u_{B2}) - (m_{A1}u_{A1} + m_{B1}u_{B1})$

$= (2.42 \times 2711.3 + 1.15 \times 2630.6)$

$- (3.292 \times 2785.2 + 0.278 \times 2654.4) = -320.3$ kJ

$\Delta S_{SYST} = (m_{A2}s_{A2} + m_{B2}s_{B2}) - (m_{A1}s_{A1} + m_{B1}s_{B1})$

$= (2.42 \times 6.9534 + 1.15 \times 6.8159)$

$- (3.292 \times 6.9534 + 0.278 \times 7.5066) = -0.3119$ kJ/K

$\Delta S_{SURR} = -\,_1Q_2/T_0 = +320.3/298.2 = +1.0743$ kJ/K

$\Delta S_{NET} = -0.3119 + 1.0743 =$ **+0.7624 kJ/K**

8.78 A vertical cylinder/piston contains R–22 at –20°C, 70% quality, and the volume is 50 L, shown in Fig. P8.78. This cylinder is brought into a 20°C room, and an electric current of 10 A is passed through a resistor inside the cylinder. The voltage drop across the resistor is 12 V. It is claimed that after 30 min the temperature inside the cylinder is 40°C. Is this possible?

$P_1 = P_2 = 0.245$ MPa, $m = V_1/v_1 = 0.05/0.06521 = 0.767$ kg

$W_{ELEC} = -Ei\Delta t = -12 \times 10 \times 30 \times 60/1000 = -216$ kJ

$_1Q_2 = m(u_2 - u_1) + W_{BDRY} + W_{ELEC} = m(h_2 - h_1) + W_{ELEC}$

$= 0.767(282.2 - 176.0) - 216 = -134.5$ kJ

$\Delta S_{SYST} = 0.767(1.1014 - 0.6982) = 0.3093$ kJ/K

$\Delta S_{SURR} = -\,_1Q_2/T_0 = +134.5/293.15 = 0.4587$ kJ/K

$\Delta S_{NET} = +0.3093 + 0.4587 = +0.768$ kJ/K **Claim is OK.**

8.79 Redo Problem 8.57, but calculate the mass withdrawn by a first-law, control-volume analysis. Compare the result to that obtained in Problem 8.57. Show from a differential step of mass out that the first law leads to the same result. (Find the relation between dP and dT)

i) CV: Tank : $0 = m_2u_2 - m_1u_1 + (m_1 - m_2)h_{e\ AVG}$

or $0 = m_2C_{Vo}T_2 - m_1C_{Vo}T_1 + (m_1 - m_2)\,C_{Po}(T_1+T_2)/2$

Also, $m_2T_2 = P_2V/R = (150 \times 1)/0.287$

$$\Rightarrow 0 = 150/0.287 - 9.35 \times 298.2 + \left(9.35 - \frac{150}{0.287\,T_2}\right) \times 1.4 \times (298.2 + T_2)/2$$

$T_2 = 191.1$ K, $m_2 = 2.74$ kg, $m_e = m_1 - m_2 = 6.61$ kg

Approximate answer because of $h_{e\ AVE}$ value used. Answer will be closer to 8.57 if process is solved in steps.

ii) solve as in i), except in 2 steps

Let $P_1 = 800$ kPa, $P_2 = 400$ kPa, $P_3 = 150$ kPa.

Solving from 1-2: $T_2 = 245.2$ K & $m_2 = 5.684$

Now using 2 as the initial state and 3 as the final

state, solve the first law for state 3: $T_3 = 186.5$ K & $m_3 = 2.802$ kg.

Note that final T and m are closer to those in 8.57. To generalize this solution, substitute the equation of state for m_1 & m_2 into the 1st law of i). Then, dividing by P_1, get

$$0 = \frac{P_2}{P_1} - 1 + \left(\frac{T_2 - (P_2/P_1)T_1}{T_1T_2}\right)\frac{k}{2}\left(T_1 + T_2\right)$$

Let $\Delta P = P_2 - P_1$ & $P = P_1$ & $\Delta T = T_2 - T_1$ & $T = T_1$

The above equation becomes

$$\left(\frac{k-1}{k}\right)\frac{\Delta P}{P} = \frac{\Delta T}{T}$$

In the limit, Δ's $\rightarrow$ d's and integrate, get same answer as in i).

8.80 A vertical cylinder is fitted with a frictionless piston that is initially resting on stops. The cylinder contains carbon dioxide gas at 200 kPa, 300 K, and at this point the volume is 50 L. A cylinder pressure of 400 kPa is required to make the piston rise from the stops. Heat is now transferred to the gas from an aluminum cubic block, 0.1 m on each side. The block is initially at 700 K.
a) What is the temperature of the aluminum block when the piston first begins to rise?
b) The process continues until the gas and block reach a common final temperature. What is this temperature?
c) Calculate the net entropy change for the overall process.

Solution:

C.V. Aluminum and carbon dioxide. No external heat transfer.

Energy Eq.: $m(u_2 - u_1)_{AL} + m(u_2 - u_1)_{CO2} = {}_1Q_2 - {}_1W_2 = - {}_1W_2$

Process: V = constant => ${}_1W_2 = 0$

Properties Table A.3 and A.5 CO_2 ideal gas

CO_2: R = 0.1889 kJ/kg K, C_p = 0.842 kJ/kg K, C_v = 0.653 kJ/kg K

Al: ρ = 2700 kg/m3, C = 0.9 kJ/kg K, $V_{Al} = 0.001\ m^3$, $m_{Al} = \rho V = 2.7$ kg

State 1: CO_2, $V_1 = 50\ L = 0.05\ m^3$, $m_1 = P_1V_1/(RT_1) = 0.1764$ kg

State 2: CO_2, $P_2 = P_{EXT} = 400$ kPa, $V_2 = V_1 = 0.05 m^3$

$T_2 = T_1\ P_2/P_1 = 600$ K

a) Assume Constant Specific Heat

$m_{CO2}C_v(T_2 - T_1) + m_{AL}C(T_2 - T_1) = 0 = 34.55 + 2.7 \times 0.9(T_2 - 700)$

Solve for T_2 of the Aluminum: $T_{2,AL}$ = **685.8 K**

b) C.V.: Aluminum & CO_2, where ${}_2Q_3 = 0$

1st Law: ${}_2Q_3 = m_{AL}(u_3 - u_2)_{AL} + m_{CO2}(u_3 - u_2)_{CO2} + {}_2W_3$;

Process: $P_3 = P_2$; ${}_2W_3 = \int P\, dV = P(V_3 - V_2)$

$0 = m_{AL}(u_3 - u_2)_{AL} + m_{CO2}(h_3 - h_2)$

Assume Constant Specific heat

$m_{AL}C(T_2 - T_3)_{AL} = m_{CO2}C_p(T_3 - T_2)_{CO2}$ => $T_{3,AL} = T_{3,CO2}$ = **680.9 K**

c) C.V.: Aluminum & CO_2, no external heat transfer

2nd Law: 1‡3, $\Delta S_{net} = m_{AL}(s_3 - s_1) + m_{CO2}(s_3 - s_1) - 0/T_o$

$(s_3 - s_1)_{AL} = C \ln(T_3/T_1) = -0.0249$ kJ/kg K

$(s_3 - s_1)_{CO2} = C_p \ln T_3/T_1 - R \ln P_3/P_1 = 0.55902$ kJ/kg K

ΔS_{net} = **0.0314 kJ/K**

8.81 A piston/cylinder contains 2 kg water at 5 MPa, 800°C. The piston is loaded so pressure is proportional to volume, P = CV. It is now cooled by an external reservoir at 0°C to a final state of saturated vapor. Find the final pressure, work, heat transfer and the entropy generation for the process.

C.V. Water. Control mass with external irreversibility due to heat transfer.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen} = {}_1Q_2/T_o + {}_1S_{2\ gen}$ (if CV to T_o)

State 1: Table B.1.3: $s_1 = 7.744$, $v_1 = 0.09811$, $u_1 = 3646.6$

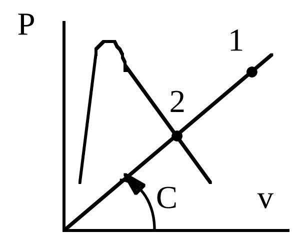
Process: P linear in volume. $P = Cv$

$C = P_1 / v_1 = 5000 / 0.09811 = 50963.2$

$P_2/ v_2 = C = P_{sat} / v_g$ so check Table B.1.1

For 235°C => $(P/ v)_{sat} = 46819$ low

For 240°C => $(P/ v)_{sat} = 55960.5$ high



Linear interpolation gives $T_2 = 237.27$°C

$s_2 = 6.1539$, $P_2 =$ **3189 kPa**, $u_2 = 2604$, $v_2 = 0.06258$

${}_1w_2 = 0.5(P_1 + P_2)(v_2 - v_1) = \_ \times 8189\ (0.06258 - 0.09811) = -145.48$ kJ/kg

${}_1q_2 = u_2 - u_1 + {}_1w_2 = 2604 - 3646.6 - 145.48 = -1188$ kJ/kg

$s_{gen} = s_2 - s_1 - {}_1q_2 / T_o = 6.1539 - 7.744 + 1188/273.15 = 2.759$

${}_1W_2 = m\ {}_1w_2 =$ **-291 kJ,** ${}_1Q_2 = m\ {}_1q_2 =$ **-2376 kJ**

${}_1S_2 = m\ s_{gen} =$ **5.52 kJ/K**

8.82 A gas in a rigid vessel is at ambient temperature and at a pressure, P_1, slightly higher than ambient pressure, P_0. A valve on the vessel is opened, so gas escapes and the pressure drops quickly to ambient pressure. The valve is closed and after a long time the remaining gas returns to ambient temperature at which point the pressure is P_2. Develop an expression that allows a determination of the ratio of specific heats, *k*, in terms of the pressures.

C.V.: air remaining in tank,

First part of the process is an isentropic expansion s = constant.

$$P_1, T_0 \rightarrow P_0, T_x \qquad T_x/T_0 = (P_0/P_1)^{\frac{k-1}{k}}$$

Second part of the process is a const. vol. heat transfer. $P_0, T_x \rightarrow P_2, T_0$

$$\frac{P_0}{P_2} = \frac{T_x}{T_0} \;\Rightarrow\; \frac{P_0}{P_2} = \left(\frac{P_0}{P_1}\right)^{\frac{k-1}{k}} \;\rightarrow\; \mathbf{k = \frac{\ln (P_1/P_0)}{\ln (P_1/P_2)}}$$

English Unit Problems

8.83E Consider the steam power plant in Problem 7.57 and show that this cycle satisfies the inequality of Clausius.

Solution:

$$\int dQ/T \le 0$$

$$Q_H / T_H - Q_L / T_L = 1000/(1200 + 460) - 580/(100 + 460)$$
$$= 0.6024 - 1.0357 = -0.433 \text{ Btu/s R} < 0$$

8.84E Find the missing properties and give the phase of the substance

a. H_2O $s = 1.75$ Btu/lbm R, $P = 4$ lbf/in.^{2} $h = ?$ $T = ?$ $x = ?$

b. H_2O $u = 1350$ Btu/lbm, $P = 1500$ lbf/in.^{2} $T = ?$ $x = ?$ $s = ?$

c. R-22 $T = 30$ F, $P = 60$ lbf/in.^{2} $s = ?$ $x = ?$

d. R-134a $T = 10$ F, $x = 0.45$ $v = ?$ $s = ?$

e. NH_3 $T = 60$ F, $s = 1.35$ Btu/lbm R $u = ?$ $x = ?$

a) Table C.8.1: $s < s_g$ so 2 phase $T = T_{sat}(P) = 152.93$ F

$x = (s - s_f)/s_{fg} = (1.75 - 0.2198)/1.6426 = 0.9316$

$h = 120.9 + 0.9316 \times 1006.4 = 1058.5$ Btu/lbm

b) Table C.8.2, x = undefined, T = 1020 F, s = 1.6083 Btu/lbm R

c) Table C.10.1, x = undefined, $s_g(P) = 0.2234$ Btu/lbm R, $T_{sat} = 22.03$ F

$$s = 0.2234 + (30 - 22.03)\ (0.2295 - 0.2234) / (40 - 22.03)$$
$$= 0.2261 \text{ Btu/lbm R}$$

d) Table C.11.1 $v = v_f + xv_{fg} = 0.01202 + 0.45 \times 1.7162 = 0.7843$ ft^3/lbm,

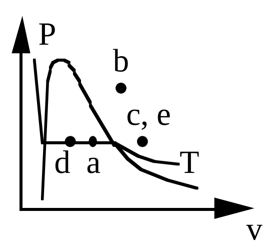
$s = s_f + xs_{fg} = 0.2244 + 0.45 \times 0.1896 = 0.3097$ Btu/lbm R

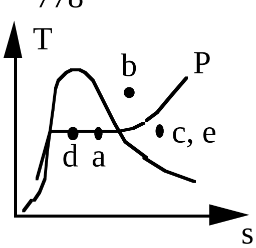
e) Table C.9.1: $s > s_g$ so superheated vapor Table C.9.2: x = undefined

$P = 40 + (50-40) \times (1.35-1.3665)/(1.3372-1.3665) = 45.6$ psia

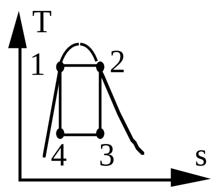
Interpolate to get $v = 6.995$ft^3/lbm, $h = 641.0$ Btu/lbm

$$u = h - Pv = 641.0 - 45.6 \times 6.995 \times \frac{144}{778} = 581.96 \text{ Btu/lbm}$$





8.85E In a Carnot engine with water as the working fluid, the high temperature is 450 F and as Q_L is received, the water changes from saturated liquid to saturated vapor. The water pressure at the low temperature is 14.7 lbf/in.^{2}. Find T_L, cycle thermal efficiency, heat added per pound-mass, and entropy, *s*, at the beginning of the heat rejection process.



Constant T $\Rightarrow$ constant P from 1 to 2

$q_H = h_2 - h_1 = h_{fg} = 775.4$ Btu/lbm

States 3 & 4 are two-phase

$\Rightarrow T_L = T_3 = T_4 =$ **212 F**

$$\eta_{cycle} = 1 - T_L/T_H = 1 - \frac{212 + 459.67}{450 + 459.67} = \mathbf{0.262}$$

$s_3 = s_2 = s_g(T_H) =$ **1.4806 Btu/lbm R**

8.86E Consider a Carnot-cycle heat pump with R-22 as the working fluid. Heat is rejected from the R-22 at 100 F, during which process the R-22 changes from saturated vapor to saturated liquid. The heat is transferred to the R-22 at 30 F.
a. Show the cycle on a *T–s* diagram.
b. Find the quality of the R-22 at the beginning and end of the isothermal heat addition process at 30 F.
c. Determine the coefficient of performance for the cycle.

a)

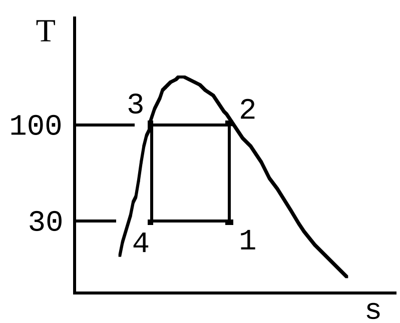


Table C.10.1

b) $s_4 = s_3 = 0.0794 = 0.0407 + x_4(0.1811)$

$x_4 =$ **0.214**

$s_1 = s_2 = 0.2096 = 0.0407 + x_1(0.1811)$

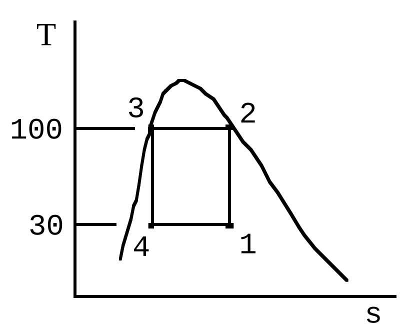
$x_1 =$ **0.9326**

c) $\beta' = q_H/w_{IN} = T_H/(T_H - T_L)$

$= 559.67/(100 - 30) =$ **7.995**

8.87E Do Problem 8.86 using refrigerant R-134a instead of R-22.

a)



b) Table C.11.1

$s_4 = s_3 = 0.2819 = 0.2375 + x_4(0.1749)$

$x_4 =$ **0.254**

$s_1 = s_2 = 0.4091 = 0.2375 + x_1(0.1749)$

$x_1 =$ **0.9811**

c) $\beta' = q_H / w_{IN} = T_H/(T_H - T_L)$

$= 559.67/(100 - 30) =$ **7.995**

8.88E Water at 30 lbf/in.^{2}, x = 1.0 is compressed in a piston/cylinder to 140 lbf/in.^{2}, 600 F in a reversible process. Find the sign for the work and the sign for the heat transfer.

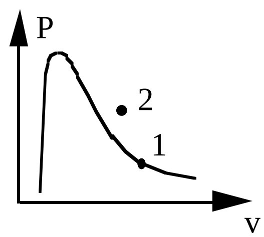
Solution:

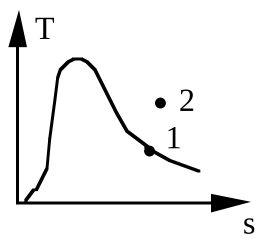
Table C.8.1: s_1 = 1.70 Btu/lbm R $\quad$ v_1 = 13.76 ft^3/lbm

Table C.8.2: s_2 = 1.719 Btu/lbm R $\quad$ v_2 = 4.41 ft^3/lbm $\quad$ =>

ds >0 : $\quad$ dq = Tds > 0 $\quad$ => q is positive

dv < 0 : $\quad$ dw = Pdv < 0 $\quad$ => w is negative





8.89E Two pound-mass of ammonia in a piston/cylinder at 120 F, 150 lbf/in.^{2} is expanded in a reversible adiabatic process to 15 lbf/in.^{2}. Find the work and heat transfer for this process.

Control mass: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

$$m(s_2 - s_1) = \int_1^2 dQ/T + {}_1S_{2,gen}$$

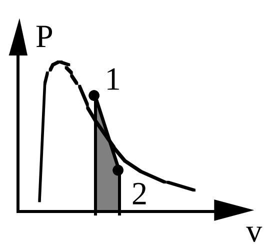
Process: $\mathbf{{}_1Q_2 = \emptyset}$, $\quad {}_1S_{2,gen} = \emptyset \;\Rightarrow\; s_2 = s_1 = 1.2504$ Btu/lbm R

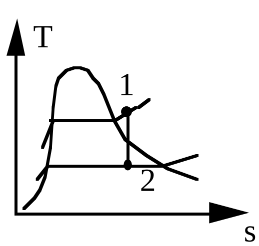
State 2: P_2 , s_2 $\Rightarrow$ 2 phase Table C.9.1 (sat. vap. C.9.2 also)

Interpolate: $\quad s_{g2}$ = 1.3921 Btu/lbm R, s_f = 0.0315 Btu/lbm R

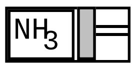
x_2 = (1.2504-0.0315)/1.3606 = 0.896 , $\quad u_2 = 13.36 + 0.896 \times 539.35 = 496.6$

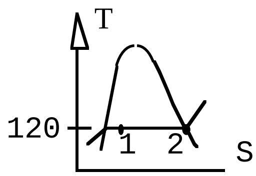
${}_1W_2 = 2 \times (596.6 - 496.6) =$ **100 Btu**





8.90E A cylinder fitted with a piston contains ammonia at 120 F, 20% quality with a volume of 60 in.^{3}. The ammonia expands slowly, and during this process heat is transferred to maintain a constant temperature. The process continues until all the liquid is gone. Determine the work and heat transfer for this process.





T_1 = 120 F, x_1 = 0.20, V_1 = 60 in^3

T = const to x_2 = 1, Table C.9.1: P = 286.5 lbf/in^2

$v_1 = 0.02836 + 0.2 \times 1.0171 = 0.2318$

$v_2 = 1.045, \quad m = V/v = \dfrac{60}{1728 \times 0.2318} = 0.15$ lbm

$${}_1W_2 = \frac{286.5 \times 144}{778} \times 0.15 \times (1.045 - 0.2318) = \mathbf{6.47\ Btu}$$

$s_1 = 0.3571 + 0.2 \times 0.7829 = 0.5137$ Btu/lbm R, $s_2 = 1.140$ Btu/lbm R

${}_1Q_2 = 579.7 \times 0.15(1.1400 - 0.5137) =$ **54.46 Btu**

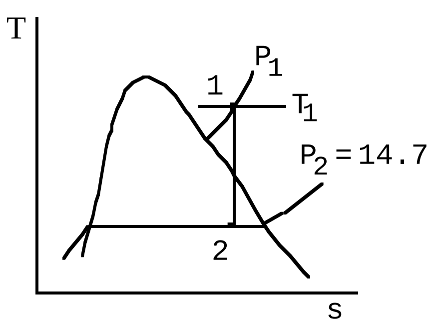
\- **or** - $h_1 = 178.79 + 0.2 \times 453.84 = 269.56$ Btu/lbm; $h_2 = 632.63$ Btu/lbm

${}_1Q_2 = m(h_2 - h_1) = 0.15(632.63 - 269.56) =$ **54.46 Btu**

8.91E One pound-mass of water at 600 F expands against a piston in a cylinder until it reaches ambient pressure, 14.7 lbf/in.^{2}, at which point the water has a quality of 90%. It may be assumed that the expansion is reversible and adiabatic.

a. What was the initial pressure in the cylinder?

b. How much work is done by the water?



C.V. Water m = 1 lbm, T_1 = 600 F

Process: Q = 0, ${}_1S_{2\,gen} = 0$ => $s_2 = s_1$

Table C.9.1: P_2 = 14.7 lbf/in^2, x_2 = 0.90

a) $s_1 = s_2 = 0.31212 + 0.9 \times 1.4446 = 1.6123$

Table C.8.2: at T_1 = 600 F, s_1

$\Rightarrow P_1 =$ **335 lbf/in^2**

b) u_1 = 1201.2 Btu/lbm, $u_2 = 180.1 + 0.9 \times 897.5 = 987.9$ Btu/lbm

${}_1W_2 = 1(1201.2 - 987.9) =$ **213.3 Btu**

8.92E A closed tank, $V = 0.35\ \text{ft}^3$, containing 10 lbm of water initially at 77 F is heated to 350 F by a heat pump that is receiving heat from the surroundings at 77 F. Assume that this process is reversible. Find the heat transfer to the water and the work input to the heat pump.

C.V.: Water from state 1 to state 2.

Process: constant volume (reversible isometric)

1: $v_1 = V/m = 0.35/10 = 0.035\ \text{ft}^3/\text{lbm} \Rightarrow x_1 = 2.692\times10^{-5}$

$u_1 = 45.11$ Btu/lbm, $s_1 = 0.08779$ Btu/lbm R

Continuity eq. (same mass) and constant volume fixes v_2

State 2: T_2, $v_2 = v_1 \Rightarrow x_2 = (0.035 - 0.01799) / 3.3279 = 0.00511$

$u_2 = 321.35 + 0.00511\times788.45 = 325.38$ Btu/lbm

$s_2 = 0.5033 + 0.00511\times1.076 = 0.5088$ Btu/lbm R

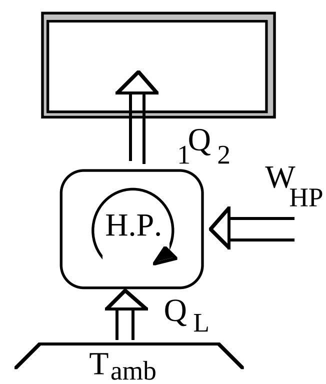
Energy eq. has zero work, thus provides heat transfer as

$${}_1Q_2 = m(u_2 - u_1) = 10(325.38 - 45.11) = \mathbf{2802.7\ Btu}$$

Entropy equation for the total control volume gives for a reversible process:

$$m(s_2 - s_1) = Q_L/T_0$$

$$\Rightarrow Q_L = mT_0(s_2 - s_1)$$
$$= 10(77 + 459.67)(0.5088 - 0.08779)$$
$$= 2259.4\ \text{Btu}$$



and the energy equation for the heat pump gives

$$W_{HP} = {}_1Q_2 - Q_L = 2802.7 - 2259.4 = \mathbf{543.3\ Btu}$$

8.93E A cylinder containing R-134a at 50 F, 20 lbf/in.^{2}, has an initial volume of 1 ft^3. A piston compresses the R-134a in a reversible, isothermal process until it reaches the saturated vapor state. Calculate the required work and heat transfer to accomplish this process.

C.V. R-134a. Control mass.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen} = {}_1Q_2 /T + 0$

State 1: Table C.11.2 at 50F: Since v is nonlinear in P interpolate in Pv

$v = [(2/3)\times 3.4859\times 15 + (1/3)\times 1.6963\times 30] / 20 = 2.591$ ft^3/lbm

$m = V/v_1 = 1/2.591 = 0.3859$ lbm

$u_1 = [(2/3)\times 176.96 + (1/3)\times 175.99] - 20\times 2.591\times 144/778 = 167.05$ Btu/lbm,

$s_1 = [(2/3)\times 0.443 + (1/3)\times 0.42805] = 0.438$ Btu/lbm R,

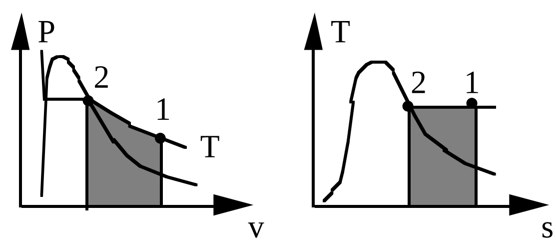
State 2: (50 F, sat. vapor) C.11.1

$u_2 = 164.95$ Btu/lbm,

$s_2 = 0.4112$ Btu/lbm R

Process: T = constant, reversible

${}_1S_{2\ gen} = 0$ =>



${}_1Q_2 = \int Tds = mT(s_2 - s_1) = 0.3859 \times 509.67\ (0.4112 - 0.438) =$ **-5.27 Btu**

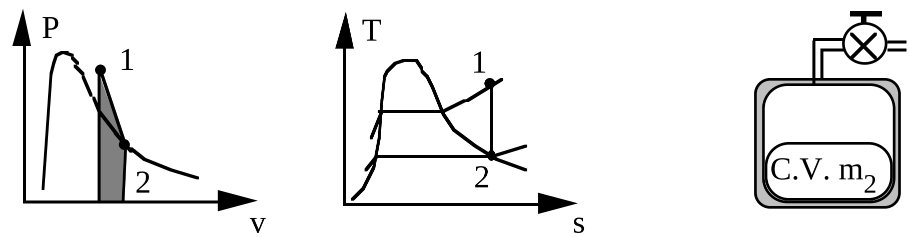
${}_1W_2 = m(u_1 - u_2) + {}_1Q_2 = 0.3859\ (167.05 - 164.95) - 5.27 =$ **-4.46 Btu**

8.94E A rigid, insulated vessel contains superheated vapor steam at 450 lbf/in.^{2}, 700 F. A valve on the vessel is opened, allowing steam to escape. It may be assumed that the steam remaining inside the vessel goes through a reversible adiabatic expansion. Determine the fraction of steam that has escaped, when the final state inside is saturated vapor.

C.V.: Steam remaining inside tank, control mass. Rev. & Adiabatic.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = 0 + 0$.



State 1: $v_1 = 1.458$ ft^3/lbm, $s_1 = 1.6248$ Btu/lbm R

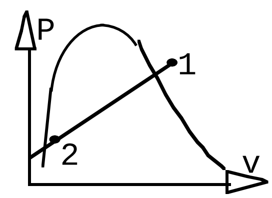
State 2: Table C.8.1 $s_2 = s_1 = 1.6248 = s_g$ at P_2

$\Rightarrow P_2 = 76.67$ lbf/in^2, $v_2 = v_g = 5.703$

$$\frac{m_e}{m_1} = \frac{m_1 - m_2}{m_1} = 1 - \frac{m_2}{m_1} = 1 - \frac{v_1}{v_2} = 1 - \frac{1.458}{5.703} = \mathbf{0.744}$$

8.95E A cylinder/piston contains 5 lbm of water at 80 lbf/in.^{2}, 1000 F. The piston has cross-sectional area of 1 ft^2 and is restrained by a linear spring with spring constant 60 lbf/in. The setup is allowed to cool down to room temperature due to heat transfer to the room at 70 F. Calculate the total (water and surroundings) change in entropy for the process.

State 1: Table B.8.2 $v_1 = 10.831$, $u_1 = 1372.3$, $s_1 = 1.9453$



State 2: T_2 & on line in P-v diagram.

$$P = P_1 + (k_s/A^2_{cyl})(V - V_1)$$

Assume state 2 is two-phase,

$$\Rightarrow P_2 = P_{sat}(T_2) = 0.3632 \text{ lbf/in}^2$$

$$v_2 = v_1 + (P_2 - P_1)A^2_{cyl}/mk_s = 10.831 + (0.3632 - 80)1\times12/5\times60$$

$$= 7.6455 \text{ ft}^3\text{/lbm} = v_f + x_2 v_{fg} = 0.01605 + x_2\ 867.579$$

$$x_2 = 0.008793,\ \ u_2 = 38.1 + 0.008793\times995.64 = 46.85,$$

$$s_2 = 0.0746 + 0.008793\times1.9896 = 0.0921$$

$$_1W_2 = \frac{1}{2}(P_1 + P_2)m(v_2 - v_1)$$

$$= \frac{5}{2}(80 + 0.3632)(7.6455 - 10.831)\frac{144}{778} = -118.46 \text{ Btu}$$

$$_1Q_2 = m(u_2 - u_1) + {_1W_2} = 5(46.85 - 1372.3) - 118.46 = -6746 \text{ Btu}$$

$$\Delta S_{tot} = S_{gen\,tot} = m(s_2 - s_1) - {_1Q_2}/T_{room}$$

$$= 5(0.0921 - 1.9453) + 6746/529.67 = \mathbf{3.47\ Btu/R}$$

8.96E An insulated cylinder/piston contains R-134a at 150 lbf/in.^{2}, 120 F, with a volume of 3.5 ft^3. The R-134a expands, moving the piston until the pressure in the cylinder has dropped to 15 lbf/in.^{2}. It is claimed that the R-134a does 180 Btu of work against the piston during the process. Is that possible?

State 1: $v_1 = 0.33316$, $u_1 = 175.33$, $s_1 = 0.41586$

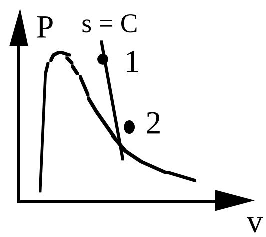
$m = V/v_1 = 3.5/0.33316 = 10.505$ lbm

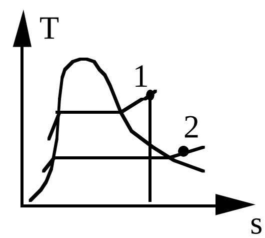
Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = \emptyset - 180 \Rightarrow u_2 = 158.196$ Btu/lbm

State 2: $P_2, u_2 \Rightarrow T_2 = -2$ F $s_2 = 0.4220$

$m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen} = {}_1S_{2\ gen} = \mathbf{0.0645\ Btu/R}$

This is **possible since ${}_1S_{2\ gen} > \emptyset$**



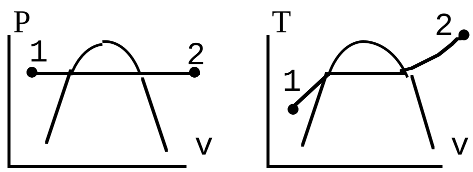


8.97E A mass and atmosphere loaded piston/cylinder contains 4 lbm of water at 500 lbf/in.^{2}, 200 F. Heat is added from a reservoir at 1200 F to the water until it reaches 1200 F. Find the work, heat transfer, and total entropy production for the system and surroundings.

C.V. Water out to reservoir, control mass.

Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = {}_1Q_2 - Pm(v_2 - v_1)$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$



State 1: Table C.8.3, $v_1 = 0.01661$

$h_1 = 169.18$, $s_1 = 0.2934$

Process: P = constant = 500 lbf/in^2

State 2: Table C.8.2, $v_2 = 1.9518$, $h_2 = 1629.8$, $s_2 = 1.8071$

${}_1W_2 = 500(4)(1.9518 - 0.01661)(144/778) =$ **716.37 Btu**

${}_1Q_2 = m(h_2 - h_1) = 4(1629.8 - 169.18) =$ **5842.48 Btu**

${}_1S_{2\ gen} = m(s_2 - s_1) - {}_1Q_2/T_{res}$

$= 4(1.8071 - 0.2934) - 5842.48/1659.67 =$ **2.535 Btu/R**

8.98E A 1 gallon jug of milk at 75 F is placed in your refrigerator where it is cooled down to the refrigerators inside temperature of 40 F. Assume the milk has the properties of liquid water and find the entropy generated in the cooling process.

Solution:

C.V. Milk, control mass, assume liquid does not change volume.

Cont.Eq.: $m_2 = m_1 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = {}_1Q_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\ gen}$

State 1: Table C.8.1, $v_1 \cong v_f = 0.01606$ ft^3/lbm, $u_1 = 43.09$, $v_1 = 0.08395$

$V_1 = 1$ Gal $= 231$ in^3 => $m = 231 / 0.01606 \times 12^3 = 8.324$ lbm

State 2: Table C.8.1, $u_2 = 8.01$ Btu/lbm, $s_2 = 0.0162$ Btu/lbm R

${}_1Q_2 = m(u_2 - u_1) = 8.324\ (8.01 - 43.09) = -292$ Btu

${}_1S_{2\ gen} = 8.324\ (0.0162 - 0.08395) - [-292 / (460 + 40)]$

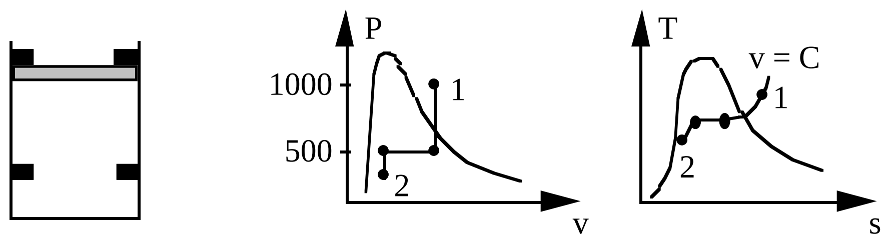
$=$ **0.02 Btu/R**

8.99E Water in a piston/cylinder is at 150 lbf/in.^{2}, 900 F, as shown in Fig. P8.33. There are two stops, a lower one at which V_{min} = 35 ft^3 and an upper one at V_{max} = 105 ft^3. The piston is loaded with a mass and outside atmosphere such that it floats when the pressure is 75 lbf/in.^{2}. This setup is now cooled to 210 F by rejecting heat to the surroundings at 70 F. Find the total entropy generated in the process.

C.V. Water.

State 1: Table C.8.2 $\quad v_1 = 5.353, \quad u_1 = 1330.2, \quad s_1 = 1.8381$

$$m = V/v_1 = 105/5.353 = 19.615 \text{ lbm}$$



State 2: 210 F and on line in P-v diagram.

Notice the following: $v_g(P_{float}) = 5.818$, $\quad v_{bot} = V_{min}/m = 1.7843$

$$T_{sat}(P_{float}) = 307.6 \text{ F}, \quad T_2 < T_{sat}(P_{float}) \quad \Rightarrow \quad V_2 = V_{min}$$

State 2: 210 F, $v_2 = v_{bot} \;\Rightarrow\; x_2 = (1.7843 - 0.0167)/27.796 = 0.06359$

$$u_2 = 178.1 + 0.06359 \times 898.9 = 235.26,$$

$$s_2 = 0.3091 + 0.06359 \times 1.4507 = 0.4014$$

$${}_1W_2 = \int PdV = P_{float}(V_2 - V_1) = 75(35 - 105)\frac{144}{778} = -971.72 \text{ Btu}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = 19.615(235.26 - 1330.2) - 971.72 = -22449 \text{ Btu}$$

Take C.V. total out to where we have 70 F:

$$m(s_2 - s_1) = {}_1Q_2/T_0 + S_{gen} \;\Rightarrow$$

$$S_{gen} = m(s_2 - s_1) - {}_1Q_2/T_0 = 19.615(0.4014 - 1.8381) + \frac{22449}{529.67}$$

$$= \mathbf{14.20\ Btu/R} \quad (= \Delta S_{water} + \Delta S_{sur})$$

8.100E A cylinder/piston contains water at 30 lbf/in.^{2}, 400 F with a volume of 1 ft^3. The piston is moved slowly, compressing the water to a pressure of 120 lbf/in.^{2}. The loading on the piston is such that the product *PV* is a constant. Assuming that the room temperature is 70 F, show that this process does not violate the second law.

C.V.: Water + cylinder out to room at 70 F

Process: PV = constant = Pmv $\Rightarrow$ $v_2 = P_1v_1/P_2$

$_1w_2 = \int P\,dv = P_1v_1 \ln(v_2/v_1)$

State 1: $v_1 = 16.891$, $u_1 = 1144.0$, $s_1 = 1.7936$

State 2: P_2, $v_2 = P_1v_1/P_2 = 30\times16.891/120 = 4.223$ ft^3/lbm

=> $T_2 = 425.4$ F, $u_2 = 1144.4$, $s_2 = 1.6445$

$_1w_2 = 30 \times 16.891(144/778) \ln(4.223/16.891) = -130.0$ Btu

$_1q_2 = u_2 - u_1 + {_1w_2} = 1144.4 - 1144 - 130 = -129.6$ Btu

$_1s_{s,gen} = (s_2 - s_1) - {_1q_2}/T_{room} = 1.6445 - 1.7936 + 129.6/529.67$

$= 0.0956$ Btu/lbm R $> \emptyset$ **satisfy 2$^{\underline{nd}}$ law.**

8.101E One pound mass of ammonia (NH_3) is contained in a linear spring-loaded piston/cylinder as saturated liquid at 0 F. Heat is added from a reservoir at 225 F until a final condition of 125 lbf/in.^{2}, 160 F is reached. Find the work, heat transfer, and entropy generation, assuming the process is internally reversible.

C.V. = NH_3 Cont. $m_2 = m_1 = m$

Energy: $E_2 - E_1 = {_1Q_2} - {_1W_2} = m(u_2 - u_1)$

Entropy: $S_2 - S_1 = \int dQ/T + {_1S_{2,gen}}$

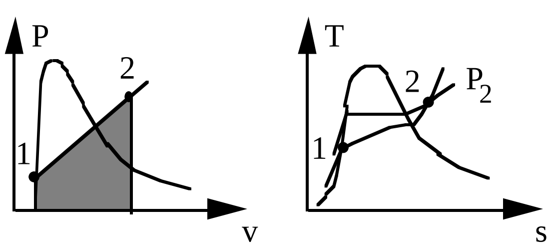
Process: $_1W_2 = \int P\,dV = \frac{1}{2}(P_1 + P_2)(V_2 - V_1) = \frac{1}{2}(P_1 + P_2)m(v_2 - v_1)$

$P_1 = 30.4$, $v_1 = 0.0242$

$u_1 = 42.5$, $s_1 = 0.0967$

State 2: Table C.9.2 sup. vap.

$v_2 = 2.9574$, $s_2 = 1.3178$



$u_2 = 686.9 - 125\times2.9574\times144/778 = 618.5$ Btu/lbm

$_1W_2 = \frac{1}{2}(30.4 + 125)1(2.9574 - 0.0242)\times144/778 = $ **42.2 Btu**

$_1Q_2 = m(u_2 - u_1) + {_1W_2} = 1(618.5 - 42.5) + 42.2 = $ **618.2 Btu**

$S_{gen} = m(s_2 - s_1) - {_1Q_2}/T_{res} = 1(1.3178 - 0.0967) - \frac{618.2}{684.7} = $ **0.318 Btu/R**

8.102E A foundry form box with 50 lbm of 400 F hot sand is dumped into a bucket with 2 ft^3 water at 60 F. Assuming no heat transfer with the surroundings and no boiling away of liquid water, calculate the net entropy change for the process.

C.V. Sand and water, P = const.

$$m_{sand}(u_2 - u_1)_{sand} + m_{H_2O}(u_2 - u_1)_{H_2O} = -P(V_2 - V_1)$$

$$\Rightarrow\ m_{sand}\Delta h_{sand} + m_{H_2O}\Delta h_{H_2O} = 0, \qquad m_{H_2O} = \frac{2}{0.016035} = 124.73 \text{ lbm}$$

$$50 \times 0.19(T_2 - 400) + 124.73 \times 1.0(T_2 - 60) = 0, \qquad T_2 = 84 \text{ F}$$

$$\Delta S = 50 \times 0.19 \times \ln\left(\frac{544}{860}\right) + 124.73 \times 1.0 \times \ln\left(\frac{544}{520}\right) = \mathbf{1.293\ Btu/R}$$

8.103E A hollow steel sphere with a 2-ft inside diameter and a 0.1-in. thick wall contains water at 300 lbf/in.^{2}, 500 F. The system (steel plus water) cools to the ambient temperature, 90 F. Calculate the net entropy change of the system and surroundings for this process.

C.V.: STEEL + H_2O

$$V_{STEEL} = \frac{\pi}{6}\left[2.0083^3 - 2^3\right] = 0.0526 \text{ ft}^3$$

$$m_{STEEL} = (\rho V)_{STEEL} = 490 \times 0.0526 = 25.763 \text{ lbm}$$

$$\Delta U_{STEEL} = (mC)(T_2 - T_1) = 25.763 \times 0.107(90-500) = -1130 \text{ Btu}$$

$$V_{H_2O} = \pi/6 \times 2^3 = 4.189 \text{ ft}^3 \qquad m_{H_2O} = V/v = 2.372 \text{ lbm}$$

$$v_2 = v_1 = 1.7662 = 0.016099 + x_2 \times 467.7 \Rightarrow x_2 = 3.74 \times 10^{-3}$$

$$u_2 = 61.745 \qquad s_2 = 0.1187$$

$$\Delta U_{H_2O} = 2.372(61.74 - 1159.5) = -2603.9 \text{ Btu}$$

$$Q_{12} = \Delta U_{STEEL} + \Delta U_{H_2O} = -1130 - 2603.9 = -3734 \text{ Btu}$$

$$\Delta S_{SYS} = \Delta S_{STEEL} + \Delta S_{H_2O} = 25.763 \times 0.107 \times \ln(550/960)$$

$$+ 2.372(0.1187 - 1.5701) = -4.979 \text{ Btu/R}$$

$$\Delta S_{SUR} = -Q_{12}/T_{SUR} = 3734/549.67 = 6.793 \text{ Btu/R}$$

$$\Delta S_{NET} = S_{GEN,TOT} = \Delta S_{SYS} + \Delta S_{SUR} = \mathbf{1.814\ Btu/R}$$

8.104E A handheld pump for a bicycle has a volume of 2 in.^{2} when fully extended. You now press the plunger (piston) in while holding your thumb over the exit hole so an air pressure of 45 lbf/in.^{2} is obtained. The outside atmosphere is at P_o, T_o. Consider two cases: (1) it is done quickly (~1 s), and (2) it is done slowly (~1 h).

a. State assumptions about the process for each case.

b. Find the final volume and temperature for both cases.

C.V. Air in pump. Assume that both cases result in a reversible process.

Case I) Quickly means no time for heat transfer

$Q = \emptyset$, so a reversible adiabatic compression.

$u_2 - u_1 = -{}_1w_2$, $\quad s_2 = s_1 = \emptyset$

Table C.6 $\quad \Rightarrow P_{r2} = P_{r1} \times P_2/P_1 = 1.0925(45/14.7) = 3.344$

$T_2 =$ **737.7 R** , $V_2 = P_1V_1T_2/T_1P_2 =$ **0.898 in^3**

Case II) Slowly, time for heat transfer so $T = T_0$. The process is then a reversible isothermal compression.

$T_2 = T_0 =$ **536.67 R,** $\quad V_2 = V_1P_1/P_2 =$ **0.653 in^3**

8.105E A piston/cylinder contains air at 2500 R, 2200 lbf/in.^{2}, with V_1 = 1 in.^{3}, A_{cyl} = 1 in.^{2} as shown in Fig. P8.53. The piston is released and just before the piston exits the end of the cylinder the pressure inside is 30 lbf/in.^{2}. If the cylinder is insulated, what is its length? How much work is done by the air inside?

C.V. Air. $\quad m_2 = m_1, \quad m(u_2 - u_1) = {}_1Q_2 - {}_1W_2 = - {}_1W_2$

$m(s_2 - s_1) = \int dQ/T + {}_1S_2 = 0 + 0 = 0$

State 1: Table C.6, $\quad P_{r1} = 349.78, \quad v_{r1} = 2.6479, \quad u_1 = 474.33$

State 2: $\quad P_{r2} = P_{r1}P_2/P_1 = 4.77, \quad T_2 = 816, \quad u_2 = 139.91, \quad v_{r2} = 63.38$

$V_2 = V_1(v_{r2}/v_{r1}) = 23.94 \text{ in}^3 \Rightarrow \quad L = V_2 /A_{CYL} = 23.94$ in

$$m = P_1V_1/RT_1 = \frac{2200 \times 1.0}{53.34 \times 2500 \times 12} = 1.375 \times 10^{-3} \text{ lbm}$$

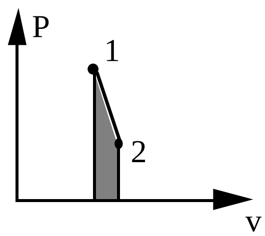
${}_1W_2 = m(u_1 - u_2) = 1.375 \times 10^{-3}(474.33 - 139.91) =$ **0.46 Btu**

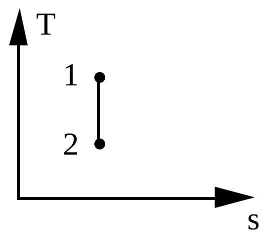
8.106E A 25-ft^3 insulated, rigid tank contains air at 110 lbf/in.^{2}, 75 F. A valve on the tank is opened, and the pressure inside quickly drops to 15 lbf/in.^{2}, at which point the valve is closed. Assuming that the air remaining inside has undergone a reversible adiabatic expansion, calculate the mass withdrawn during the process.

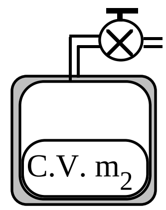
C.V.: Air remaining inside tank, m_2.

Cont.Eq.: $m_2 = m$; Energy Eq.: $m(u_2 - u_1) = {}_1Q_2 - {}_1W_2$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = 0 + 0$







$s_2 = s_1 \rightarrow T_2 = T_1(P_2/P_1)^{\frac{k-1}{k}} = 535\ (15/110)^{0.286} = 302.6$ R

$m_1 = P_1V/RT_1 = 110 \times 144 \times 25 /(53.34 \times 535) = 13.88$ lbm

$m_2 = P_2V/RT_2 = 15 \times 144 \times 25 /(53.34 \times 302.6) = 3.35$ lbm

$m_e = m_1 - m_2 =$ **10.53 lbm**

8.107E A rigid container with volume 7 ft^3 is divided into two equal volumes by a partition. Both sides contain nitrogen, one side is at 300 lbf/in.^{2}, 400 F, and the other at 30 lbf/in.^{2}, 200 F. The partition ruptures, and the nitrogen comes to a uniform state at 160 F. Assume the temperature of the surroundings is 68 F, determine the work done and the net entropy change for the process.

Solution:

C.V.: A + B Control mass no change in volume => $\mathbf{{}_1W_2 = 0}$

$$m_{A1} = P_{A1}V_{A1}/RT_{A1} = 300\times144\times 3.5 /(55.15 \times 859.7) = 3.189 \text{ lbm}$$

$$m_{B1} = P_{B1}V_{B1}/RT_{B1} = 30\times144\times 3.5 / (55.15\times 659.7) = 0.416 \text{ lbm}$$

$$P_2 = m_{TOT}RT_2/V_{TOT} = 3.605 \times 55.15 \times 619.7/(144 \times 7) = 122.2 \text{ lbf/in}^2$$

$$\Delta S_{SYST} = 3.189 \left[0.249 \ln \frac{619.7}{859.7} - \frac{55.15}{778} \ln \frac{122.2}{300}\right]$$

$$+ 0.416 \left[0.249 \ln \frac{619.7}{659.7} - \frac{55.15}{778} \ln \frac{122.2}{30}\right]$$

$$= -0.0569 - 0.0479 = -0.1048 \text{ Btu/R}$$

$${}_1Q_2 = m_{A1}(u_2 - u_1) + m_{B1}(u_2 - u_1)$$

$$= 3.189 \times 0.178(160 - 400) + 0.416 \times 0.178(160 - 200) = -139.2 \text{ Btu}$$

$$\Delta S_{SURR} = -\,{}_1Q_2/T_0 = 139.2 / 527.7 = +0.2638 \text{ Btu/R}$$

$$\Delta S_{NET} = -0.1048 + 0.2638 = \mathbf{+0.159\ Btu/R}$$

8.108E Nitrogen at 90 lbf/in.^{2}, 260 F is in a 20 ft^3 insulated tank connected to a pipe with a valve to a second insulated initially empty tank of volume 20 ft^3. The valve is opened and the nitrogen fills both tanks. Find the final pressure and temperature and the entropy generation this process causes. Why is the process irreversible?

C.V. Both tanks + pipe + valve. Insulated : Q = 0, Rigid: W = 0

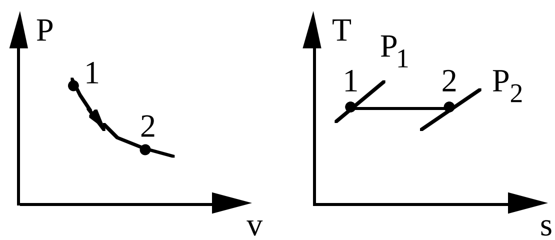
$m(u_2 - u_1) = 0 - 0 \quad => \quad u_2 = u_1 = u_{a1}$

Entropy Eq.: $m(s_2 - s_1) = \int dQ/T + {}_1S_{2\,gen} = {}_1S_{2\,gen}$

State 1: P_1, T_1, V_a => Ideal gas

$m = PV/RT = (90 \times 20 \times 144)/(55.15 \times 720) = 6.528$ lbm

2: $V_2 = V_a + V_b$; uniform final state $v_2 = V_2 / m$; $u_2 = u_{a1}$



Ideal gas u (T) => $u_2 = u_{a1}$ => $T_2 = T_{a1}$ = **720 R**

$P_2 = mR\,T_2 / V_2 = (V_1 / V_2)\,P_1 = \_ \times 90 =$ **45 lbf/in.^{2}**

$S_{gen} = m(s_2 - s_1) = m\,(s_{T2}^o - s_{T1}^o - R \ln (P_2 / P_1))$

$= m\,(0 - R \ln (P_2 / P_1)) = -6.528 \times 55.15 \times (1/778) \ln \_ = 0.32$ Btu/R

Irreversible due to unrestrained expansion in valve P ↓ but no work out.

If not a uniform final state then flow until $P_{2b} = P_{2a}$ and valve is closed. Assume no Q between A and B

$m_{a2} + m_{b2} = m_{a1}$; $m_{a2}\,v_{a2} + m_{b2}\,v_{b2} = m_{a1} v_{a1}$

$m_{a2}\,s_{a2} + m_{b2}\,s_{b2} - m_{a1} s_{a1} = 0 + {}_1S_{2\,gen}$

Now we must assume m_{a2} went through rev adiabatic expansion

1) $V_2 = m_{a2}\,v_{a2} + m_{b2}\,v_{b2}$; 2) $P_{b2} = P_{a2}$; 3) $s_{a2} = s_{a1}$; 4) Energy eqs.

4 Eqs 4 unknowns : P_2, T_{a2}, T_{b2}, $x = m_{a2} / m_{a1}$

$V_2 / m_{a1} = x\,v_{a2} + (1 - x)\,v_{b2} = x \times (R\,T_{a2} / P_2) + (1 - x)\,(R\,T_{b2} / P_2)$

$m_{a2}\,(u_{a2} - u_{a1}) + m_{b2}\,(u_{b2} - u_{a1}) = 0$

$x\,C_v\,(T_{a2} - T_{a1}) + (1 - x)\,(T_{b2} - T_{a1})\,C_v = 0$

$x\,T_{a2} + (1 - x) T_{b2} = T_{a1}$

$P_2\,V_2 / m_{a1} R = x\,T_{a2} + (1 - x)\,T_{b2} = T_{a1})$

$P_2 = m_{a1}\ R\ T_{a1} / V_2 = m_{a1}\ R\ T_{a1} / 2V_{a1} = \_\ P_{a1}$ = **45 lbf/in.^{2}**

$s_{a2} = s_{a1}$ => $T_{a2} = T_{a1} (P_2 / P_{a1})^{k-1/k} = 720 \times (1/2)^{0.2857}$ = **590.6 R**

Now we have final state in A

$v_{a2} = R\ T_{a2} / P_2 = 5.0265$; $m_{a2} = V_a / v_{a2} = 3.979$ lbm

$x = m_{a2} / m_{a1} = 0.6095$ $\qquad$ $m_{b2} = m_{a1} - m_{a2} = 2.549$ lbm

Substitute into energy equation

$T_{b2} = (T_{a1} - x\ T_{a2}) / (1 - x) = 922$ R

$_1S_{2\ gen} = m_{b2} (s_{b2} - s_{a1}) = m_{b2} (C_p \ln (T_{b2} / T_{a1}) - R \ln (P_2 / P_{a1})$

$= 2.549 [0.249 \ln (922/720) - (55.15/778) \ln (1/2)]$

= **0.2822 Btu/R**

8.109E A cylinder/piston contains carbon dioxide at 150 lbf/in.^{2}, 600 F with a volume of 7 ft^3. The total external force acting on the piston is proportional to V^3. This system is allowed to cool to room temperature, 70 F. What is the total entropy generation for the process?

State 1: $P_1 = 150$ lbf/in^2, $T_1 = 600$ F = 1060 R, $V_1 = 7$ ft^3 Ideal gas

$$m = \frac{P_1V_1}{RT_1} = \frac{150 \times 144 \times 7}{35.10 \times 1060} = 4.064 \text{ lbm}$$

Process: $P = CV^3$ or PV^{-3} = const. polytropic with n= -3.

$$P_2 = P_1(T_2/T_1)^{\frac{n}{n-1}} = 150 \left(\frac{530}{1060}\right)^{0.75} = 89.2 \text{ lbf/in}^2$$

$$\& \ V_2 = V_1(T_1/T_2)^{\frac{1}{n-1}} = V_1 \times \frac{P_1}{P_2} \times \frac{T_2}{T_1} = 7 \times \frac{150}{89.2} \times \frac{530}{1060} = 5.886$$

$$_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - n} = \frac{(89.2 \times 5.886 - 150 \times 7)}{1 + 3} \times \frac{144}{778} = -24.3 \text{ Btu}$$

$$_1Q_2 = 4.064 \times 0.158 \times (530 - 1060) - 24.3 = -346.6 \text{ Btu}$$

$$\Delta S_{SYST} = 4.064 \times \left[.203 \times \ln\left(\frac{530}{1060}\right) - \frac{35.10}{778} \ln\left(\frac{89.2}{150}\right)\right] = -0.4765$$

$$\Delta S_{SURR} = 364.6/530 = +0.6879$$

ΔS_{NET} = **+0.2114 Btu/R**

8.110E Helium in a piston/cylinder at 20°C, 100 kPa is brought to 400 K in a reversible polytropic process with exponent n = 1.25. You may assume helium is an ideal gas with constant specific heat. Find the final pressure and both the specific heat transfer and specific work.

Solution:

C.V. Helium, control mass. $C_v = 0.744$ $R = 386$ ft lbf/ lbm R

Process $Pv^n = C$ & $Pv = RT$ => $Tv^{n-1} = C$

$T_1 = 70 + 460 = 530$ R $T_2 = 720$ R

$T_1 v^{n-1} = T_2 v^{n-1}$ => $v_2 / v_1 = (T_1 / T_2)^{1/n-1} = 0.2936$

$P_2 / P_1 = (v_1 / v_2)^n = 4.63$ => $P_2 =$ **69.4 lbf/in.^{2}**

${}_1w_2 = \int P\, dv = \int C\, v^{-n}\, dv = [\, C / (1-n)\,] \times (\, v_2^{1-n} - v_1^{1-n})$

$= 1/(1-n)\ (P_2 v_2 - P_1 v_1) = R/(1-n)\ (T_2 - T_1) =$ **-377 Btu/lbm**

${}_1q_2 = u_2 - u_1 + {}_1w_2 = C_v\, (T_2 - T_1) + - 377 =$ **-235.6 Btu/lbm**

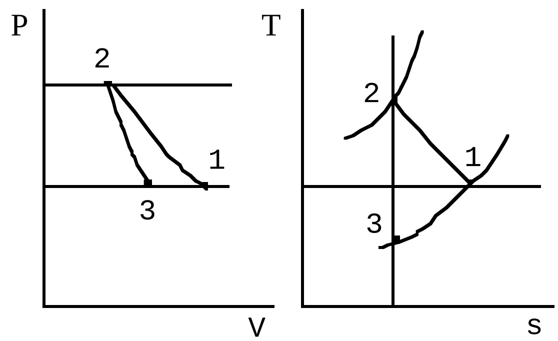
8.111E A cylinder/piston contains air at ambient conditions, 14.7 lbf/in.^{2} and 70 F with a volume of 10 ft^3. The air is compressed to 100 lbf/in.^{2} in a reversible polytropic process with exponent, $n = 1.2$, after which it is expanded back to 14.7 lbf/in.^{2} in a reversible adiabatic process.

a. Show the two processes in *P–v* and *T–s* diagrams.

b. Determine the final temperature and the net work.

c. What is the potential refrigeration capacity (in British thermal units) of the air at the final state?

a)



b) $m = P_1V_1/RT_1 = 14.7 \times 144 \times 10/(53.34 \times 529.7\ ) = 0.7492$ lbm

$$T_2 = T_1(P_2/P_1)^{\frac{n-1}{n}} = 529.7\left(\frac{100}{14.7}\right)^{0.167} = 729.6 \text{ R}$$

$$_1w_2 = \int_1^2 P dv = \frac{P_2v_2 - P_1v_1}{1 - n} = \frac{R(T_2 - T_1)}{1 - n}$$

$$= \frac{53.34(729.6 - 529.7)}{778(1 - 1.20)} = -68.5 \text{ Btu/lbm}$$

$$T_3 = T_2(P_3/P_2)^{\frac{k-1}{k}} = 729.6\left(\frac{14.7}{100}\right)^{0.286} = \mathbf{421.6\ R}$$

$$_2w_3 = C_{V0}(T_2 - T_3) = 0.171(729.6 - 421.6) = +52.7 \text{ Btu/lbm}$$

$$w_{NET} = 0.7492(-68.5 + 52.7) = \mathbf{-11.8\ Btu}$$

c) Refrigeration: warm to T_0 at const P,

$$Q_{31} = mC_{P0}(T_1 - T_3) = 0.7492 \times 0.24(529.7 - 421.6) = \mathbf{19.4\ Btu}$$

8.112E A cylinder/piston contains 4 ft^3 of air at 16 lbf/in.^{2}, 77 F. The air is compressed in a reversible polytropic process to a final state of 120 lbf/in.^{2}, 400 F. Assume the heat transfer is with the ambient at 77 F and determine the polytropic exponent *n* and the final volume of the air. Find the work done by the air, the heat transfer and the total entropy generation for the process.

Solution:

$$m = (P_1V_1)/(RT_1) = (16 \times 4 \times 144)/(53.34 \times 537) = 0.322 \text{ lbm}$$

$$T_2/T_1 = (P_2/P_1)^{\frac{n-1}{n}} \quad \Rightarrow \quad \frac{n-1}{n} = \ln(T_2 / T_1) / \ln(P_2 / P_1) = 0.2337$$

$$\mathbf{n = 1.305}, \quad V_2 = V_1(P_1/P_2)^{1/n} = 4 \times (16/20)1/1.305 = \mathbf{0.854\ ft^3}$$

$${}_1W_2 = \int PdV = \frac{P_2V_2 - P_1V_1}{1 - n}$$

$$= [(120 \times 0.854 - 16 \times 4) (144 / 778)] / (1 - 1.305) = \mathbf{-23.35\ Btu / lbm}$$

$${}_1Q_2 = m(u_2 - u_1) + {}_1W_2 = mC_V(T_2 - T_1) + {}_1W_2$$

$$= 0.322 \times 0.171 \times (400 - 77) - 23.35 = \mathbf{-5.56\ Btu / lbm}$$

$$s_2 - s_1 = C_p \ln(T_2 / T_1) - R \ln(P_2 / P_1)$$

$$= 0.24 \ln (860/537) - (53.34/778) \ln (120/16) = -0.0251 \text{ Btu/lbm R}$$

$${}_1S_{2\ gen} = m(s_2 - s_1) - {}_1Q_2/T_0$$

$$= 0.322 \times (-0.0251) + (5.56/537) = \mathbf{0.00226\ Btu/R}$$

8.113E A cylinder with a linear spring-loaded piston contains carbon dioxide gas at 300 lbf/in.^{2} with a volume of 2 ft^3. The device is of aluminum and has a mass of 8 lbm. Everything (Al and gas) is initially at 400 F. By heat transfer the whole system cools to the ambient temperature of 77 F, at which point the gas pressure is 220 lbf/in.^{2}. Find the total entropy generation for the process.

Solution:

CO_2: $m = P_1V_1/RT_1 = 300 \times 2 \times 144/(35.10 \times 860) = 2.862$ lbm

$$V_2 = V_1(P_1/P_2)\ (T_2 / T_1) = 2(300/220)(537/860) = 1.703 \text{ ft}^3$$

$${}_1W_{2\ CO_2} = \int PdV = 0.5(P_1 + P_2)\ (V_2 - V_1)$$

$$= [(300 + 220)/2]\ (1.703 - 2)\ (144/778) = -14.29 \text{ Btu}$$

$${}_1Q_{2\ CO_2} = mC_{V0}(T_2\text{-}T_1) + {}_1W_2 = 0.156 \times 2.862(77\text{- } 400)\text{-}14.29 = -158.5 \text{ Btu}$$

$${}_1Q_{2\ Al} = mC\ (T_2\text{-}T_1) = 8 \times 0.21(77 - 400) = -542.6 \text{ Btu}$$

System: CO_2 + Al

$${}_1Q_2 = -542.6 - 158.5 = -701.14 \text{ Btu}$$

$$\Delta S_{SYST} = m_{CO_2}(s_2 - s_1)_{CO_2} + m_{AL}(s_2 - s_1)_{AL}$$

$$= 2.862[0.201 \ln (537/860) - (35.10/778) \ln (220/300)]$$

$$+ 8 \times 0.21 \ln(537/860) = -0.23086 - 0.79117 = -1.022 \text{ Btu/R}$$

$$\Delta S_{SURR} = -({}_1Q_2/T_0) = + (701.14/537) = 1.3057 \text{ Btu/R}$$

$$\Delta S_{NET} = 1.3057 - 1.022 = \mathbf{+0.2837\ Btu/R}$$

CHAPTER 9

The correspondence between the new problem set and the previous 4th edition second half of chapter 7 problem set.

New	Old	New	Old	New	Old
1	63	28	87	55	96
2	64	29	new	56	117
3	66	30	88	57	97
4	new	31	90	58	99
5	104 mod	32	92	59	101
6	105 mod	33	new	60	102
7	675	34	new	61	new
8	new	35	new	62	104
9	new	36	new	63	105
10	new	37	new	64	108
11	new	38	77	65	110
12	65	39	110 mod	66	111
13	69	40	78	67	new
14	70	41	new	68	112
15	new	42	new	69	113
16	72	43	new	70	115
17	new	44	new	71	120
18	82	45	new	72	118
19	new	46	68	73	121
20	74	47	80	74	new
21	75	48	84	75	new
22	79	49	new	76	new
23	new	50	71	77	new
24	109 mod	51	103	78	new
25	85	52	94	79	new
26	91	53	106	80	new
27	86	54	95	81	109
				82	98

The problems that are labeled advanced are:

New	Old	New	Old	New	Old
83	73	86	114	89	100 mod
84	83	87	81	90	107
85	116	88	new		

The English unit problems are:

New	Old	New	Old	New	Old
91	149	101	159	111	163
92	150	102	new	112	166
93	166 mod	103	156	113	167
94	new	104	168 mod	114	168
95	151	105	new	115	169
96	153	106	152	116	172
97	155	107	157	117	new
98	new	108	154	118	new
99	new	109	165	119	171
100	158	110	162		

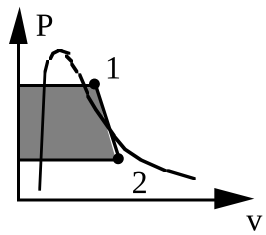
9.1 Steam enters a turbine at 3 MPa, 450°C, expands in a reversible adiabatic process and exhausts at 10 kPa. Changes in kinetic and potential energies between the inlet and the exit of the turbine are small. The power output of the turbine is 800 kW. What is the mass flow rate of steam through the turbine?

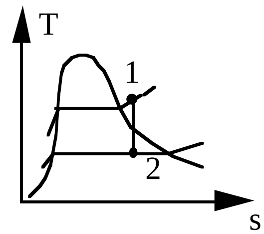
C.V. Turbine, SSSF, single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Mass: $\dot{m}_i = \dot{m}_e = \dot{m}$, Energy Eq.: $\dot{m}h_i = \dot{m}h_e + \dot{W}_T$,

Entropy Eq.: $\dot{m}s_i + \emptyset = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)

Explanation for the work term is in 9.3 Eq. (9.19)





Inlet state: Table B.1.3 h_i = 3344 kJ/kg, s_i = 7.0833 kJ/kg K

Exit state: P_e , $s_e = s_i$ $\Rightarrow$ Table B.1.2 sat. as $s_e < s_g$

$x_e = (7.0833 - 0.6492)/7.501 = 0.8578$,

$h_e = 191.81 + 0.8578 \times 2392.82 = 2244.4$ kJ/kg

$\dot{m} = \dot{W}_T/w_T = \dot{W}_T/(h_i - h_e) = 800/(3344 - 2244.4) =$ **0.728 kg/s**

9.2 In a heat pump that uses R-134a as the working fluid, the R-134a enters the compressor at 150 kPa, −10°C at a rate of 0.1 kg/s. In the compressor the R-134a is compressed in an adiabatic process to 1 MPa. Calculate the power input required to the compressor, assuming the process to be reversible.

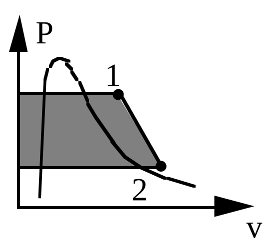
C.V.: Compressor (SSSF reversible: $\dot{S}_{gen} = 0$ & adiabatic: $\dot{Q} = 0$.)

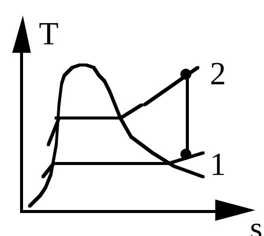
Inlet state: Table B.5.2 h_1 = 393.84 kJ/kg, s_1 = 1.7606 kJ/kg K

Exit state: P_2 = 1 MPa & $s_2 = s_1$ $\Rightarrow$ h_2 = 434.9 kJ/kg

$\dot{W}_c = \dot{m}w_c = \dot{m}(h_1 - h_2) = 0.1 \times (393.84 - 434.9) =$ **-4.1 kW**

Explanation for the work term is in 9.3 Eq. (9.19)





9.3 Consider the design of a nozzle in which nitrogen gas flowing in a pipe at 500 kPa, 200°C, and at a velocity of 10 m/s, is to be expanded to produce a velocity of 300 m/s. Determine the exit pressure and cross-sectional area of the nozzle if the mass flow rate is 0.15 kg/s, and the expansion is reversible and adiabatic.

C.V. Nozzle. SSSF, no work out and no heat transfer.

Energy Eq.: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2$ Entropy: $s_i + 0 = s_e$

$$C_{Po}(T_e - T_i) = 1.0416(T_e - 473.2) = (10^2 - 300^2)/(2\times1000)$$

$$T_e = 430 \text{ K},\ \ P_e = P_i(T_e/T_i)^{\frac{k}{k-1}} = 500\left(\frac{430}{473.2}\right)^{3.5} = \mathbf{357.6\ kPa}$$

$$v_e = RT_e/P_e = (0.2968\times 430)/357.6 = 0.35689 \text{ m}^3\text{/kg}$$

$$A_e = \dot{m}v_e/\mathbf{V}_e = \big((0.15 \times 0.35689)/300\big)\times10^{+6} = \mathbf{178\ mm^2}$$

9.4 A compressor is surrounded by cold R-134a so it works as an isothermal compressor. The inlet state is 0°C, 100 kPa and the exit state is saturated vapor. Find the specific heat transfer and specific work.

C.V. compressor. SSSF, single inlet and single exit flow.

Energy Eq.: $h_i + q = w + h_e$; Entropy Eq.: $s_i + q/T = s_e$

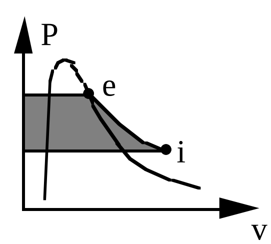
Inlet state: Table B.5.2, $h_i = 403.4$ kJ/kg, $s_i = 1.8281$ kJ/kg K

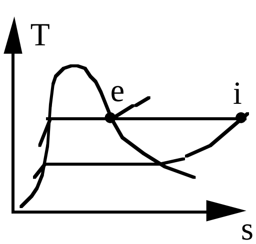
Exit state: Table B.5.1, $h_e = 398.36$ kJ/kg, $s_e = 1.7262$ kJ/kg K

$$q = T(s_e – s_i) = 273.15(1.7262 – 1.8281) = \mathbf{- 27.83\ kJ/kg}$$

$$w= 403.4 + (-27.83) – 398.36 = \mathbf{-22.8\ kJ/kg}$$

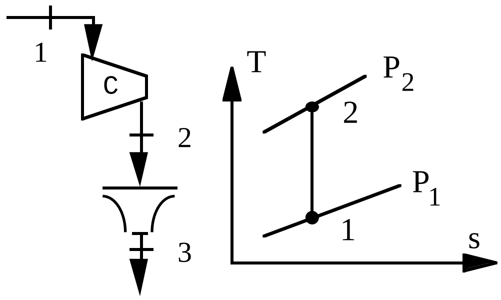
Explanation for the work term is in 9.3 Eq. (9.19)





9.5 Air at 100 kPa, 17°C is compressed to 400 kPa after which it is expanded through a nozzle back to the atmosphere. The compressor and the nozzle are both reversible and adiabatic and kinetic energy in/out of the compressor can be neglected. Find the compressor work and its exit temperature and find the nozzle exit velocity.

Solution:



SSSF separate control volumes around compressor and nozzle. For ideal compressor we have inlet : 1 and exit : 2

Adiabatic : $q = 0$.

Reversible: $s_{gen} = 0$

Energy Eq.: $h_1 + 0 = w_C + h_2$;

Entropy Eq.: $s_1 + 0/T + 0 = s_2$

$$-w_C = h_2 - h_1, \quad s_2 = s_1$$

State 1: $\Rightarrow$ Air Table A.7: $h_1 = 290.43$ kJ/kg

$$P_{r2} = P_{r1} \times P_2/P_1 = 0.9899 \times 400 / 100 = 3.98$$

State 2: $P_{r2} = 3.98$ in Table A.7 gives $T_2 = 430.5$ K, $h_2 = 432.3$ kJ/kg

$$\Rightarrow \quad -w_C = 432.3 - 290.43 = 141.86 \text{ kJ/kg}$$

The ideal nozzle then expands back down to state 1 (constant s) so energy equation gives:

$$\frac{1}{2}\mathbf{V}^2 = h_2 - h_1 = -w_C = 141860 \text{ J/kg} \quad \text{(remember conversion to J)}$$

$$\Rightarrow \quad \mathbf{V} = \sqrt{2\times 141860} = \mathbf{532.7\ m/s}$$

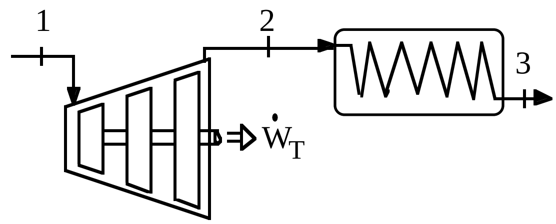
9.6 A small turbine delivers 150 kW and is supplied with steam at 700°C, 2 MPa. The exhaust passes through a heat exchanger where the pressure is 10 kPa and exits as saturated liquid. The turbine is reversible and adiabatic. Find the specific turbine work, and the heat transfer in the heat exchanger.

Continuity Eq.: (SSSF)

$\dot m_1 = \dot m_2 = \dot m_3 = \dot m$

Turbine: Energy Eq.:

$w_T = h_1 - h_2$



Entropy Eq.: $s_2 = s_1 + s_{T\ gen}$

Heat exch: Energy Eq.: $q = h_3 - h_2$, Entropy Eq.: $s_3 = s_2 + \int dq/T + s_{He\ gen}$

Inlet state: Table B.1.3 $h_1 = 3917.45$ kJ/kg, $s_1 = 7.9487$ kJ/kg K

Ideal turbine $s_{T\ gen} = 0$, $s_2 = s_1 = 7.9487 = s_{f2} + x\ s_{fg2}$

State 3: P = 10 kPa, $s_2 < s_g$ => saturated 2-phase in Table B.1.2

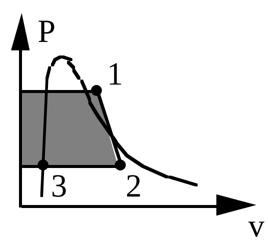
$\Rightarrow\ x_{2,s} = (s_1 - s_{f2})/s_{fg2} = (7.9487 - 0.6492)/7.501 = 0.9731$

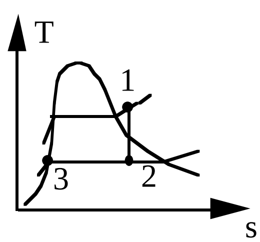
$\Rightarrow\ h_{2,s} = h_{f2} + x \times h_{fg2} = 191.8 + 0.9731 \times 2392.8 = 2520.35$ kJ/kg

$w_{T,s} = h_1 - h_{2,s} =$ **1397.05 kJ/kg**

$q = h_3 - h_{2,s} = 191.83 - 2520.35 =$ **-2328.5 kJ/kg**

Explanation for the work term is in 9.3 Eq. (9.19)





9.7 A counterflowing heat exchanger, shown in Fig. P9.7, is used to cool air at 540 K, 400 kPa to 360 K by using a 0.05 kg/s supply of water at 20°C, 200 kPa. The air flow is 0.5 kg/s in a 10-cm diameter pipe. Find the air inlet velocity, the water exit temperature, and total entropy generation in the process.

SSSF heat exchanger with constant pressure in each line.

Air in 1: Table A.7, $h_1 = 544.686$ kJ/kg, $s^o_{T1} = 7.46642$ kJ/kg K,

$$v_1 = RT/P = 0.287 \times 540/400 = 0.3824 \text{ m}^3/\text{kg}$$

Air out 2: $h_2 = 360.863$, $s^o_{T2} = 7.05276$

H_2O in 3: Table B.1.1 $h_3 = 83.96$, $s_3 = 0.2966$ H_2O out: 4

$A = \pi D^2/4 = 0.007854 \text{ m}^2$ => $\mathbf{V} = \dot{m}v/A =$ **24.34 m/s**

As the lines exchange energy select a control volume that includes both with no external heat transfer. Energy and entropy equations for the heat exchanger give

Energy Eq.: $\dot{m}_{air}(h_1 - h_2) = \dot{m}_{H2O}(h_4 - h_3)$

$$h_4 = 83.96 + (0.5/0.05)(544.69\text{-}360.86) = 1922.2 \text{ kJ/kg}$$

$h_4 < h_g \Rightarrow$ Table B.1.2 $x_4 = (1922.2\text{-}504.68)/2202 = 0.64375$

$T_4 = T_{sat}(P) =$ **120.23°C** , $s_4 = 1.530 + 0.64375 \times 5.597 = 5.1331$ kJ/kg K

Entropy Eq.: $0 = \dot{m}_{air}(s_1 - s_2) + \dot{m}_{H2O}(s_3 - s_4) + \dot{S}_{gen}$

$$\dot{S}_{gen} = \dot{m}_{H2O}(4.8365) - \dot{m}_{air}(0.41366) = \mathbf{0.02017 \text{ kW/K}}$$

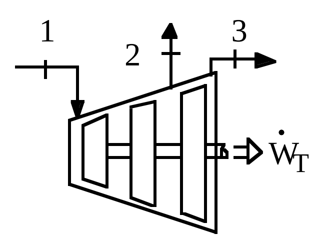
9.8 Analyse the steam turbine described in Problem 6.29. Is it possible?

C.V. Turbine. SSSF and adiabatic.

Continuity: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$;

Energy: $\dot{m}_1h_1 = \dot{m}_2h_2 + \dot{m}_3h_3 + \dot{W}$

Entropy: $\dot{m}_1s_1 + \dot{S}_{gen} = \dot{m}_2s_2 + \dot{m}_3s_3$



States from Table B.1.3: $s_1 = 6.6775$, $s_2 = 6.9562$, $s_3 = 7.14413$ kJ/kg K

$$\dot{S}_{gen} = 20 \times 6.9562 + 80 \times 7.14413 - 100 \times 6.6775 = 42.9 \text{ kW/K} \quad > 0$$

Since it is positive => possible.

Notice the entropy is increasing through turbine: $s_1 < s_2 < s_3$

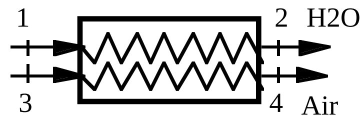
9.9 A coflowing heat exchanger has one line with 2 kg/s saturated water vapor at 100 kPa entering. The other line is 1 kg/s air at 200 kPa, 1200 K. The heat exchanger is very long so the two flows exit at the same temperature. Find the exit temperature by trial and error. Calculate the rate of entropy generation.

Solution:

C.V. Heat exchanger. No W, no external Q

Flows: $\dot{m}_1 = \dot{m}_2 = \dot{m}_{H_2O}$; $\dot{m}_3 = \dot{m}_4 = \dot{m}_{air}$

Energy: $\dot{m}_{H_2O}(h_2 - h_1) = \dot{m}_{air}(h_3 - h_4)$



State 1: Table B.1.2 $h_1 = 2675.5$ kJ/kg State 2: 100 kPa, T_2

State 3: Table A.7 $h_3 = 1277.8$ kJ/kg, State 4: 200 kPa, T_2

Only one unknown T_2 and one equation the energy equation:

$$2(h_2 - 2675.5) = 1(1277.8 - h_4) \quad => \quad 2h_2 + h_4 = 6628.8 \text{ kW}$$

At 500 K: $h_2 = 2902.0$, $h_4 = 503.36$ => LHS = 6307 too small

At 700 K: $h_2 = 3334.8$, $h_4 = 713.56$ => LHS = 7383 too large

Linear interpolation $T_2 = 560$ K, $h_2 = 3048.3$, $h_4 = 565.47$ => LHS = 6662

Final states are with $\mathbf{T_2 = 554.4\ K = 281\ °C}$

H2O: Table B.1.3, $h_2 = 3036.8$ kJ/kg, $s_2 = 8.1473$, $s_1 = 7.3593$ kJ/kg K

AIR: Table A.7, $h_4 = 559.65$ kJ/kg, $s_{T4} = 7.4936$, $s_{T3} = 8.3460$ kJ/kg K

The entropy balance equation is solved for the generation term:

$$\dot{S}_{gen} = \dot{m}_{H_2O}(s_2 - s_1) + \dot{m}_{air}(s_4 - s_3)$$

$$= 2(8.1473 - 7.3593) + 1(7.4936 - 8.3460) = \mathbf{0.724\ kW/K}$$

No pressure correction is needed as the air pressure for 4 and 3 is the same.

9.10 Atmospheric air at -45°C, 60 kPa enters the front diffuser of a jet engine with a velocity of 900 km/h and frontal area of 1 m^2. After the adiabatic diffuser the velocity is 20 m/s. Find the diffuser exit temperature and the maximum pressure possible.

C.V. Diffuser, SSSF single inlet and exit flow, no work or heat transfer.

Energy Eq.: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2$, and $h_e - h_i = C_p(T_e - T_i)$

Entropy Eq.: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$ (Reversible, adiabatic)

Heat capacity and ratio of specific heats from Table A.5 in the energy equation then gives:

$$1.004[\ T_e - (-45)] = 0.5[(900\times1000/3600)^2 - 20^2\ ]/1000 = 31.05 \text{ kJ/kg}$$

$$\Rightarrow \quad T_e = -14.05\ °C = \mathbf{259.1\ K}$$

Constant s: $P_e = P_i\,(T_e/T_i)^{\frac{k}{k-1}} = 60\ (259.1/228.1)^{3.5} = \mathbf{93.6\ kPa}$

9.11 A Hilch tube has an air inlet flow at 20°C, 200 kPa and two exit flows of 100 kPa, one at 0°C and the other at 40°C. The tube has no external heat transfer and no work and all the flows are SSSF and have negligible kinetic energy. Find the fraction of the inlet flow that comes out at 0°C. Is this setup possible?

C.V. The Hilch tube. SSSF, single inlet and two exit flows. No q or w.

Continuity Eq.: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$; Energy: $\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3$

Entropy: $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2 + \dot{m}_3 s_3$

States all given by temperature and pressure. Use constant heat capacity to evaluate changes in h and s. Solve for $x = \dot{m}_2/\dot{m}_1$ from the energy equation

$$\dot{m}_3/\dot{m}_1 = 1 - x; \qquad h_1 = x\, h_2 + (1-x)\, h_3$$

$$\Rightarrow \quad x = (h_1 - h_3)/(h_2 - h_3) = (T_1 - T_3)/(T_2 - T_3) = (20-40)/(0-40) = 0.5$$

Evaluate the entropy generation

$$\dot{S}_{gen}/\dot{m}_1 = x\, s_2 + (1-x)s_3 - s_1 = 0.5(s_2 - s_1) + 0.5(s_3 - s_1)$$

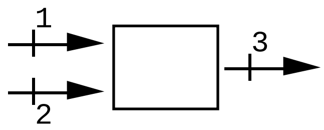
$$= 0.5\,[C_p \ln(T_2 / T_1) - R \ln(P_2 / P_1)] + 0.5[C_p \ln(T_3 / T_1) - R \ln(P_3/ P_1)]$$

$$= 0.5\left[1.004 \ln\left(\frac{273.15}{293.15}\right) - 0.287 \ln\left(\frac{100}{200}\right)\right]$$

$$+ 0.5\left[1.004 \ln\left(\frac{313.15}{293.15}\right) - 0.287 \ln\left(\frac{100}{200}\right)\right]$$

= **0.1966 kJ/kg K > 0** **So this is possible**.

9.12 Two flowstreams of water, one at 0.6 MPa, saturated vapor, and the other at 0.6 MPa, 600°C, mix adiabatically in a SSSF process to produce a single flow out at 0.6 MPa, 400°C. Find the total entropy generation for this process.



1: B.1.2 h_1 = 2756.8 kJ/kg, s_1 = 6.760 kJ/kg K

2: B.1.3 h_2 = 3700.9 kJ/kg, s_2 = 8.2674 kJ/kg K

3: B.1.3 h_3 = 3270.3 kJ/kg, s_3 = 7.7078 kJ/kg K

Cont.: $\dot{m}_3 = \dot{m}_1 + \dot{m}_2$, Energy Eq.: $\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$

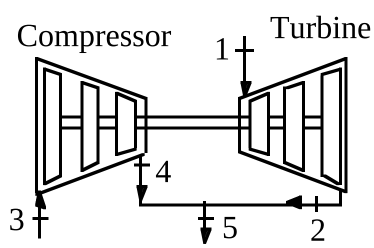
=> $\dot{m}_1/\dot{m}_3 = (h_3 - h_2) / (h_1 - h_2) = 0.456$

Entropy Eq.: $\dot{m}_3 s_3 = \dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{gen}$ =>

$\dot{S}_{gen}/\dot{m}_3 = s_3 - (\dot{m}_1/\dot{m}_3)\, s_1 - (\dot{m}_2/\dot{m}_3)\, s_2$

$= 7.7078 - 0.456 \times 6.760 - 0.544 \times 8.2674 =$ **0.128 kJ/kg K**

9.13 In a heat-driven refrigerator with ammonia as the working fluid, a turbine with inlet conditions of 2.0 MPa, 70°C is used to drive a compressor with inlet saturated vapor at –20°C. The exhausts, both at 1.2 MPa, are then mixed together. The ratio of the mass flow rate to the turbine to the total exit flow was measured to be 0.62. Can this be true?



C.V. Total: $\dot{m}_5 = \dot{m}_1 + \dot{m}_3$, Call $y = \dot{m}_1/\dot{m}_5$

Energy: $\dot{m}_5 h_5 = \dot{m}_1 h_1 + \dot{m}_3 h_3$,

Entropy: $\dot{m}_5 s_5 = \dot{m}_1 s_1 + \dot{m}_3 s_3 + \dot{S}_{C.V.,gen}$

$h_5 = y h_1 + (1-y) h_3$,

$s_5 = y s_1 + (1-y) s_3 + \dot{S}_{C.V.,gen}/\dot{m}_5$

$h_1 = 1542.7$, $s_1 = 4.982$, $h_3 = 1418.1$, $s_3 = 5.616$

$h_5 = 1495.4$, $P_5 = 1200$ kPa $\Rightarrow$ $s_5 = 5.056$

$\Rightarrow$ $\dot{S}_{C.V.,gen}/\dot{m}_5 = s_5 - y s_1 - (1-y) s_3 =$ **-0.1669 Impossible**

9.14 A diffuser is a steady-state, steady-flow device in which a fluid flowing at high velocity is decelerated such that the pressure increases in the process. Air at 120 kPa, 30°C enters a diffuser with velocity 200 m/s and exits with a velocity of 20 m/s. Assuming the process is reversible and adiabatic what are the exit pressure and temperature of the air?

C.V. Diffuser, SSSF single inlet and exit flow, no work or heat transfer.

Energy Eq.: $h_i + \mathbf{V}_i^2/2 = h_e + \mathbf{V}_e^2/2, \quad => \quad h_e - h_i = C_{Po}(T_e - T_i)$

Entropy Eq.: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$ (Reversible, adiabatic)

Energy equation then gives:

$C_{Po}(T_e - T_i) = 1.004(T_e - 303.2) = (200^2 - 20^2)/(2\times1000) \quad => \quad T_e = \mathbf{322.9\ K}$

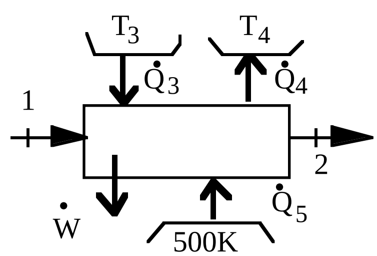
$$P_e = P_i(T_e/T_i)^{\frac{k}{k-1}} = 120(322.9/303.2)^{3.5} = \mathbf{149.6\ kPa}$$

9.15 A reversible SSSF device receives a flow of 1 kg/s air at 400 K, 450 kPa and the air leaves at 600 K, 100 kPa. Heat transfer of 800 kW is added from a 1000 K reservoir, 100 kW rejected at 350 K and some heat transfer takes place at 500 K. Find the heat transferred at 500 K and the rate of work produced.

C.V. Device, single inlet and exit flows.

Energy equation

$$\dot{m}h_1 + \dot{Q}_3 - \dot{Q}_4 + \dot{Q}_5 = \dot{m}h_2 + \dot{W}$$



Entropy equation with zero generation

$$\dot{m}\, s_1 + \dot{Q}_3/T_3 - \dot{Q}_4/T_4 + \dot{Q}_5/T_5 = \dot{m}s_2$$

$$\dot{Q}_5 = T_5\ [s_2 - s_1]\dot{m} + \frac{T_5}{T_4}\dot{Q}_4 - \frac{T_5}{T_3}\dot{Q}_3$$

$$= 500 \times 1\ (7.5764 - 7.1593 - 0.287 \ln \frac{100}{450}) + \frac{500}{350}\times 100 - \frac{500}{1000}\times 80$$

$$= 424.4 + 142.8 - 400 = 167.2\ \text{kW}$$

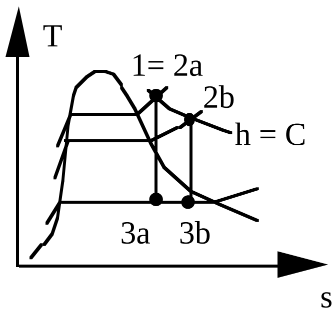
$\dot{W} = 1 \times (401.3 - 607.3) + 800 - 100 + 167.2 = \mathbf{661.2\ kW}$

9.16 One technique for operating a steam turbine in part-load power output is to throttle the steam to a lower pressure before it enters the turbine, as shown in Fig. P9.16. The steamline conditions are 2 MPa, 400°C, and the turbine exhaust pressure is fixed at 10 kPa. Assuming the expansion inside the turbine to be reversible and adiabatic, determine

a. The full-load specific work output of the turbine

b. The pressure the steam must be throttled to for 80% of full-load output

c. Show both processes in a *T–s* diagram.



a) C.V Turbine. Full load reversible

$s_3 = s_1 = 7.1271 = 0.6493 + x_{3a} \times 7.5009$

$\Rightarrow \quad x_{3a} = 0.8636$

$h_{3a} = 191.83 + 0.8636 \times 2392.8 = 2258.3$ kJ/kg

${}_1w_{3a} = h_1 - h_{3a}$

$= 3247.6 - 2258.3 =$ **989.3 kJ/kg**

b) $w_T = 0.80 \times 989.3 = 791.4 = 3247.6 - h_{3b}$

$h_{3b} = 2456.2 = 191.83 + x_{3b} \times 2392.8 \quad \Rightarrow \quad x_{3b} = 0.9463$

$s_{3b} = 0.6492 + 0.9463 \times 7.501 = 7.7474$ kJ/kg

$$\left.\begin{array}{l} s_{2b} = s_{3b} = 7.7474 \\ h_{2b} = h_1 = 3247.6 \end{array}\right\} \rightarrow \begin{array}{l} P_{2b} = \mathbf{510\ kPa} \\ \&\ T_{2b} = 388.4°C \end{array}$$

9.17 Carbon dioxide at 300 K, 200 kPa is brought through a SSSF device where it is heated to 500 K by a 600 K reservoir in a constant pressure process. Find the specific work, heat transfer and entropy generation.

C.V. Heater and walls out to the source. SSSF single inlet and exit flows.

Since the pressure is constant and there are no changes in kinetic or potential energy between the inlet and exit flows the work is zero. **w = 0**

Continuity: $\dot{m}_i = \dot{m}_e = \dot{m}$; Energy Eq.: $h_i + q = h_e$;

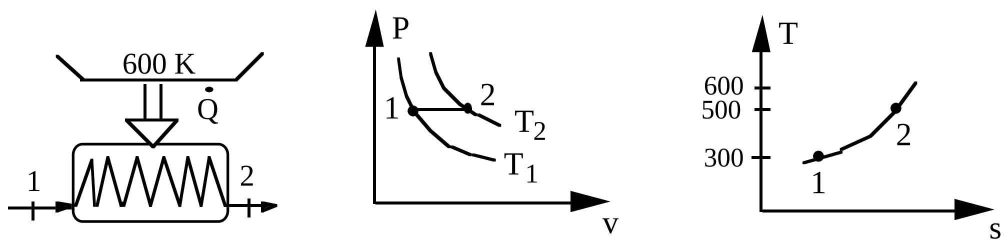
Entropy Eq.: $s_i + \int dq/T + s_{gen} = s_e = s_i + q/T_{source} + s_{gen}$

Properties are from Table A.8 (mole basis so divide by M = 44.01)

$q = h_e - h_i = (8305 - 69)/44.01 = \mathbf{187.1\ kJ/kg}$

$s_{gen} = s_e - s_i - q/T_{source} = (234.9 - 214.02)/44.01 - 187.1/600$

$= 0.4744 - 0.312 = \mathbf{0.1626\ kJ/kg\ K}$



9.18 One type of feedwater heater for preheating the water before entering a boiler operates on the principle of mixing the water with steam that has been bled from the turbine. For the states as shown in Fig. P9.18, calculate the rate of net entropy increase for the process, assuming the process to be steady flow and adiabatic.

CV: Feedwater heater, SSSF, no external heat transfer.

Continuity Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

Energy Eq.,1st law: $\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_1)h_2 = \dot{m}_3 h_3$

Properties: All states are given by (P,T) table B.1.1 and B.1.3

$h_1 = 168.42,\ \ h_2 = 2828\ ,\ \ h_3 = 675.8$ all kJ/kg

$s_1 = 0.572,\ \ s_2 = 6.694\ ,\ \ s_3 = 1.9422$ all kJ/kg K

Solve for the flow rate from the energy equation

$$\dot{m}_1 = \frac{\dot{m}_3(h_3 - h_2)}{(h_1 - h_2)} = \frac{4(675.8 - 2828)}{(168.42 - 2828)} = 3.237 \text{ kg/s}$$

$$\Rightarrow \quad \dot{m}_2 = 4 - 3.237 = 0.763 \text{ kg/s}$$

The second law for SSSF, $\dot{S}_{CV} = 0$, and no heat transfer

$\dot{S}_{C.V.,gen} = \dot{S}_{SURR} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2$

$= 4(1.9422) - 3.237(0.572) - 0.763(6.694) = \mathbf{0.8097\ kJ/K\ s}$

9.19 Air at 327°C, 400 kPa with a volume flow 1 m^3/s runs through an adiabatic turbine with exhaust pressure of 100 kPa. Neglect kinetic energies and use constant specific heats. Find the lowest and highest possible exit temperature. For each case find also the rate of work and the rate of entropy generation.

C.V Turbine. SSSF, single inlet and exit flows, q = 0.

Inlet state: (T, P) $\quad v_i = RT_i / P_i = 0.287 \times 600/400 = 0.4305\ m^3/kg$

$\dot{m} = \dot{V}/v_i = 1/0.4305 = 2.323$ kg/s

The lowest exit T is for max work out i.e. reversible case

Constant s => $\quad T_e = T_i(P_e/P_i)^{\frac{k-1}{k}} = 600 \times (100/400)^{0.2857} = \mathbf{403.8\ K}$

$\Rightarrow \quad w = h_i - h_e = C_{Po}(T_i - T_e) = 1.004 \times (600 - 403.8) = 197$ kJ/kg

$\dot{W}_T = \dot{m}w = 0.4305 \times 197 = \mathbf{457.6\ kW}$ and $\quad \dot{\mathbf{S}}_{\mathbf{gen}} \mathbf{= 0}$

Highest exit T occurs when there is no work out, throttling

$q = \varnothing; \quad w = \varnothing \quad \Rightarrow \quad h_i - h_e = 0 \quad \Rightarrow \quad T_e = T_i = \mathbf{600\ K}$

$\dot{S}_{gen} = \dot{m}(s_e - s_i) = -\dot{m}R \ln P_e/P_i = -2.323 \times 0.287 \ln \frac{100}{400} = \mathbf{0.924\ kW/K}$

9.20 A certain industrial process requires a steady supply of saturated vapor steam at 200 kPa, at a rate of 0.5 kg/s. Also required is a steady supply of compressed air at 500 kPa, at a rate of 0.1 kg/s. Both are to be supplied by the process shown in Fig. P9.20. Steam is expanded in a turbine to supply the power needed to drive the air compressor, and the exhaust steam exits the turbine at the desired state. Air into the compressor is at the ambient conditions, 100 kPa, 20°C. Give the required steam inlet pressure and temperature, assuming that both the turbine and the compressor are reversible and adiabatic.

C.V. Each device. SSSF. Both adiabatic (q = 0), reversible ($s_{gen} = 0$)

Compressor: $s_4 = s_3 \quad => \quad T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 293.2\left(\frac{500}{100}\right)^{0.286} = 464.6$ K

$\dot{W}_C = \dot{m}_3(h_3 - h_4) = 0.1 \times 1.004(293.2 - 464.6) = -17.2$ kW

Turbine: Energy: $\dot{W}_T = +17.2\ kW = \dot{m}_1(h_1 - h_2)$; Entropy: $s_2 = s_1$

Table B.1.2: $P_2 = 200$ kPa, $x_2 = 1$ => $h_2 = 2706.6$, $s_2 = 7.1271$

$h_1 = 2706.6 + 17.2/0.5 = 2741.0$ kJ/kg

$s_1 = s_2 = 7.1271$ kJ/kg K $\quad$ At $h_1, s_1 \rightarrow$ $P_1 = \mathbf{242\ kPa}$, $T_1 = \mathbf{138.3°C}$

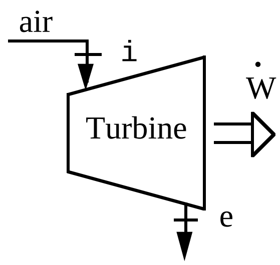
9.21 Air enters a turbine at 800 kPa, 1200 K, and expands in a reversible adiabatic process to 100 kPa. Calculate the exit temperature and the work output per kilogram of air, using

a. The ideal gas tables, Table A.7

b. Constant specific heat, value at 300 K from table A.5

c. Constant specific heat, value at an intermediate temperature from Fig. 5.10

Discuss why the method of part (b) gives a poor value for the exit temperature and yet a relatively good value for the work output.



C.V. Air turbine. Adiabatic; $q = 0$, reversible: $s_{gen} = 0$

Energy: $w_T = h_i - h_e$, Entropy Eq.: $s_e = s_i$

a) Table A.7: $h_i = 1277.8$, $P_{ri} = 191.174$

$\Rightarrow P_{re} = P_{ri} \times P_e/P_i = 191.174 \times 100/800 = 23.897$

$\Rightarrow T_e = \mathbf{706\ K}$, $h_e = 719.9$ kJ/kg

$w = h_i - h_e = \mathbf{557.9\ kJ/kg}$

b) $T_e = T_i\,(P_e/P_i)^{\frac{k-1}{k}} = 1200\left(\frac{100}{800}\right)^{0.286} = \mathbf{662.1\ K}$

$w = C_{Po}(T_i - T_e) = 1.004(1200 - 662.1) = \mathbf{539.8\ kJ/kg}$

c) Fig. 5.10 at ~ 1000 K: $\bar{C}_{Po} \sim 32.5$, $\bar{C}_{Vo} = \bar{C}_{Po} - \bar{R} \sim 24.2$

$k = \bar{C}_{Po}/\bar{C}_{Vo} \sim 1.343$, $T_e = 1200\,(100/800)^{0.255} = \mathbf{706.1\ K}$

$w = (32.5/28.97)(1200 - 706.1) = \mathbf{554.1\ kJ/kg}$

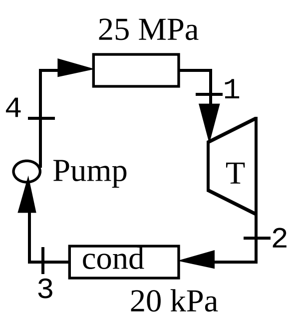
In b) $k = 1.4$ is too large and C_p too small.

9.22 Consider a steam turbine power plant operating at supercritical pressure, as shown in Fig. P9.22. As a first approximation, it may be assumed that the turbine and the pump processes are reversible and adiabatic. Neglecting any changes in kinetic and potential energies, calculate

a. The specific turbine work output and the turbine exit state

b. The pump work input and enthalpy at the pump exit state

c. The thermal efficiency of the cycle



a) 1: $h_1 = 3777.51$, $s_1 = 6.67074$

2_s: $s_{2s} = s_1$, => $\mathbf{x_2} = (s - s_f)/s_{fg}$

$= (6.6707-0.8319)/7.0766 = \mathbf{0.8251}$

$h_{2s} = 251.4 + 0.8251*2358.33 = \mathbf{2197.2}$

$w_{T,s} = h_1 - h_{2s} = \mathbf{1580.3\ kJ/kg}$

b) 3: Sat. liquid $h_3 = 167.56$, $s_3 = 0.5724$

4_s: $s_{4s} = s_3$, P => T = 40.75°C, $h_{4s} = \mathbf{192.6}$

$w_{P,s} = h_{4s} - h_3 = \mathbf{25.0\ kJ/kg}$

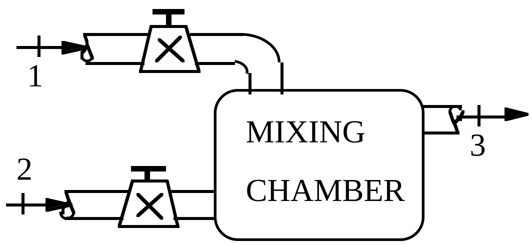
c) $\eta_{TH} = w_{net}/q_H = (w_{T,s} - w_{P,s})/(h_1 - h_{4s}) = \frac{1555.3}{3584.9} = \mathbf{0.434}$

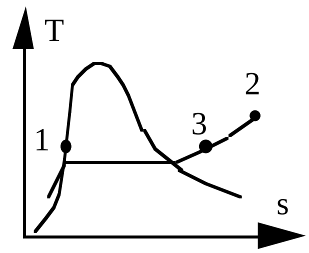
9.23 A supply of 5 kg/s ammonia at 500 kPa, 20°C is needed. Two sources are available one is saturated liquid at 20°C and the other is at 500 kPa, 140°C. Flows from the two sources are fed through valves to an insulated SSSFmixing chamber, which then produces the desired output state. Find the two source mass flow rates and the total rate of entropy generation by this setup.

C.V. mixing chamber + valve. SSSF, no heat transfer, no work.

Continuity Eq.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$; Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

Entropy Eq.: $\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{gen} = \dot{m}_3 s_3$





State 1: Table B.2.1 $h_1 = 273.4$ kJ/kg, $s_1 = 1.0408$ kJ/kg K

State 2: Table B.2.2 $h_2 = 1773.8$ kJ/kg, $s_2 = 6.2422$ kJ/kg K

State 3: Table B.2.2 $h_3 = 1488.3$ kJ/kg, $s_3 = 5.4244$ kJ/kg K

$\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_2) h_2 = \dot{m}_3 h_3$ => $\dot{m}_1 = \dot{m}_3 \dfrac{h_3 - h_2}{h_1 - h_2} = 0.952$ kg/s

$\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 4.05$ kg/s

$\dot{S}_{gen} = 5 \times 5.4244 - 0.95 \times 1.0408 - 4.05 \times 6.2422 =$ **0.852 kW/K**

9.24 A turbo charger boosts the inlet air pressure to an automobile engine. It consists of an exhaust gas driven turbine directly connected to an air compressor, as shown in Fig. P9.24. For a certain engine load the conditions are given in the figure. Assume that both the turbine and the compressor are reversible and adiabatic having also the same mass flow rate. Calculate the turbine exit temperature and power output. Find also the compressor exit pressure and temperature.

CV: Turbine, SSSF, 1 inlet and 1 exit, adibatic: $q = 0$, reversible: $s_{gen} = 0$

Energy: $w_T = h_3 - h_4$, Entropy Eq.: $s_4 = s_3$

$$s_4 = s_3 \;\rightarrow\; T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 923.2 \left(\frac{100}{170}\right)^{0.286} = \mathbf{793.2\ K}$$

$$w_T = h_3 - h_4 = C_{P0}(T_3 - T_4) = 1.004(923.2 - 793.2) = 130.5 \text{ kJ/kg}$$

$$\dot{W}_T = \dot{m}w_T = \mathbf{13.05\ kW}$$

C.V. Compressor, SSSF 1 inlet and 1 exit, same flow rate as turbine.

Energy: $-w_C = h_2 - h_1$, Entropy Eq.: $s_2 = s_1$

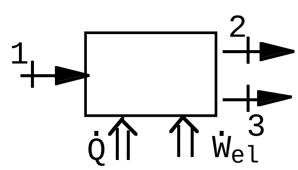
$$-w_C = w_T = 130.5 = C_{P0}(T_2 - T_1) = 1.004(T_2 - 303.2)$$

$$T_2 = \mathbf{433.2\ K}$$

$$s_2 = s_1 \;\rightarrow\; P_2 = P_1(T_2/T_1)^{\frac{k}{k-1}} = 100\left(\frac{433.2}{303.2}\right)^{3.5} = \mathbf{348.7\ kPa}$$

9.25 A stream of ammonia enters a steady flow device at 100 kPa, 50°C, at the rate of 1 kg/s. Two streams exit the device at equal mass flow rates; one is at 200 kPa, 50°C, and the other as saturated liquid at 10°C. It is claimed that the device operates in a room at 25°C on an electrical power input of 250 kW. Is this possible?

Control volume: SSSF device out to ambient 25°C.



$$\dot{m}_1h_1 + \dot{Q} + \dot{W}_{el} = \dot{m}_2h_2 + \dot{m}_3h_3$$

$$\dot{m}_1s_1 + \dot{Q}/T_{room} + \dot{S}_{gen} = \dot{m}_2s_2 + \dot{m}_3s_3$$

State 1: Table B.2.2, $h_1 = 1581.2$, $s_1 = 6.4943$

2: $h_2 = 1576.6$, $s_2 = 6.1453$, 3: $h_3 = 226.97$, $s_3 = 0.8779$

$$\dot{Q} = 0.5 \times 1576.6 + 0.5 \times 226.97 - 1 \times 1581.2 - 250 = -929.4 \text{ kW}$$

$$\dot{S}_{gen} = 0.5\times6.1453 + 0.5 \times 0.8779 - 1 \times 6.4943 - (-929.4)/298.15$$

$$= 0.1345 \text{ kW/K} > 0$$

since $\dot{S}_{gen} > 0$ this is possible

9.26 An initially empty 0.1 m^3 cannister is filled with R-12 from a line flowing saturated liquid at −5°C. This is done quickly such that the process is adiabatic. Find the final mass, liquid and vapor volumes, if any, in the cannister. Is the process reversible?

C.V. cannister USUF where: ${}_1Q_2 = \emptyset$; ${}_1W_2 = \emptyset$; $m_1 = \emptyset$

Mass: $m_2 - \emptyset = m_{in}$; Energy: $m_2u_2 - \emptyset = m_{in}h_{line} + \emptyset + \emptyset \;\Rightarrow\; u_2 = h_{line}$

2: $P_2 = P_L$; $u_2 = h_L \Rightarrow$ 2 phase $u_2 > u_f$; $u_2 = u_f + x_2u_{fg}$

Table B.3.1: $u_f = 31.26$; $u_{fg} = 137.16$; $h_f = 31.45$ all kJ/kg

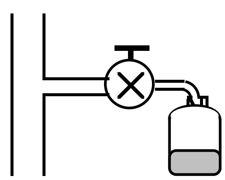
$x_2 = (31.45 - 31.26)/137.16 = 0.001385$

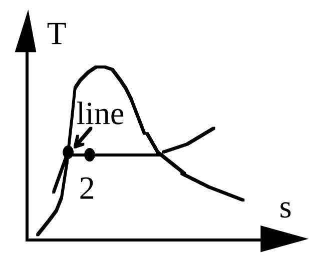
$\Rightarrow v_2 = v_f + x_2v_{fg} = 0.000708 + 0.001385\times0.06426 = 0.000797\ m^3/kg$

$\Rightarrow m_2 = V/v_2 =$ **125.47 kg** ; $m_f = 125.296$ kg; $m_g = 0.174$ kg

$V_f = m_fv_f =$ **0.0887** m^3; $V_g = m_gv_g =$ **0.0113 m^3**

Process is irreversible (throttling) $s_2 > s_f$





9.27 Air from a line at 12 MPa, 15°C, flows into a 500-L rigid tank that initially contained air at ambient conditions, 100 kPa, 15°C. The process occurs rapidly and is essentially adiabatic. The valve is closed when the pressure inside reaches some value, P_2. The tank eventually cools to room temperature, at which time the pressure inside is 5 MPa. What is the pressure P_2? What is the net entropy change for the overall process?

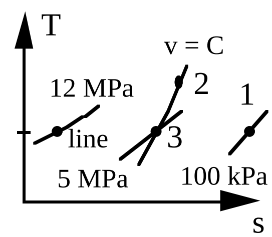
CV: Tank. Mass flows in, so this is USUF. Find the mass first

$m_1 = P_1V/RT_1 = 100\times0.5/(0.287\times288.2) = 0.604$ kg

Fill to P_2, then cool to $T_3 = 15°C$, $P_3 = 5$ MPa

$m_3 = m_2 = P_3V/RT_3$

$= (5000 \times 0.5)/(0.287 \times 288.2) = 30.225$ kg



Mass: $m_i = m_2 - m_1 = 30.225 - 0.604 = 29.621$ kg

In the process 1-2 heat transfer = 0

1st law: $m_ih_i = m_2u_2 - m_1u_1$; $m_iC_{P0}T_i = m_2C_{V0}T_2 - m_1C_{V0}T_1$

$$T_2 = \frac{(29.621\times1.004 + 0.604\times0.717)\times288.2}{30.225 \times 0.717} = 401.2 \text{ K}$$

$P_2 = m_2RT_2/V = (30.225 \times 0.287 \times 401.2)/0.5 =$ **6.960 MPa**

Consider now the total process from the start to the finish at state 3.

Energy: $Q_{CV} + m_ih_i = m_2u_3 - m_1u_1 = m_2h_3 - m_1h_1 - (P_3 - P_1)V$

But, since $T_i = T_3 = T_1$, $m_ih_i = m_2h_3 - m_1h_1$

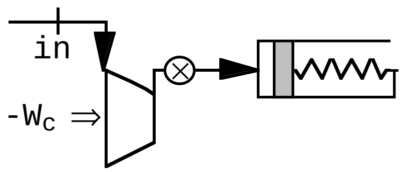
$\Rightarrow Q_{CV} = -(P_3 - P_1)V = -(5000 - 100)0.5 = -2450$ kJ

$\Delta S_{NET} = m_3s_3 - m_1s_1 - m_is_i - Q_{CV}/T_0 = m_3(s_3 - s_i) - m_1(s_1 - s_i) - Q_{CV}/T_0$

$$= 30.225\left[0\text{-}0.287\ln\frac{5}{12}\right]\text{-}\ 0.604\left[0\text{-}0.287\ln\frac{0.1}{12}\right] + (2450 / 288.2)$$

= **15.265 kJ/K**

9.28 An initially empty spring-loaded piston/cylinder requires 100 kPa to float the piston. A compressor with a line and valve now charges the cylinder with water to a final pressure of 1.4 MPa at which point the volume is 0.6 m^3, state 2. The inlet condition to the reversible adiabatic compressor is saturated vapor at 100 kPa. After charging the valve is closed and the water eventually cools to room temperature, 20°C, state 3. Find the final mass of water, the piston work from 1 to 2, the required compressor work, and the final pressure, P_3.



Process 1→2: USUF, adiabatic.
for C.V. compressor + cylinder
Assume process is reversible

Continuity: $m_2 - 0 = m_{in}$, Energy: $m_2u_2 - \emptyset = (m_{in}h_{in}) - W_c - {}_1W_2$

Entropy Eq.: $m_2s_2 - \emptyset = m_{in}s_{in} + 0 \quad \Rightarrow \quad s_2 = s_{in}$

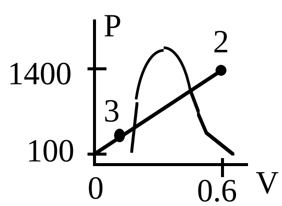
Inlet state: Table B.1.2, h_{in} = 2675.5 kJ/kg, s_{in} = 7.3594 kJ/kg K

$${}_1W_2 = \int PdV = \frac{1}{2}(P_{float} + P_2)(V_2 - \emptyset) = \frac{1}{2}(100+1400)0.6 = \mathbf{450\ kJ}$$

State 2: P_2 , $s_2 = s_{in}$ Table B.1.3 $\Rightarrow$ v_2 = 0.2243, u_2 = 2984.4 kJ/kg

$m_2 = V_2/v_2 = 0.6/0.2243 =$ **2.675 kg**

$W_c = m_{in}h_{in} - m_2u_2 - {}_1W_2 = 2.675 \times (2675.5 - 2984.4) - 450 =$ **-1276.3 kJ**



State 3 must be on line & 20°C

Assume 2-phase ⇒ $P_3 = P_{sat}(20°C)$ = 2.339 kPa

less than P_{float} so compressed liquid

Table B.1.1: $v_3 \cong v_f(20°C) = 0.001002 \quad \Rightarrow \quad V_3 = m_3v_3 = 0.00268\ m^3$

On line: $P_3 = 100 + (1400 - 100) \times 0.00268/0.6 =$ **105.8 kPa**

9.29 An initially empty cannister of volume 0.2 m^3 is filled with carbon dioxide from a line at 1000 kPa, 500 K. Assume the process is adiabatic and the flow continues until it stops by itself. Find the final mass and temperature of the carbon dioxide in the cannister and the total entropy generated by the process.

C.V. Cannister + valve out to line. No boundary/shaft work, $m_1 = 0$; $Q = 0$.

Continuity Eq.: $m_2 - 0 = m_i$ Energy: $m_2 u_2 - 0 = m_i h_i$

Entropy Eq.: $m_2 s_2 - 0 = m_i s_i + {}_1S_{2\ gen}$

State 2: $P_2 = P_i$ and $u_2 = h_i = h_{line} = h_2 - RT_2$ (ideal gas)

To reduce or eliminate guess use: $h_2 - h_{line} = C_{Po}(T_2 - T_{line})$

Energy Eq. becomes: $C_{Po}(T_2 - T_{line}) - RT_2 = 0$

$T_2 = T_{line}\ C_{Po}/(C_{Po} - R) = T_{line}\ C_{Po}/C_{Vo} = k\ T_{line}$

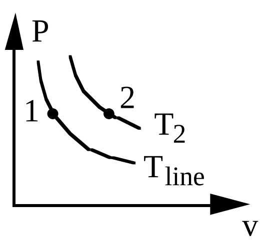
Use A.5: $C_P = 0.842$, $k = 1.289$ => $T_2 = 1.289 \times 500 =$ **644 K**

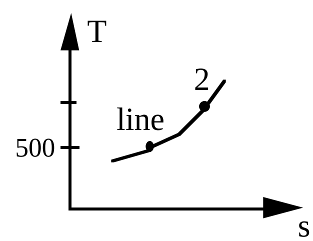
$m_2 = P_2V/RT_2 = 1000 \times 0.2/(0.1889 \times 644) =$ **1.644 kg**

${}_1S_{2\ gen} = m_2 (s_2 - s_i) = m_2[\ C_P \ln(T_2 / T_{line}) - R \ln(P_2 / P_{line})]$

$= 1.644[0.842 \times \ln(1.289) - 0] =$ **0.351 kJ/K**

If we use A.8 at 550 K: $C_P = 1.045$, $k = 1.22$ => $T_2 = 610$ K, $m_2 = 1.735$ kg





9.30 A 1-m^3 rigid tank contains 100 kg R-22 at ambient temperature, 15°C. A valve on top of the tank is opened, and saturated vapor is throttled to ambient pressure, 100 kPa, and flows to a collector system. During the process the temperature inside the tank remains at 15°C. The valve is closed when no more liquid remains inside. Calculate the heat transfer to the tank and total entropy generation in the process.

C.V. Tank out to surroundings. This is USUF. Rigid tank so no work term.

Continuity Eq.: $m_2 - m_1 = -\,m_e$;

Energy Eq.: $m_2u_2 - m_1u_1 = Q_{CV} - m_eh_e$

Entropy Eq.: $m_2s_2 - m_1s_1 = Q_{CV}/T_{SUR} - m_es_e + S_{gen}$

State 1: Table B.3.1, $v_1 = V_1/m_1 = 1/100 = 0.000812 + x_1\ 0.02918$

$x_1 = 0.3149$, $u_1 = 61.88 + 0.3149 \times 169.47 = 115.25$

$s_1 = 0.2382 + 0.3149 \times 0.668 = 0.44855$; $h_e = h_g = 255.0$

State 2: $v_2 = v_g = 0.02999$, $u_2 = u_g = 231.35$, $s_2 = 0.9062$

Exit state: $h_e = 255.0$, $P_e = 100$ kPa $\rightarrow$ $T_e = -4.7°C$, $s_e = 1.0917$

$m_2 = 1/0.02999 = 33.34$ kg; $m_e = 100 - 33.34 = 66.66$ kg

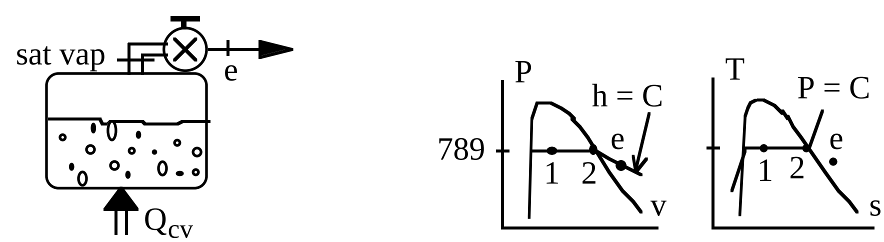
$Q_{CV} = m_2u_2 - m_1u_1 + m_eh_e$

$= 33.34\times231.35 - 100\times115.25 + 66.66\times255 =$ **13 186 kJ**

$\Delta S_{CV} = m_2s_2 - m_1s_1 = 33.34(0.9062) - 100(0.44855) = -14.642$

$\Delta S_{SUR} = -\,Q_{CV}/T_{SUR} + m_es_e = -13186/288.2 + 66.66(1.0917) = +27.012$

$S_{gen} = \Delta S_{NET} = -14.642 + 27.012 =$ **+12.37 kJ/K**



9.31 An old abandoned saltmine, 100000 m^3 in volume, contains air at 290 K, 100 kPa. The mine is used for energy storage so the local power plant pumps it up to 2.1 MPa using outside air at 290 K, 100 kPa. Assume the pump is ideal and the process is adiabatic. Find the final mass and temperature of the air and the required pump work. Overnight, the air in the mine cools down to 400 K. Find the final pressure and heat transfer.

(USUF) C.V. = Air in mine + pump

Continuity Eq.: $m_2 - m_1 = m_{in}$

Energy: $m_2u_2 - m_1u_1 = {}_1Q_2 - {}_1W_2 + m_{in}h_{in}$

Entropy: $m_2s_2 - m_1s_1 = \int dQ/T + {}_1S_{2\ gen} + m_{in}s_{in}$

Process: Adiabatic ${}_1Q_2 = 0$, Process ideal ${}_1S_{2\ gen} = 0$, $s_1 = s_{in}$

$\Rightarrow\ m_2s_2 = m_1s_1 + m_{in}s_{in} = (m_1 + m_{in})s_1 = m_2s_1 \ \Rightarrow\ s_2 = s_1$

Const. s $\Rightarrow P_{r2} = P_{r1}P_2/P_1 = 0.9899(21) = 20.788$

$\Rightarrow T_2 =$ **680 K** , $u_2 = 496.97$ kJ/kg

$m_1 = P_1V_1/RT_1 = 100\times10^5/(0.287 \times 290) = 1.20149\times10^5$ kg

$m_2 = P_2V_2/RT_2 = 100 \times 21\times10^5/(0.287 \times 680) =$ $\mathbf{10.760\times10^5}$ **kg**

$\Rightarrow\ m_{in} = 9.5585\times10^5$ kg

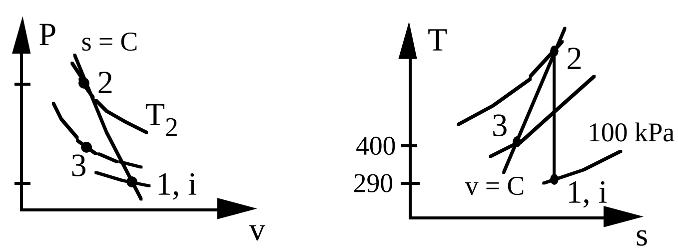
${}_1W_2 = m_{in}h_{in} + m_1u_1 - m_2u_2$

$= m_{in}(290.43) + m_1(207.19) - m_2(496.97) =$ $\mathbf{-2.322\times10^8}$ **kJ**

$2\to3$: Process : $V_3 = V_2 = V_1 \ \Rightarrow\ {}_2W_3 = 0$

$P_3 = P_2T_3/T_2 =$ **1235 kPa**

${}_2Q_3 = m_2(u_3 - u_2) = 10.760\times10^5(286.49 - 496.97) =$ $\mathbf{-2.265\times10^8}$ **kJ**



9.32 A rigid steel bottle, $V = 0.25\ m^3$, contains air at 100 kPa, 300 K. The bottle is now charged with air from a line at 260 K, 6 MPa to a bottle pressure of 5 MPa, state 2, and the valve is closed. Assume that the process is adiabatic, and the charge always is uniform. In storage, the bottle slowly returns to room temperature at 300 K, state 3. Find the final mass, the temperature T_2, the final pressure P_3, the heat transfer ${}_1Q_3$ and the total entropy generation.

C.V. Bottle. Flow in, USUF, no work, no heat transfer.

Continuity Eq.: $m_2 - m_1 = m_{in}$; Energy Eq.: $m_2u_2 - m_1u_1 = m_{in}h_{in}$

State 1 and inlet: Table A.7, $u_1 = 214.36$, $h_{in} = 260.32$

$$m_1 = P_1V/RT_1 = (100 \times 0.25)/(0.287 \times 300) = 0.290 \text{ kg}$$

$$m_2 = P_2V/RT_2 = 5000 \times 0.25/(0.287 \times T_2) = 4355.4/T_2$$

Substitute into energy equation

$$u_2 + 0.00306\ T_2 = 260.32$$

Now trial and error on T_2

$T_2 = 360$ => LHS = 258.63 (low); $T_2 = 370$ => LHS = 265.88 (high)

Interpolation $T_2 = 362.3$ K (LHS = 260.3 OK)

$m_2 = 4355.4/362.3 = 12.022$ kg ; $P_3 = m_2RT_3/V =$ **4140 kPa**

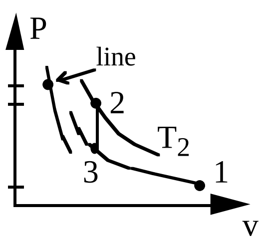
${}_1Q_3 = m_2u_3 - m_1u_1 - m_{in}h_{in} = (12.022 - 0.29)\ 214.36 - 11.732 \times 260.32$

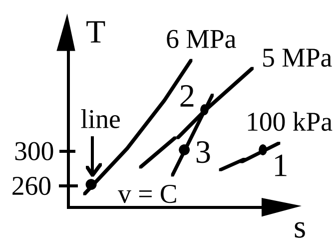
$=$ **-539.2 kJ**

$S_{gen} = m_2s_3 - m_1s_1 - m_{in}s_{in} - {}_1Q_3/T = m_2(s_3 - s_{in}) - m_1(s_1 - s_{in}) - {}_1Q_3/T$

$= 12.022[6.8693 - 6.7256 - R \ln(4140/6000)]$

$- 0.29[6.8693 - 6.7256 - R \ln(100/6000)] + 539.2/300 =$ **4.423 kJ/K**





9.33 An insulated 2 m^3 tank is to be charged with R-134a from a line flowing the refrigerant at 3 MPa. The tank is initially evacuated, and the valve is closed when the pressure inside the tank reaches 3 MPa. The line is supplied by an insulated compressor that takes in R-134a at 5°C, quality of 96.5 %, and compresses it to 3 MPa in a reversible process. Calculate the total work input to the compressor to charge the tank.

C.V.: Compressor, R-134a. SSSF, 1 inlet and 1 exit, no heat transfer.

1st Law: $q_c + h_1 = h_2 + w_c$; Entropy Eq.: $s_1 + \int dq/T + s_{gen} = s_2$

inlet: $T_1 = 5^oC$, $x_1 = 0.965$ use Table B.5.1

$s_1 = s_f + x_1 s_{fg} = 1.0243 + 0.965 \times 0.6995 = 1.6993$ kJ/kg K,

$h_1 = h_f + x_1 h_{fg} = 206.8 + 0.965 \times 194.6 = 394.6$ kJ/kg

exit: $P_2 = 3$ MPa

Assume process is ideal $q_c = 0$ => $s_2 = s_1 = 1.6993$ kJ/kg K;

$T_2 = 90^oC$, $h_2 = 436.2$ kJ/kg

$w_c = h_1 - h_2 = -41.6$ kJ/kg

C.V.: Tank; $V_T = 2\ m^3$, $P_T = 3$ MPa

1st Law: $Q + m_i h_i = m_2 u_2 - m_1 u_1 + m_e h_e + W$;

$Q=0$, $W=0$, $m_e = 0$, $m_1=0$, $m_2=m_i$

$u_2 = h_i = 436.2$ kJ/kg

$P_T = 3$ MPa, $u_2 = 436.2$ kJkg ‡ $T_T = 101.9^oC$, $v_T = 0.006783 m^3/kg$

$m_T = V_T/v_T = 294.84$ kg; $-W_c = m_T(-w_c) =$ **12295 kJ**

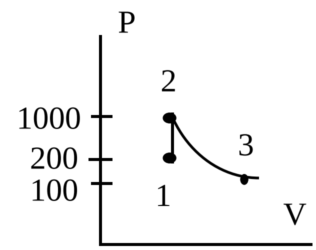
9.34 A horizontal, insulated cylinder has a frictionless piston held against stops by an external force of 500 kN. The piston cross-sectional area is 0.5 m^2, and the initial volume is 0.25 m^3. Argon gas in the cylinder is at 200 kPa, 100°C. A valve is now opened to a line flowing argon at 1.2 MPa, 200°C, and gas flows in until the cylinder pressure just balances the external force, at which point the valve is closed. The external force is now slowly reduced so the gas expands moving the piston to a final pressure of 100 kPa. Find the final temperature of the argon and the work done during the overall process.

The process 1 to 2 has inlet flow, no work (volume constant) and no heat transfer.

Cont.: $m_2 - m_1 = m_i$ Energy: $m_2 u_2 - m_1 u_1 = m_i h_i$

$m_1 = P_1V_1/RT_1 = 200 \times 0.25/(0.2081 \times 373.15) = 0.644$ kg

Force balance: $P_2A = F \Rightarrow P_2 = \dfrac{500}{0.5} = 1000$ kPa



For argon use constant heat capacities so the energy equation is:

$$m_2\ C_{Vo}\, T_2 - m_1\, C_{Vo}\, T_1 = (m_2 - m_1)\, C_{Po}\, T_{in}$$

We know P_2 so only 1 unknown for state 2.

Use ideal gas law to write

$m_2T_2 = P_2V_1/R$ and $m_1 T_1 = P_1V_1/R$

and divide the energy equation with C_{Vo} to solve for the change in mass

$$(P_2 V_1 - P_1V_1)/R = (m_2 - m_1)(C_{Po}/C_{Vo})\, T_{in}$$

$$(m_2 - m_1) = (P_2 - P_1)V_1/(R\, k\, T_{in})$$

$$= (1000 - 200)\times 0.25/(0.2081\times 1.667\times 473.15) = 1.219 \text{ kg}$$

$$m_2 = 1.219 + 0.644 = 1.863 \text{ kg.}$$

$$T_2 = P_2V_1/(m_2R) = 1000\times 0.25/(1.863\times 0.2081) = 645 \text{ K}$$

$$T_3 = T_2(P_3/P_2)^{\frac{k-1}{k}} = 6\ 45 \times (100/1000)^{0.4} = 256.8 \text{ K}$$

$${}_1W_3 = {}_1W_2 + {}_2W_3 = {}_2W_3 = \frac{mR}{1-k}(T_3 - T_2)$$

$$= \frac{1.863 \times 0.2081}{1-1.667}(256.8\text{-}645) = \mathbf{225.6\ kJ}$$

9.35 A rigid 1.0 m^3 tank contains water initially at 120°C, with 50 % liquid and 50% vapor, by volume. A pressure-relief valve on the top of the tank is set to 1.0 MPa (the tank pressure cannot exceed 1.0 MPa - water will be discharged instead). Heat is now transferred to the tank from a 200°C heat source until the tank contains saturated vapor at 1.0 MPa. Calculate the heat transfer to the tank and show that this process does not violate the second law.

C.V. Tank and walls out to the source. Neglect storage in walls. There is flow out and no boundary or shaft work.

Cont.: $m_2 - m_1 = - m_e$ Energy: $m_2 u_2 - m_1 u_1 = - m_e h_e + {}_1Q_2$

Entropy Eq.: $m_2 s_2 - m_1 s_1 = - m_e s_e + \int dQ/T + {}_1S_{2\ gen}$

State 1: $T_1 = 120^oC$, Table B.1.1

$v_f = 0.00106\ m^3/kg$, $m_{liq} = 0.5V_1/v_f = 471.7$ kg

$v_g = 0.8919\ m^3/kg$, $m_g = 0.5V_1/v_g = 0.56$ kg,

$m_1 = 472.26$ kg, $x_1 = m_g/m_1 = 0.001186$

$u_1 = u_f + x_1 u_{fg} = 503.5 + 0.001186 \times 2025.8 = 505.88$ kJ/kg,

$s_1 = s_f + x_1 s_{fg} = 1.5275 + 0.001186 \times 5.602 = 1.5341$ kJ/kg-K

State 2: $P_2 = 1.0$ MPa, sat. vap. $x_2 = 1.0$, $V_2 = 1m^3$

$v_2 = v_g = 0.19444\ m^3/kg$, $m_2 = V_2/v_2 = 5.14$ kg

$u_2 = u_g = 2583.6$ kJ/kg, $s_2 = s_g = 6.5864$ kJ/kg-K

Exit: $P_e = 1.0$ MPa, sat. vap. $x_e = 1.0$, $h_e = h_g = 2778.1$ kJ/kg,

$s_e = s_g = 6.5864$ kJ/kg, $m_e = m_1 - m_2 = 467.12$ kg

${}_1Q_2 = m_2 u_2 - m_1 u_1 + m_e h_e =$ **1 072 080 kJ**

$${}_1S_{2\ gen} = m_2 s_2 - m_1 s_1 + m_e s_e - \frac{{}_1Q_2}{T_H}; \qquad T_H = 200^oC = 473\ K$$

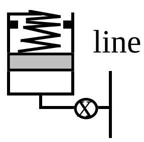
${}_1S_{2\ gen} = \Delta S_{net} =$ **120.4 kJ/K $\geq$ 0 Process Satisfies 2nd Law**

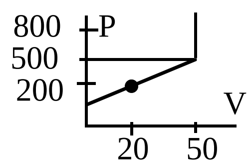
9.36 A frictionless piston/cylinder is loaded with a linear spring, spring constant 100 kN/m and the piston cross-sectional area is 0.1 m^2. The cylinder initial volume of 20 L contains air at 200 kPa and ambient temperature, 10°C. The cylinder has a set of stops that prevent its volume from exceeding 50 L. A valve connects to a line flowing air at 800 kPa, 50°C. The valve is now opened, allowing air to flow in until the cylinder pressure reaches 800 kPa, at which point the temperature inside the cylinder is 80°C. The valve is then closed and the process ends.

a) Is the piston at the stops at the final state?

b) Taking the inside of the cylinder as a control volume, calculate the heat transfer during the process.

c) Calculate the net entropy change for this process.





Air from Table A.5:

$R = 0.287$ kJ/kg-K, $C_p = 1.004$ kJ/kg-K

$C_v = 0.717$ kJ/kg-K, $k = 1.4$

$A_p = 0.1\ m^2$, $V_{stop} = 50$ L

State 1: $T_1 = 10^oC$, $P_1 = 200$ kPa, $V_1 = 20\ L = 0.02\ m^3$,

$m_1 = P_1V_1/RT_1 = 200\times0.02/(0.287\times283.15) = 0.0492$ kg

State 2: $T_2 = 80^oC$, $P_2 = 800$ kPa, Inlet: $T_i = 50^oC$, $P_i = 800$ kPa

a) $P_{stop} = P_1 + \frac{k_s}{A_p^2}(V_{stop} - V_1) = 500$ kPa, $\mathbf{P_2 > P_{stop}}$ **‡ Piston hits stops**

$V_2 = V_{stop} = 50$ L, $m_2 = PV/RT = 0.3946$ kg

b) 1^{st} Law: ${}_1Q_2 + m_ih_i = m_2u_2 - m_1u_1 + m_eh_e + {}_1W_2$; $m_e = 0$, $m_i = m_2 - m_1$

${}_1W_2 = \int P\,dV = (P_1 + P_{stop})(V_{stop} - V_1)/2 = 10.5$ kJ

Assume constant specific heat

${}_1Q_2 = m_2C_vT_2 - m_1C_vT_1 - (m_2 - m_1)\,C_pT_i + {}_1W_2$ **= -11.6 kJ**

c) 2^{nd} Law: $\Delta S_{net} = m_2s_2 - m_1s_1 - m_is_i - \frac{Q_{CV}}{T_o}$; $T_o = 10^oC = 283.15$ K

$\Delta S_{net} = m_2(s_2 - s_i) - m_1(s_1 - s_i) - \frac{Q_{CV}}{T_o}$

$s_2 - s_i = C_p \ln(T_2 / T_i) – R \ln(P_2 / P_i) = 0.08907$ kJ/kg-K $(P_2 = P_i)$

$s_1 - s_i = C_p \ln(T_1 / T_i) – R \ln(P_1 / P_i) = 0.26529$ kJ/kg-K

$\mathbf{\Delta S_{net} = 0.063}$ **kJ/K**

9.37 An insulated piston/cylinder contains R-22 at 20°C, 85% quality, at a cylinder volume of 50 L. A valve at the closed end of the cylinder is connected to a line flowing R-22 at 2 MPa, 60°C. The valve is now opened, allowing R-22 to flow in, and at the same time the external force on the piston is decreased, and the piston moves. When the valve is closed, the cylinder contents are at 800 kPa, 20°C, and a positive work of 50 kJ has been done against the external force. What is the final volume of the cylinder? Does this process violate the second law of thermodynamics?

State 1: $T_1 = 20^oC$, $x_1 = 0.85$, $V_1 = 50\ L = 0.05\ m^3$

$P_1 = P_g = 909.9$ kPa, $u_1 = u_f + x_1 u_{fg} = 208.1$ kJ/kg

$v_1 = v_f + x_1 v_{fg} = 0.000824 + 0.85\times0.02518 = 0.022226\ m^3/kg$,

$s_1 = s_f + x_1 s_{fg} = 0.259 + 0.85\times0.6407 = 0.8036$ kJ/kg K

$m_1 = V_1/v_1 = 2.25$ kg

State 2: $T_2 = 20^oC$, $P_2 = 800$ kPa, superheated, $v_2 = .030336\ m^3/kg$,

$h_2 = 258.7$ kJ/kg, $u_2 = h_2 - P_2v_2 = 234.4$ kJ/kg, $s_2 = 0.91787$ kJ/kg K

Inlet: $T_i = 60^oC$, $P_i = 2$ MPa, $h_i = 271.6$ kJ/kg, $s_i = 0.8873$ kJ/kg K

Energy: ${}_1Q_2 + m_ih_i = m_2u_2 - m_1u_1 + {}_1W_2$; ${}_1Q_2 = 0$, $m_e = 0$, ${}_1W_2 = 50$ kJ

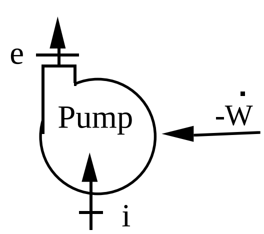
$m_i = m_2 - m_1$; $(m_2 - m_1)h_i = m_2u_2 - m_1u_1$

solve for $m_2 = 5.185$ kg, $\mathbf{V_2 = m_2v_2 = 0.157\ m^3}$

2^{nd} Law: $\Delta S_{net} = m_2s_2 - m_1s_1 - m_is_i - \dfrac{Q_{cv}}{T_o}$, $Q_{CV} = 0$, $T_o = 20^oC$

$\Delta S_{net} = m_2s_2 - m_1s_i - (m_2 - m_1)s_i =$ **0.3469 kJ/K ≥ 0, Satisfies 2nd Law**

9.38 Liquid water at ambient conditions, 100 kPa, 25°C, enters a pump at the rate of 0.5 kg/s. Power input to the pump is 3 kW. Assuming the pump process to be reversible, determine the pump exit pressure and temperature.



$-\dot{W} = 3$ kW, $P_i = 100$ kPa

$T_i = 25°C$, $\dot{m} = 0.5$ kg/s

$\dot{W}/\dot{m} = w = -\int v dP \approx -v_i(P_e - P_i)$

$-3/0.5 = -6.0 \cong -0.001003(P_e - 100)$

$\Rightarrow P_e = 6082$ kPa = **6.082 MPa**

Energy Eq.: $h_e = h_i - w = 104.87 - (-6) = 110.87$ kJ/kg

Use Table B.1.4 at 5 MPa => $\mathbf{T_e = 25.3°C}$

If we use the software we get: $\left.\begin{array}{l} s_i = 0.36736 = s_e \\ \text{At } s_e \ \&\ P_e \end{array}\right\} \rightarrow T_e =$ **25.1°C**

9.39 A firefighter on a ladder 25 m above ground should be able to spray water an additional 10 m up with the hose nozzle of exit diameter 2.5 cm. Assume a water pump on the ground and a reversible flow (hose, nozzle included) and find the minimum required power.

C.V.: pump + hose + water column, total height difference 35 m. Here **V** is velocity, not volume.

Continuity Eq.: $\dot{m}_{in} = \dot{m}_{ex} = (\rho A \mathbf{V})_{nozzle}$

Energy Eq.: $\dot{m}w_p + \dot{m}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}(h + \mathbf{V}^2/2 + gz)_{ex}$

$h_{in} \cong h_{ex}$, $\mathbf{V}_{in} \cong \mathbf{V}_{ex} = 0$, $z_{ex} - z_{in} = 35$ m, $\rho = 1/v \cong 1/v_f$

$w_p = g(z_{ex} - z_{in}) = 9.81 \times (35-0) = 343.2$ J/kg

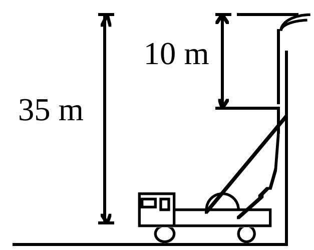
The velocity in the exit nozzle is such that it can rise 10 m, so make that column C.V.

$$gz_{noz} + \frac{1}{2}\mathbf{V}^2_{noz} = gz_{ex} + 0$$

$$\mathbf{V}_{noz} = \sqrt{2g(z_{ex} - z_{noz})} = \sqrt{2 \times 9.81 \times 10} = 14 \text{ m/s}$$

$$\dot{m} = \frac{\pi}{v_f}\left(\frac{D}{2}\right)^2 \mathbf{V}_{noz} = 6.873 \text{ kg/s ;}$$

$$\dot{W}_p = \dot{m}w_p = \mathbf{2.36\ kW}$$



9.40 A large storage tank contains liquefied natural gas (LNG), which may be assumed to be pure methane. The tank contains saturated liquid at ambient pressure, 100 kPa; it is to be pumped to 500 kPa and fed to a pipeline at the rate of 0.5 kg/s. How much power input is required for the pump, assuming it to be reversible?

C.V. Pump, liquid is assumed to be incompressible.

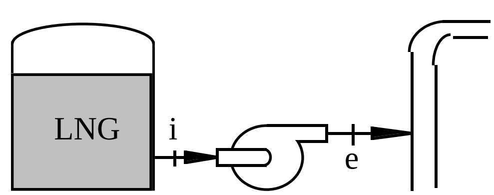
Table B.7 at $P_i = 100$ kPa , $v_{Fi} = 0.002366$ m^3/kg

$$w_{PUMP} = - w_{cv} = \int vdP \approx v_{Fi}(P_e - P_i)$$

$$= 0.002366(500 - 100) = 0.946 \text{ kJ/kg}$$

$$\dot{W}_{PUMP} = \dot{m}w_{PUMP} = 0.5(0.946)$$

$$= \mathbf{0.473\ kW}$$



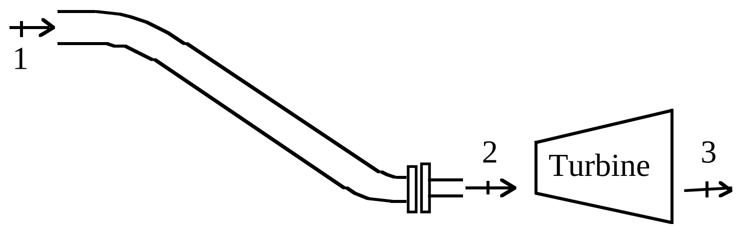
9.41 A small dam has a pipe carrying liquid water at 150 kPa, 20°C with a flow rate of 2000 kg/s in a 0.5 m diameter pipe. The pipe runs to the bottom of the dam 15 m lower into a turbine with pipe diameter 0.35 m. Assume no friction or heat transfer in the pipe and find the pressure of the turbine inlet. If the turbine exhausts to 100 kPa with negligible kinetic energy what is the rate of work?

C.V. Pipe. No work, no heat transfer, $v \approx$ const. Bernoulli

so find kin energy at 1, 2

$v_2 \approx v_1 \approx v_f = 0.001002$

$\dot{m} = \rho\, A\mathbf{V} = A\mathbf{V}/v$



$$\mathbf{V}_1 = \dot{m}v_1/A_1 = 2000 \times 0.001002 / (\frac{\pi}{4}0.5^2) = 10.2 \text{ m s}^{-1}$$

$$\mathbf{V}_2 = \dot{m}v_2/A_2 = 2000 \times 0.001002 / (\frac{\pi}{4}0.35^2) = 20.83 \text{ m s}^{-1}$$

$$v(P_e\text{-}P_i) + \frac{1}{2}(\mathbf{V}_e^2\text{-}\mathbf{V}_i^2) + g\,(Z_e - Z_i) = \varnothing \Rightarrow$$

$$P_e = P_i + \left[\frac{1}{2}(\mathbf{V}_e^2\text{-}\mathbf{V}_i^2) + g\,(Z_i - Z_e)\right]/v$$

$$= 150 + [\frac{1}{2}\times 10.2^2 - \frac{1}{2}\times 20.83^2 + 9.80665 \times 15]/(1000 \times 0.001002)$$

$$= 150 - 17.8 = 132.2 \text{ kPa}$$

$$w = -\int v\, dP + \frac{1}{2}(\mathbf{V}_1^2\text{-}\mathbf{V}_3^2) + g(Z_1 - Z_3)$$

$$= -0.001002\,(100 - 150) + [\frac{1}{2}\times 10.2^2 + 9.80665 \times 15]/1000 = 0.25 \text{ kJ/kg}$$

$$\dot{W} = \dot{m}w = 2000 \times 0.25 = \mathbf{500\ kW}$$

9.42 A small pump is driven by a 2 kW motor with liquid water at 150 kPa, 10°C entering. Find the maximum water flow rate you can get with an exit pressure of 1 MPa and negligible kinetic energies. The exit flow goes through a small hole in a spray nozzle out to the atmosphere at 100 kPa. Find the spray velocity.

C.V. Pump. Liquid water is incompressible

$$\dot{W} = \dot{m}w = \dot{m}v(P_e\text{-}P_i) \Rightarrow$$

$$\dot{m} = \dot{W}/[v(P_e\text{-}P_i)] = 2/[0.001003\,(1000 - 150)] = 2.35 \text{ kg/s}$$

C.V Nozzle. No work, no heat transfer, $v \approx$ constant => Bernoulli

$$\frac{1}{2}\mathbf{V}_{ex}^2 = v(P_e\text{-}P_i) = 0.001\,(1000 - 100) = 0.9 \text{ kJ/kg} = 900 \text{ J/kg}$$

$$\mathbf{V}_{ex} = \mathbf{42.4\ m\ s^{-1}}$$

9.43 Saturated R-134a at -10°C is pumped/compressed to a pressure of 1.0 MPa at the rate of 0.5 kg/s in a reversible adiabatic SSSF process. Calculate the power required and the exit temperature for the two cases of inlet state of the R-134a:

a) quality of 100 %.
b) quality of 0 %.

C.V.: Pump/Compressor, $\dot{m}$ = 0.5 kg/s, R-134a

a) State 1: Table B.5.1, $T_1 = -10^oC$, $x_1 = 1.0$ Saturated vapor

$P_1 = P_g = 202$ kPa, $h_1 = h_g = 392.3$ kJ/kg, $s_1 = s_g = 1.7319$ kJ/kg K

Assume Compressor is Isentropic, $s_2 = s_1 = 1.7319$ kJ/kg-K

$h_2 = 425.7$ kJ/kg, $\mathbf{T_2 = 45^oC}$

1^{st} Law: $q_C + h_1 = h_2 + w_C$; $q_C = 0$

$w_{CS} = h_1 - h_2 = -33.4$ kJ/kg; => $\dot{W}_C = \dot{m}w_C = \mathbf{-16.7\ kW}$

b) State 1: $T_1 = -10^oC$, $x_1 = 0$ Saturated liquid. This is a pump.

$P_1 = 202$ kPa, $h_1 = h_f = 186.72$ kJ/kg, $v_1 = v_f = 0.000755\ m^3/kg$

1^{st} Law: $q_p + h_1 = h_2 + w_p$; $q_p = 0$

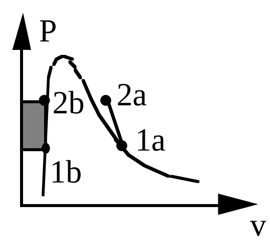
Assume Pump is isentropic and the liquid is incompressible:

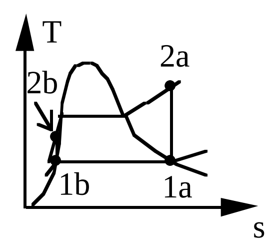
$w_{ps} = - \int v\, dP = -v_1(P_2 - P_1) = -0.6$ kJ/kg

$h_2 = h_1 - w_p = 186.72 - (- 0.6) = 187.3$ kJ/kg, $P_2 = 1$MPa

Assume State 2 is a saturated liquid => $\mathbf{T_2 \cong -9.6^oC}$

$\dot{W}_P = \dot{m}w_P = \mathbf{-0.3\ kW}$





9.44 A small water pump on ground level has an inlet pipe down into a well at a depth H with the water at 100 kPa, 15°C. The pump delivers water at 400 kPa to a building. The absolute pressure of the water must be at least twice the saturation pressure to avoid cavitation. What is the maximum depth this setup will allow?

C.V. Pipe in well, no work, no heat transfer

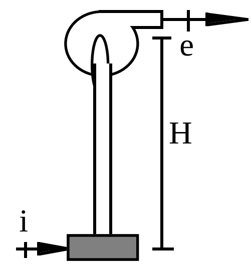
$P_{\text{inlet pump}} \geq 2\ P_{\text{sat, 15C}} = 2\times1.705 = 3.41$

Assume Δ KE ≈ ∅ , v ≈ constant. => Bernoulli.

$v\ \Delta P + g\ H = 0$ =>

$1000 \times 0.001001\ (3.41 - 100) + 9.80665 \times H = \varnothing$

$\Rightarrow \quad H =$ **9.86 m**

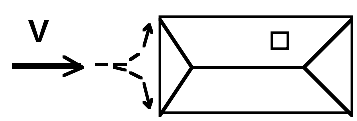


Since flow has some kinetic energy and there are losses in the pipe the height is overestimated. Also the start transient would generate a very low inlet pressure (it moves flow by suction)

9.45 Atmospheric air at 100 kPa, 17°C blows at 60 km/h towards the side of a building. Assume the air is nearly incompressible find the pressure and the temperature at the stagnation point (zero velocity) on the wall.

C.V. A stream line of flow from the freestream to the wall.

$$v(P_e - P_i) + \frac{1}{2}(\mathbf{V}_e^2 - \mathbf{V}_i^2) + g(Z_e - Z_i) = \varnothing$$



$$\Delta P = \frac{1}{2v}\mathbf{V}_i^2 = \frac{1}{2}\frac{60 \times 1000}{3600} /(0.287 \times 290.15/100)$$

$$= \frac{1}{2} 16.667^2 / (0.8323 \times 1000) = 0.17 \text{ kPa}$$

$P_e = P_i + \Delta P = 100.17$ kPa

$T_e = T_i\ (P_e/P_i)^{0.286} = 290.15 \times 1.0005 =$ **290.3 K**

Very small efffect due to low velocity and air is light (large specific volume)

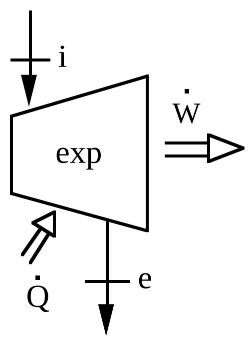
9.46 A small pump takes in water at 20°C, 100 kPa and pumps it to 2.5 MPa at a flow rate of 100 kg/min. Find the required pump power input.

C.V. Pump. Assume reversible pump and incompressible flow.

$$w_p = -\int v dP = -v_i(P_e - P_i) = -0.001002(2500 - 100) = -2.4 \text{ kJ/kg}$$

$$\dot{W}_p = \dot{m} w_p = (100/60)(-2.4) = \mathbf{-4.0\ kW}$$

9.47 Helium gas enters a steady-flow expander at 800 kPa, 300°C, and exits at 120 kPa. The mass flow rate is 0.2 kg/s, and the expansion process can be considered as a reversible polytropic process with exponent, *n* = 1.3. Calculate the power output of the expander.



CV: expander, reversible polytropic process.

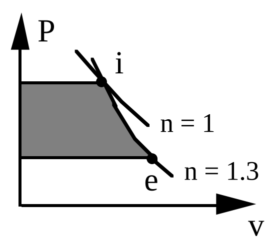
$$T_e = T_i\left(\frac{P_e}{P_i}\right)^{\frac{n-1}{n}} = 573.2\left(\frac{120}{800}\right)^{\frac{0.3}{1.3}} = 370 \text{ K}$$

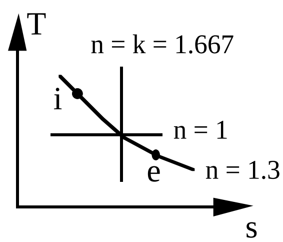
Work evaluated from Eq.9.20

$$w = -\int v dP = -\frac{nR}{n-1}(T_e - T_i)$$

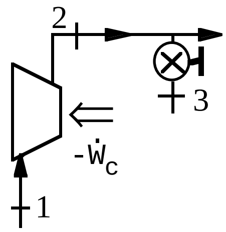
$$= \frac{-1.3 \times 2.07703}{0.3}(370 - 573.2) = 1828.9 \text{ kJ/kg}$$

$$\dot{W} = 0.2 \times 1828.9 = \mathbf{365.8\ kW}$$





9.48 A pump/compressor pumps a substance from 100 kPa, 10°C to 1 MPa in a reversible adiabatic SSSF process. The exit pipe has a small crack, so that a small amount leaks to the atmosphere at 100 kPa. If the substance is (a) water, (b) R-12, find the temperature after compression and the temperature of the leak flow as it enters the atmosphere neglecting kinetic energies.



C.V.: Compressor, reversible adiabatic

$h_1 - w_c = h_2$; $s_1 = s_2$

State 2: P_2, $s_2 = s_1$

C.V.: Crack (SSSF throttling process)

$h_3 = h_2$; $s_3 = s_2 + s_{gen}$

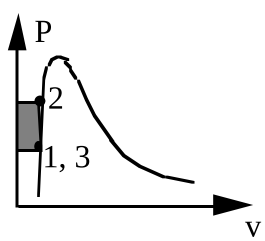
State 3: P_3, $h_3 = h_2$

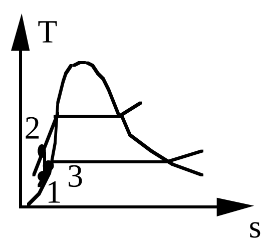
a) Water 1: compressed liquid, Table B.1.1

$-w_c = +\int vdP = v_{f1}(P_2 - P_1) = 0.001 \times (1000 - 100) = 0.9$ kJ/kg

$h_2 = h_1 - w_c = 41.99 + 0.9 = 42.89$ kJ/kg => $\mathbf{T_2 = 10.2°C}$

P_3 , h_3 $\Rightarrow$ compressed liquid at **~10.2°C**





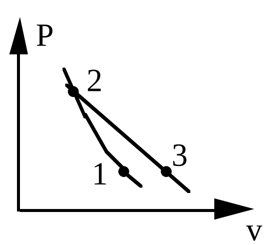
States 1 and 3 are at the same 100 kPa, and same h. You cannot separate them in the P-v fig.

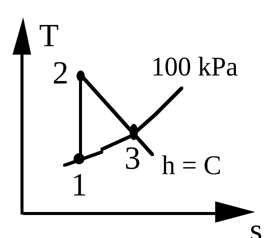
b) R-12 1: superheated vapor, Table B.3.2, $s_1 = 0.8070$ kJ/kg K

$s_2 = s_1$ & P_2 $\Rightarrow$ $\mathbf{T_2 = 98.5°C}$, $h_2 = 246.51$ kJ/kg

$-w_c = h_2 - h_1 = 246.51 - 197.77 = 48.74$ kJ/kg

P_3 , h_3 $\Rightarrow$ $\mathbf{T_3 = 86.8°C}$





9.49 A certain industrial process requires a steady 0.5 kg/s of air at 200 m/s, at the condition of 150 kPa, 300 K. This air is to be the exhaust from a specially designed turbine whose inlet pressure is 400 kPa. The turbine process may be assumed to be reversible and polytropic, with polytropic exponent n = 1.20.
a) What is the turbine inlet temperature?
b) What are the power output and heat transfer rate for the turbine?
c) Calculate the rate of net entropy increase, if the heat transfer comes from a source at a temperature 100°C higher than the turbine inlet temperature.

C.V. Turbine, this has heat transfer, PV^n = Const., n = 1.2

Air table A.5: C_p = 1.004 kJ/kg-K, R = 0.287 kJ/kg-K

Exit: T_e = 300K, P_e = 150 kPa, $\mathbf{V}_e$ = 200 m/s

a) Process polytropic: $T_e / T_i = (P_e/P_i)^{\frac{n-1}{n}} \;\Rightarrow\; T_i = 353.3\text{ K}$

b) 1^{st} Law SSSF: $\dot{m}_i(h + \mathbf{V}^2/2)_{in} + \dot{Q} = \dot{m}_{ex}(h + \mathbf{V}^2/2)_{ex} + \dot{W}_T$

Reversible shaft work in a polytropic process, Eq.9.15 and Eq.9.20

$$w_T = -\int v\,dP + (\mathbf{V}_i^2 - \mathbf{V}_e^2)/2 = -\frac{n}{n-1}(P_e v_e - P_i v_i) + (\mathbf{V}_i^2 - \mathbf{V}_e^2)/2$$

$$= -\frac{n}{n-1}R(T_e - T_i) - \mathbf{V}_e^2/2 = 71.8\text{ kJ/kg}$$

$\dot{W}_T = \dot{m}w_T$ = **35.9 kW**

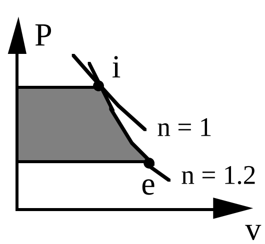
Assume Constant Specific Heat

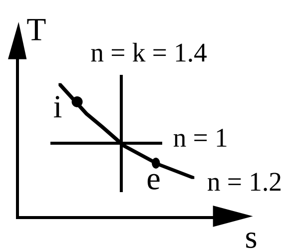
$\dot{Q} = \dot{m}[C_P(T_e - T_i) - \mathbf{V}_e^2/2] + \dot{W}_T$ = **19.2 kW**

c) 2^{nd} Law: $dS_{net}/dt = \dot{m}(s_e - s_i) - \dot{Q}_H/T_H$, $T_H = T_i + 100 = 453.3\text{ K}$

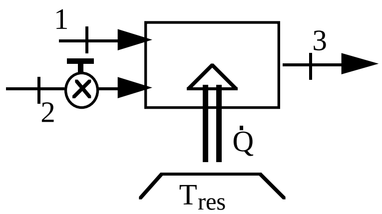
$$s_e - s_i = C_p \ln\frac{T_e}{T_i} - R\ln\frac{P_e}{P_i} = 0.1174\text{ kJ/kg-K}$$

$dS_{net}/dt = 0.5\times0.1174 - 19.2/453.3 = 0.0163$ kW/K





9.50 A mixing chamber receives 5 kg/min ammonia as saturated liquid at −20°C from one line and ammonia at 40°C, 250 kPa from another line through a valve. The chamber also receives 325 kJ/min energy as heat transferred from a 40°C reservoir. This should produce saturated ammonia vapor at −20°C in the exit line. What is the mass flow rate in the second line and what is the total entropy generation in the process?



CV: Mixing chamber out to reservoir

$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

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

$\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{Q}/T_{res} + \dot{S}_{gen} = \dot{m}_3 s_3$

From the energy equation:

$\dot{m}_2 = \left[(\dot{m}_1(h_1 - h_3) + \dot{Q}\right]/(h_3 - h_2)$

$= \left[5 \times (89.05 - 1418.05) + 325\right]/(1418.05 - 1551.7)$

$=$ **47.288 kg/min** $\Rightarrow \quad \dot{m}_3 = 52.288$ kg/min

$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{Q}/T_{res}$

$= 52.288 \times 5.6158 - 5 \times 0.3657 - 47.288 \times 5.9599 - 325/313.15$

$=$ **8.94 kJ/K min**

9.51 A compressor is used to bring saturated water vapor at 1 MPa up to 17.5 MPa, where the actual exit temperature is 650°C. Find the isentropic compressor efficiency and the entropy generation.

C.V. Compressor. Assume adiabatic and neglect kinetic energies.

IDEAL:	ACTUAL:
$h_{2,s} = 3560.1$	$h_{2,AC} = 3693.9$
$w_{c,s} = h_{2,s} - h_1 = 782$	$w_{C,AC} = h_{2,AC} - h_1 = 915.8$

1: $h_1 = 2778.1 \quad s_1 = 6.5865 \quad s_{2,AC} = 6.7357$

$\eta_c = w_{c,s}/w_{c,AC} =$ **0.8539 ~ 85%**

$s_{gen} = s_{2\ ac} - s_1 = 6.7357 - 6.5865 =$ **0.1492 kJ/kg K**

9.52 Liquid water enters a pump at 15°C, 100 kPa, and exits at a pressure of 5 MPa. If the isentropic efficiency of the pump is 75%, determine the enthalpy (steam table reference) of the water at the pump exit.

CV: pump $\dot{Q}_{CV} \approx 0$, $\Delta KE \approx 0$, $\Delta PE \approx 0$

2nd law, reversible (ideal) process

$$s_{es} = s_i \;\Rightarrow\; w_s = -\int_i^{es} v dP \approx -v_i(P_e - P_i) = -0.001001(5000 - 100) = -4.905 \text{ kJ/kg}$$

Real process: $w = w_s/\eta_s = -4.905/0.75 = -6.54$ kJ/kg

and $h_e = h_i - w = 62.99 + 6.54 =$ **69.53 kJ/kg**

9.53 A centrifugal compressor takes in ambient air at 100 kPa, 15°C, and discharges it at 450 kPa. The compressor has an isentropic efficiency of 80%. What is your best estimate for the discharge temperature?

C.V. Compressor. Assume adiabatic, no kinetic energy is important.

State 1: Table A.7: $P_{r1} = 1.2055$

$P_{r2s} = 1.2055 \times (450/100) = 5.4248 \;\rightarrow\; T_{2s} = 442.1$ K

$w_s = h_1 - h_{2s} = 288.36 - 443.75 = -155.39$

$w_{ac} = -155.39/0.8 = -194.23$

$\Rightarrow h_2 = 194.23 + 288.36 = 482.59,\quad T_2 =$ **480.1 K**

9.54 Repeat Problem 9.20 assuming the steam turbine and the air compressor each have an isentropic efficiency of 80%.

$$\text{Air,}\quad T_{4s} = T_3(P_4/P_3)^{\frac{k-1}{k}} = 293.2\left(\frac{500}{100}\right)^{0.286} = 464.6 \text{ K}$$

$\dot{W}_C = \dot{m}_3(h_3 - h_4) = \dot{m}_3(h_3 - h_{4s})/\eta_{sc}$

$= 0.1 \times 1.0035(293.2 - 464.6)/0.80 = -21.5$ kW

$\dot{W}_T = +21.5 \text{ kW} = \dot{m}_1(h_1 - h_2) = 0.5(h_1 - 2706.6) \quad\Rightarrow\quad h_1 = 2749.6$ kJ/kg

Also, $n_{sT} = 0.80 = (h_1 - h_2)/(h_1 - h_{2s}) = 43/(2749.6 - h_{2s})$

$\Rightarrow h_{2s} = 2695.8$ kJ/kg

$2695.8 = 504.7 + x_{2s}(2706.6 - 504.7) \quad => \quad x_{2s} = 0.9951$

$s_{2s} = 1.5301 + 0.9951(7.1271 - 1.5301) = 7.0996$

$(s_1 = s_{2s}, h_1) \;\rightarrow\; P_1 =$ **269 kPa**, $T_1 =$ **143.5°C**

9.55 A small air turbine with an isentropic efficiency of 80% should produce 270 kJ/kg of work. The inlet temperature is 1000 K and it exhausts to the atmosphere. Find the required inlet pressure and the exhaust temperature.

C.V. Turbine actual:

$w = h_i - h_{e,ac} = 270 \;\Rightarrow\; h_{e,ac} = 776.22$, $\mathbf{T_e = 757.9\ K}$

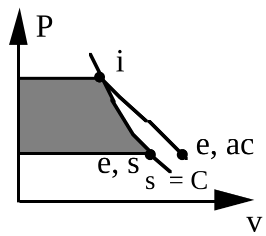
C.V. Ideal turbine:

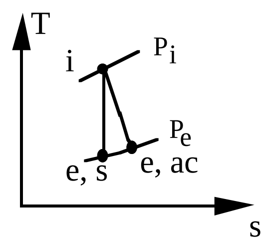
$w_s = w/\eta_s = 270/0.8 = 337.5 = h_i - h_{e,s} \Rightarrow h_{e,s} = 708.72$

$T_{e,s} = 695.5 \quad s_i = s_{e,s} \Rightarrow P_e/P_i = P_{re}/P_{ri}$ [$= (T_e/T_i)^{k/(k-1)}$ for constant Cp]

$P_i = P_e P_{ri}/P_{re} = 101.3 \times 91.651 / 22.607 =$ **410.8 kPa**

[$= 101.3\,(1000/695.5)^{3.5} = 361$ kPa for constant Cp]





9.56 Carbon dioxide, CO_2, enters an adiabatic compressor at 100 kPa, 300 K, and exits at 1000 kPa, 520 K. Find the compressor efficiency and the entropy generation for the process.

C.V. Ideal compressor

$$w_c = h_1 - h_2,\ s_2 = s_1 : T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 300\left(\frac{1000}{100}\right)^{0.2242} = 502.7\ \text{K}$$

$w_{cs} = C_p(T_1 - T_{2s}) = 0.8418(300\text{-}502.7) = -170.63$ kJ/kg

C.V. Actual compressor

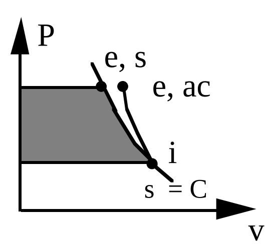
$w_{cac} = C_p(T_1 - T_{2ac}) = 0.8418(300 - 520) = -185.2$ kJ/kg

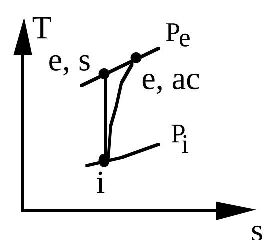
$\eta_c = w_{cs}/w_{cac} = -170.63/(-185.2) =$ **0.92**

$s_{gen} = s_{2ac} - s_1 = C_p \ln(T_{2ac}/T_1) - R \ln(P_2/P_1)$

$= 0.8418 \ln(520/300) - 0.18892 \ln(1000/100) =$ **0.028 kJ/kg K**

Constant heat capacity is a poor approximation.





9.57 Repeat Problem 9.22 assuming the turbine and the pump each have an isentropic efficiency of 85%.

$\eta_P = \eta_T = 85\%$ $\quad w_{T,AC} = \eta_T w_{T,s} = \mathbf{1343.25} = h_1 - h_{2,AC}$

$h_{2,AC} = h_1 - w_{T,AC} = 2434.36$;

$\mathbf{x_{2,AC} =}$ $(2434.3 - 251.4)/2358.3 = \mathbf{0.926}$ **,** $\quad \mathbf{T_{2,AC} = 60.06°C}$

$w_{P,AC} = w_{P,s}/\eta_\rho = \mathbf{29.5} = h_{4,AC} - h_3$

$h_{4,AC} = \mathbf{197.0} \quad T_{4,AC} \cong 42°C$

$$\eta_{TH} = \frac{w_{T,AC} - w_{P,AC}}{h_1 - h_{4,AC}} = \frac{1313.78}{3580.49} = \mathbf{0.367}$$

9.58 Air enters an insulated compressor at ambient conditions, 100 kPa, 20°C, at the rate of 0.1 kg/s and exits at 200°C. The isentropic efficiency of the compressor is 70%. What is the exit pressure? How much power is required to drive the compressor?

C.V. Compressor: P_1, T_1, T_e(real), $\eta_{s\ COMP}$ known

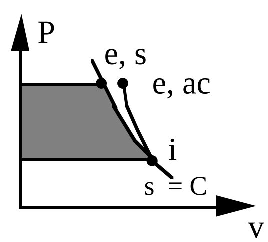
Real $\quad -w = C_{P0}(T_e - T_i) = 1.0035(200 - 20) = 180.63$

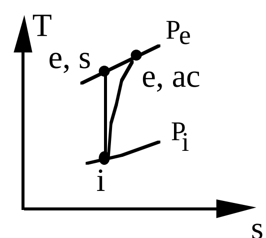
Ideal $\quad -w_s = -w \times \eta_s = 180.63 \times 0.70 = 126.44$

$126.44 = C_{P0}(T_{es} - T_i) = 1.0035(T_{es} - 293.2)$, $\quad T_{es} = 419.2$ K

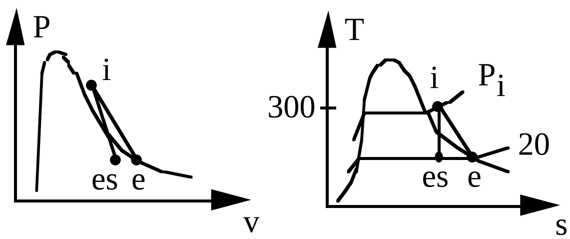
$P_e = P_i(T_{es}/T_i)^{\frac{k}{k-1}} = 100(419.2/293.20)^{3.5} = \mathbf{349\ kPa}$

$-\dot{W}_{REAL} = \dot{m}(-w) = 0.1 \times 180.63 = \mathbf{18.06\ kW}$





9.59 Steam enters a turbine at 300°C and exhausts at 20 kPa. It is estimated that the isentropic efficiency of the turbine is 70%. What is the maximum turbine inlet pressure if the exhaust is not to be in the two-phase region?



Turbine: $\eta_s = \dfrac{w}{w_s} = 0.70$,

$w = h_i - h_e$

$w_s = h_i - h_{es}$, $s_{es} = s_i$

Increasing P_i shifts process left.

For state e to stay out of 2 phase but with max P_i,

$x_e = 1.0 \Rightarrow h_e = 2609.7$ Assume $P_i = 0.66$ MPa

Then, at $T_i = 300°C$; $h_i = 3060.1$, $s_i = 7.3305$

$s_{es} = s_i = 7.3305 = 0.8320 + x_{es} \times 7.0766$ => $x_{es} = 0.9183$

$h_{es} = 251.4 + 0.9183 \times 2358.3 = 2417.0$

$w = 3060.1 - 2609.7 = 450.4$

$w_s = 3060.1 - 2417.0 = 643.1$

$\eta_s = (450.4/643.1) = 0.700$ **OK** $\Rightarrow$ $P_i =$ **0.66 MPa**

9.60 A nozzle is required to produce a flow of air at 200 m/s at 20°C, 100 kPa. It is estimated that the nozzle has an isentropic efficiency of 92%. What nozzle inlet pressure and temperature is required assuming the inlet kinetic energy is negligible?

C.V. Air nozzle: P_e, T_e(real), V_e(real), η_s(real)

For the real process: $h_i = h_e + \mathbf{V}_e^2/2$ or

$T_i = T_e + \mathbf{V}_e^2/2C_{P0} = 293.2 + 200^2/2 \times 1000 \times 1.004 = \mathbf{313.1\ K}$

For the ideal process:

$\mathbf{V}_{es}^2/2 = \mathbf{V}_e^2/2\eta_s = 200^2/2 \times 1000 \times 0.92 = 21.74$ kJ/kg

and $h_i = h_{es} + (\mathbf{V}_{es}^2/2)$

$T_{es} = T_i - \mathbf{V}_{es}^2/(2C_{P0}) = 313.1 - 21.74/1.004 = 291.4$ K

$\Rightarrow \quad P_i = P_e\ (T_i/T_{es})^{\frac{k}{k-1}} = 100\left(\dfrac{313.1}{291.4}\right)^{3.50} = \mathbf{128.6\ kPa}$

9.61 A turbine receives air at 1500 K, 1000 kPa and expands it to 100 kPa. The turbine has an isentropic efficiency of 85%. Find the actual turbine exit air temperature and the specific entropy increase in the actual turbine.

C.V. Turbine. SSSF, single inlet and exit flow.

To analyze the actual turbine we must first do the ideal one (the reference).

Energy: $w_T = h_1 - h_2$; Entropy: $s_2 = s_1 + s_{gen} = s_1$

Table A.7 => $P_{r2} = P_{r1} P_2/P_1 = 483.155 *100/1000 = 48.3155$

=> $T_{2s} = 849.2$, $h_{2s} = 876.56$ => $w_T = 1635.8 - 876.56 = 759.24$ kJ/kg

Now we can consider the actual turbine:

$$w_{ac}^{T} = \eta_T\, w_T = 0.85*759.24 = 645.35 = h_1 - h_{2ac}$$

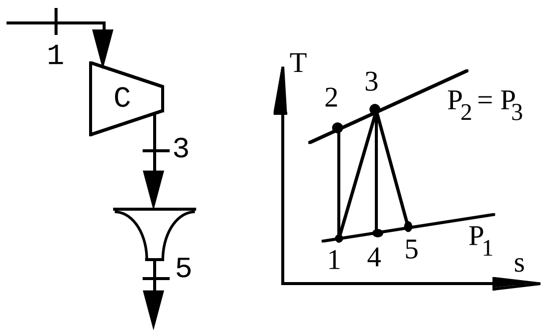
$$\Rightarrow \quad h_{2ac} = h_1 - w_{ac}^{T} = 990.45 \quad \Rightarrow \quad T_{2ac} = 951 \text{ K}$$

The entropy balance equation is solved for the generation term

$$s_{gen} = s_{2ac} - s_1 = 8.078 - 8.6121 - 0.287 \ln(100/1000) = 0.1268 \text{ kJ/kg K}$$

9.62 Assume both the compressor and the nozzle in Problem 9.5 have an isentropic efficiency of 90% the rest being unchanged. Find the actual compressor work and its exit temperature and find the actual nozzle exit velocity.

Solution:



C.V. Ideal compressor, inlet: 1 exit: 2.

$w_C = h_2 - h_1$, $s_2 = s_1$

$\Rightarrow$ $P_{r2} = P_{r1}P_2/P_1 = 3.98$

State 2: A.7 $T_2 = 430.5$ K, $h_2 = 432.3$

$\Rightarrow$ $w_{Cs} = 141.86$ kJ/kg

The ideal nozzle then expands back down to state 1 (constant s) so energy equation gives:

$$\frac{1}{2}\mathbf{V}^2 = h_2 - h_1 = w_{Cs} = 141860 \text{ J/kg} \;\Rightarrow\; \mathbf{V} = 532.7 \text{ m/s}$$

The actual compressor discharges at state 3 so we have:

$$w_C = w_{Cs}/\eta_C = \mathbf{157.62} \;\Rightarrow\; h_3 = h_1 + w_C = 448 \text{ kJ/kg}$$

Table A.7: h => $T_3 = \mathbf{446}$ K, $P_{r3} = 4.509$

Nozzle receives air at 3 and exhausts at 5. We must do the ideal (exit at 4) first.

$$s_4 = s_3 \;\Rightarrow\; P_{r4} = P_{r3}/4 = 1.127 \Rightarrow T_4 = 300.9 \text{ K} \qquad h_4 = 301.4 \text{ kJ/kg}$$

$$\frac{1}{2}\mathbf{V}_s^2 = h_3 - h_4 = 146.67 \;\Rightarrow\; \frac{1}{2}\mathbf{V}_{ac}^2 = 132 \text{ kJ/kg} \;\Rightarrow V_{ac} = \mathbf{513.8 \; m/s}$$

If we need it, the actual nozzle exit (5) can be found:

$$h_5 = h_3 - \mathbf{V}_{ac}^2/2 = 316 \text{ kJ/kg} \quad\Rightarrow\quad T_5 = 316 \text{ K}$$

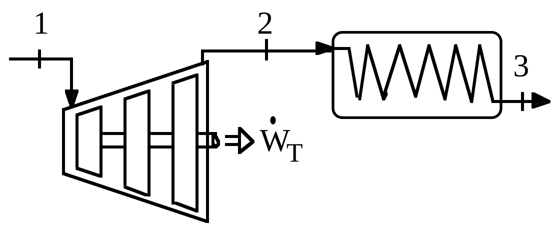
9.63 The small turbine in Problem 9.6 was ideal. Assume instead the isentropic turbine efficiency is 88%. Find the actual specific turbine work, the entropy generated in the turbine and the heat transfer in the heat exchanger.

Continuity Eq.: (SSSF)

$\dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}$

Turbine: Energy Eq.:

$w_T = h_1 - h_2$



Entropy Eq.: $s_2 = s_1 + s_{T\ gen}$

Heat exch: Energy Eq.: $q = h_3 - h_2$, Entropy Eq.: $s_3 = s_2 + \int dq/T + s_{He\ gen}$

Inlet state: Table B.1.3 $h_1 = 3917.45$ kJ/kg, $s_1 = 7.9487$ kJ/kg K

Ideal turbine $s_{T\ gen} = 0$, $s_2 = s_1 = 7.9487 = s_{f2} + x\ s_{fg2}$

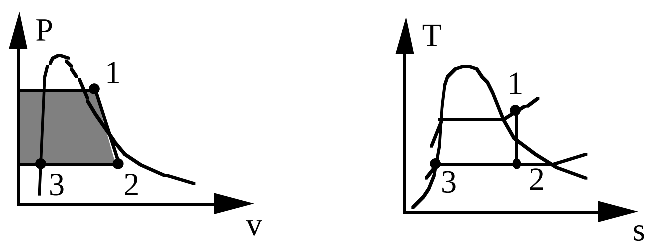
State 3: P = 10 kPa, $s_2 < s_g$ => saturated 2-phase in Table B.1.2

$\Rightarrow\ x_{2,s} = (s_1 - s_{f2})/s_{fg2} = (7.9487 - 0.6492)/7.501 = 0.9731$

$\Rightarrow\ h_{2,s} = h_{f2} + x \times h_{fg2} = 191.8 + 0.9731 \times 2392.8 = 2520.35$ kJ/kg

$w_{T,s} = h_1 - h_{2,s} = 1397.05$ kJ/kg

Explanation for the work term is in 9.3 Eq. (9.19)



$w_{T,AC} = \eta \times w_{T,s} =$ **1229.9 kJ/kg**

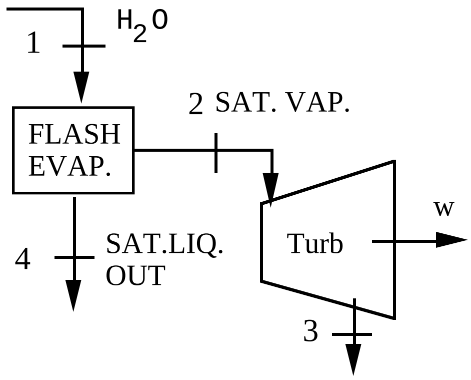
$= h_1 - h_{2,AC} \Rightarrow h_{2,AC} = h_1 - w_{T,AC} = 2687.5$ kJ/kg

$\Rightarrow T_{2,AC} = 100°C$, $s_{2,AC} = 8.4479$

$s_{T\ gen} = s_{2,AC} - s_1 =$ **0.4992 kJ/kg K**

$q = h_3 - h_{2,AC} = 191.83 - 2687.5 =$ **-2495.67 kJ/kg**

9.64 A geothermal supply of hot water at 500 kPa, 150°C is fed to an insulated flash evaporator at the rate of 1.5 kg/s. A stream of saturated liquid at 200 kPa is drained from the bottom of the chamber, and a stream of saturated vapor at 200 kPa is drawn from the top and fed to a turbine. The turbine has an isentropic efficiency of 70% and an exit pressure of 15 kPa. Evaluate the second law for a control volume that includes the flash evaporator and the turbine.



CV: flash evaporator.

$h_1 = 632.2 = 504.7 + x \times 2201.9$

$\Rightarrow \quad x = 0.0579 = \dot{m}_{VAP}/\dot{m}_1$

$\Rightarrow \dot{m}_{VAP} = 0.0579 \times 1.5 = 0.08686$ kg/s

$\dot{m}_{LIQ} = 1.413$ kg/s

Turbine:

$s_{3s} = s_2 = s_g$ at 200 kPa

$s_{3s} = 7.1271 = 0.7594 + x_{3s} \times 7.2536$

$\Rightarrow \quad x_{3s} = 0.8785$

$h_{3s} = 225.94 + 0.8785 \times 2373.1 = 2310.7$

$w_s = h_2 - h_{3s} = 2706.7 - 2310.7 = 396$ kJ/kg

$w = \eta_s w_s = 0.7 \times 396 = 277.2$ kJ/kg

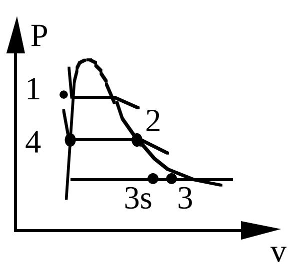
$h_3 = h_2 - w = 2706.7 - 277.2 = 2429.5$ kJ/kg

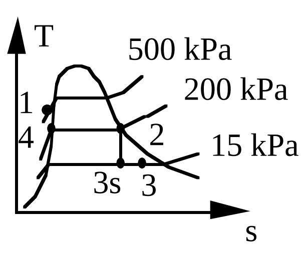
$= 225.94 + x_3 \times 2373.1; \quad \Rightarrow \quad x_3 = 0.9286$

$s_3 = 0.7594 + 0.9286 \times 7.2536 = 7.4903$

$\dot{S}_{gen} = \dot{S}_{NET} = \dot{S}_{SURR} = \dot{m}_4 s_4 + \dot{m}_3 s_3 - \dot{m}_1 s_1$

$= 1.413 \times 1.5301 + 0.08686 \times 7.4903 - 1.5 \times 1.8418 =$ **+0.05 kW/K > 0**





9.65 Redo Problem 9.39 if the water pump has an isentropic efficiency of 85% (hose, nozzle included).

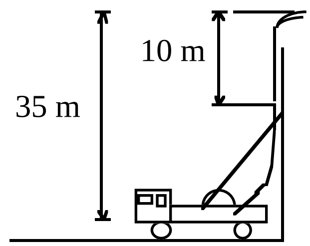
C.V.: pump + hose + water column, height difference 35 m. **V** is velocity.

Continuity Eq.: $\dot{m}_{in} = \dot{m}_{ex} = (\rho A\mathbf{V})_{nozzle}$;

Energy Eq.: $\dot{m}(-w_p) + \dot{m}(h + \mathbf{V}^2/2 + gz)_{in} = \dot{m}(h + \mathbf{V}^2/2 + gz)_{ex}$

Process: $h_{in} \cong h_{ex}$, $\mathbf{V}_{in} \cong \mathbf{V}_{ex} = 0$,

$z_{ex} - z_{in} = 35$ m , $\rho = 1/v \cong 1/v_f$



$-w_p = g(z_{ex} - z_{in}) = 9.80665(35 - 0) = 343.2$ J/kg

The velocity in nozzle is such that it can rise 10 m, so make that column C.V.

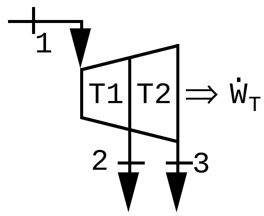
$$gz_{noz} + \frac{1}{2}\mathbf{V}^2_{noz} = gz_{ex} + 0$$

$$\Rightarrow \mathbf{V}_{noz} = \sqrt{2g(z_{ex} - z_{noz})} = \sqrt{2 \times 9.81 \times 10} = 14 \text{ m/s}$$

$\dot{m} = (\pi/v_f)\ (D^2/4)\ \mathbf{V}_{noz} = (\ \pi/4)\ 0.025^2 \times 14\ /\ 0.001 = 6.873$ kg/s ;

$-\dot{W}_p = \dot{m}(-w_p)/\eta = 6.872 \times 0.343/0.85 =$ **2.77 kW**

9.66 A flow of 20 kg/s steam at 10 MPa, 550°C enters a two-stage turbine. The exit of the first stage is at 2 MPa where 4 kg/s is taken out for process steam and the rest continues through the second stage, which has an exit at 50 kPa. Assume both stages have an isentropic efficiency of 85% find the total actual turbine work and the entropy generation.



C.V.: T1 Ideal

State 1: Table B.1.2, $h_1 = 3500.9$ kJ/kg, $s_1 = 6.7561$

$h_1 = h_{2s} + w_{T1,s}$; $s_1 + \emptyset = s_{2s}$

State 2s: P_2, $s_{2s} = s_1 \Rightarrow h_{2s} = 3017.9$ kJ/kg

$w_{T1,s} = 3500.9 - 3017.9 = 483$ kJ/kg

C.V. T1 Actual

$w_{T1,ac} = w_{T1,s}\eta_{T1} = 410.5 = h_1 - h_{2ac} \Rightarrow h_{2ac} = 3090.4$ kJ/kg

State 2ac: P_2 $h_{2,ac} \Rightarrow s_{2ac} = 6.8802$ kJ/kg K

C.V. T2 Ideal

$h_{2ac} = h_{3,s} + w_{T2s}$; $s_{2ac} + \emptyset = s_{3s}$

State 3s: P_3 , $s_{3s} = s_{2ac} \Rightarrow x_{3s} = (6.8802-1.091)/6.5029 = 0.890$,

$h_{3s} = 340.5 + 0.89\times2305.4 = 2392.9$ kJ/kg

$w_{T2s} = 3090.4 - 2392.9 = 697.5$ kJ/kg

C.V. T2 Actual

$w_{T2,ac} = w_{T2s}\eta_{T2} = 592.9 = h_{2ac} - h_{3ac}$ => $h_{3ac} = 2497.5$

State 3ac: P_3 , $h_{3ac} \Rightarrow x_{3ac} = (2497.5-340.5)/2305.4 = 0.9356$,

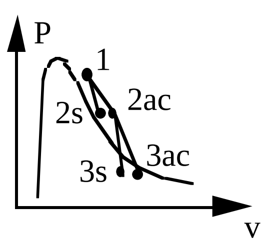
$s_{3ac} = 1.091 + 0.9356\times6.5029 = 7.1754$

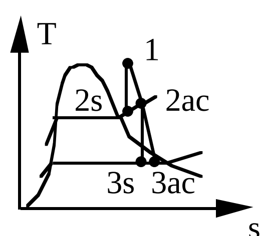
C.V. T1 + T2 Actual

$\dot{W}_T = \dot{m}_1 w_{T1ac} + (\dot{m}_1 - \dot{m}_2)w_{T2ac} = 20 \times 410.5 + 16 \times 592.9 =$ **17696 kW**

$\dot{S}_{gen} = \dot{m}_2 s_{2ac} + \dot{m}_3 s_{3ac} - \dot{m}_1 s_1 = 4\times6.8802 + 16\times7.1754 - 20\times6.7561$

$=$ **7.20 kW/K**





9.67 Air flows into an insulated nozzle at 1MPa, 1200 K with 15 m/s and mass flow rate of 2 kg/s. It expands to 650 kPa and exit temperature is 1100 K. Find the exit velocity, and the nozzle efficiency.

C.V. Nozzle. SSSF, 1 inlet and 1 exit, no heat transfer, no work.

Energy: $h_i + (1/2)\mathbf{V}_i^2 = h_e + (1/2)\mathbf{V}_e^2$ Entropy: $s_i + s_{gen} = s_e$

Ideal nozzle $s_{gen} = 0$ and assume same exit pressure as actual

$P_e / P_i = P_{re} / P_{ri} \Rightarrow P_{re} = P_{ri} P_e / P_i = 191.174 \times 650 / 1000 = 124.26$

$\Rightarrow T_{e\,s} = 1078.2$ K, $h_{e\,s} = 1136$ kJ/kg

$$\frac{1}{2}\mathbf{V}_{e\,s}^2 = \frac{1}{2}\mathbf{V}_i^2 + h_i - h_{e\,s} = \frac{1}{2}\times 15^2 + (1277.8 - 1136) \times 1000$$

$= 112.5 + 141800 = 141913$ J/kg $\Rightarrow$ $\mathbf{V}_{e\,s} = 533$ m/s

Actual nozzle with given exit temperature

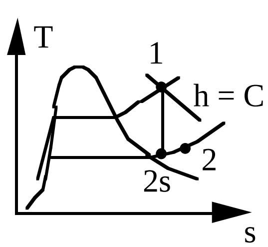
$$\frac{1}{2}\mathbf{V}_{e\,ac}^2 = \frac{1}{2}\mathbf{V}_i^2 + h_i - h_{e\,ac} = 112.5 + (1277.8 - 1161.2) \times 1000 = 116712.5$$

$\Rightarrow$ $\mathbf{V}_{e\,ac} = \mathbf{483\ m/s}$

$$\eta_{noz} = \left(\frac{1}{2}\mathbf{V}_{e\,ac}^2 - \frac{1}{2}\mathbf{V}_i^2\right) / \left(\frac{1}{2}\mathbf{V}_{e\,s}^2 - \frac{1}{2}\mathbf{V}_i^2\right) = (h_i - h_{e,\,AC})/(h_i - h_{e,\,s})$$

$$= \frac{1277.8 - 1161.2}{1277.8 - 1136} = \mathbf{0.8}$$

9.68 A nozzle is required to produce a steady stream of R–134a at 240 m/s at ambient conditions, 100 kPa, 20°C. The isentropic efficiency may be assumed to be 90%. Find by trial and error or verify that the inlet pressure is 375 kPa. What is the rquired inlet temperature in the line upstream of the nozzle?



$KE_2 = (240^2/2000) = 28.8$ kJ/kg

$KE_{2s} = 28.8/\eta = 32$

$h_1 = h_2 + KE_2 = 420.05 + 28.8 = 448.85$

$h_{2s} = h_1 - KE_{2s} = 448.85 - 32 = 416.85$

State 2s: P_2, h_{2s} $\Rightarrow$ $T_{2s} = 16.2$°C, $s_{2s} = 1.8759$ kJ/kg K

State 1: h_1, $s_1 = s_{2s}$ $\Rightarrow$ Trial and error on P_1 checking s_1:

300 kPa, h_1 : => T = 56.11°C, s = 1.89269 too large

400 kPa, h_1 : => T = 57.6°C, s = 1.87039 too small

Linear interpolation then gives: $\mathbf{P_1 = 375\ kPa}$, $\mathbf{T_1 = 57.2°C}$

9.69 Calculate the isentropic efficiency for each of the stages in the steam turbine shown in Problem 6.41. Find also the total entropy generated in the turbine.

The properties at the inlet and two exit states are from Table B.1

$h_1 = 3373.6$, $s_1 = 6.5965$, $h_2 = 2755.9$, $s_2 = 6.8382$

$h_3 = 251.4 + 0.9 \times 2358.3 = 2373.9$, $s_3 = 0.8319 + 0.9 \times 7.0766 = 7.2008$

The ideal turbine sections are reversible and adiabatic so the exit states are 2s and 3s. Assume the second stage receives the actual exit 2ac from the first stage.

$s_{2s} = s_1 = 6.5965 = 1.8606 + x_{2s} \times 4.9606 \Rightarrow x_{2s} = 0.9547$

$h_{2s} = 640.2 + 0.9547 \times 2108.5 = 2653.2$ kJ/kg ,

$w_{Is} = 3374 - 2653 = 720.4$ kJ/kg

$s_{3s} = s_2 = 6.8382 = 0.8319 + x_{3s} \times 7.0766 \Rightarrow x_{3s} = 0.8488$

$h_{3s} = 251.4 + 0.8488 \times 2358.3 = 2253.0$ kJ/kg,

$w_{IIs} = 2756 - 2253 = 502.9$ kJ/kg

The efficiencies are

$\eta_i = w_{Iac}/w_{Is} = (3373.6 - 2755.9)/720.4 = \mathbf{0.857}$

$\eta_{II} = w_{IIac}/w_{IIs} = (2755.9 - 2373.9)/502.9 = \mathbf{0.76}$

$\dot{S}_{gen} = \dot{m}_2 s_{2ac} + \dot{m}_3 s_{3ac} - \dot{m}_1 s_1 = 5 \times 6.8382 + 15 \times 7.2008 - 20 \times 6.5965$

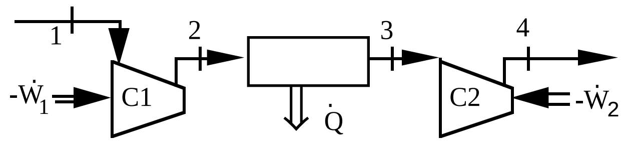
$= \mathbf{10.273\ kW/K}$

9.70 A two-stage compressor having an interstage cooler takes in air, 300 K, 100 kPa, and compresses it to 2 MPa, as shown in Fig. P9.70. The cooler then cools the air to 340 K, after which it enters the second stage, which has an exit pressure of 15.74 MPa. The isentropic efficiency of stage one is 90% and the air exits the second stage at 630 K. Both stages are adiabatic, and the cooler dumps *Q* to reservoir at *T*0. Find *Q* in the cooler, the efficiency of the second stage, and the total entropy generated in this process.

C.V.: Stage 1 air, SSSF

$\dot{m}_1 = \dot{m}_2$, $\quad h_1 + w_1 = h_2$

$s_1 + s_{1gen} = s_2$



IDEAL: $s_{gen} = 0 \Rightarrow s_{2s} = s_1 \Rightarrow P_{r2s} = (P_2/P_1)P_{r1} = 22.2916$

$\Rightarrow T_{2s} = 700,\ h_{2s} = 713.27 \qquad -w_{1s} = 413.08$

ACTUAL: $\quad -w_{1,AC} = -w_{1s}/\eta = 458.98 = h_{2AC} - h_1 \Rightarrow h_{2AC} = 759.17$

C.V.: COOLER AIR, SSSF

Cont.: $\dot{m}_3 = \dot{m}_2$, $\qquad$ Energy: $\qquad q_{ouT} = h_2 - h_3 = \mathbf{418.74}$

From Table A.7: $\quad h_3 = 340.7,\ P_{r3} = 6.99515$

C.V.: STAGE 2 AIR, SSSF

$\dot{m}_4 = \dot{m}_3$; $\ h_4 = h_3 - w_2$; $\ s_4 = s_3 + s_{2gen}$; $\ -w_{2s} = h_{4s} - h_3 = 266.59$

IDEAL: $s_{2gen} = 0 \Rightarrow s_{4s} = s_3 \Rightarrow P_{r4s} = (P_4/P_3)P_{r3} = 55.052$

$\Rightarrow T_{4s} = 600 \qquad h_{4s} = 607.02$

ACTUAL: $s_{2gen} > 0 \quad -w_{2,ac} = h_{4,ac} - h_3 = 298.25 \Rightarrow \eta_2 = \dfrac{w_{2s}}{w_{2AC}} = \mathbf{0.894}$

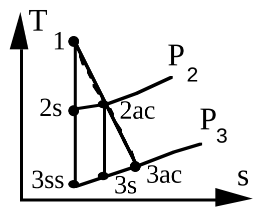
C.V.: TOTAL OUT TO T_0: $\quad \dot{m}s_1 + \dot{m}s_{gen\ tot} = (\dot{m}q_{out})/T_0 + \dot{m}s_4$

From Table A.7: $\quad s^o_{T_1} = 6.86926,\ \ h_{4AC} = 638.95,\ \ s^o_{T_4} = 7.6277$

$$s_4 - s_1 = s^o_{T_4} - s^o_{T_1} - R\ln(P_4/P_1) = -0.69$$

$$\Rightarrow s_{gen\ tot} = s_4 - s_1 + q_{out}/T_0 = \mathbf{0.77\ kJ/kg\ K}$$

9.71 A two-stage turbine receives air at 1160 K, 5.0 MPa. The first stage exit at 1 MPa then enters stage 2, which has an exit pressure of 200 kPa. Each stage has an isentropic efficiency of 85%. Find the specific work in each stage, the overall isentropic efficiency, and the total entropy generation.



C.V. around each turbine for first the ideal and then the actual produces for stage 1:

Ideal T1: $s_{2s}=s_1$ => $P_{r2} = P_{r1}P_2/P_1 = 33.297$

$\Rightarrow$ $h_{2s} = 789.93$; $w_{t1s} = h_{2s} - h_1 =$ **441.04**

$w_{T1ac} = \eta w_{T1s} = 374.88$ kJ/kg $\Rightarrow$ $h_{2ac} = 856.09$, $P_{r2ac} = 44.57$

$P_{r3} = P_{r2ac}P_3/P_2 = 8.915$ $\Rightarrow$ $h_{3s} = 544.49$, $w_{T2s} =$ **311.6**

$w_{T2ac} = \eta w_{T2s} = 264.86$ $\Rightarrow$ $h_{3ac} = 591.23$, $s^\circ_{T3ac} = 7.5491$

$T_{2s} = 770$, $T_{2ac} = 830$, $T_{3s} = 540$, $T_{3ac} \cong 585$

For the overall isentropic efficiency we need the isentropic work:

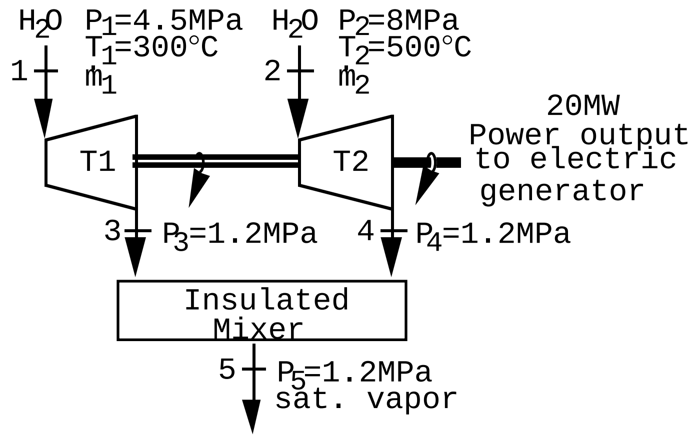
$P_{r3ss} = P_{r1}P_3/P_1 = 6.659$ $\Rightarrow$ $h_{3ss} = 500.97$ $w_{ss} = 730.0$

$\eta = (w_{T1ac} + w_{T2ac})/w_{ss} =$ **0.876**

$s_{T\ gen} = s_3 - s_1 = s^\circ_{T3} - s^\circ_{T1} - R \ln (P_3/P_1)$

$= 7.5491 - 8.30626 - 0.287 \ln \left(\frac{200}{5000}\right) =$ **0.1666 kJ/kg K**

9.72 A paper mill, shown in Fig. P9.72, has two steam generators, one at 4.5 MPa, 300°C and one at 8 MPa, 500°C. Each generator feeds a turbine, both of which have an exhaust pressure of 1.2 MPa and isentropic efficiency of 87%, such that their combined power output is 20 MW. The two exhaust flows are mixed adiabatically to produce saturated vapor at 1.2 MPa. Find the two mass flow rates and the entropy produced in each turbine and in the mixing chamber.



$h_1 = 2943.1$

$s_1 = 6.2828$

$h_2 = 3398.3$

$s_2 = 6.7240$

$h_5 = 2784.8$

$s_5 = 6.5233$

CV T1:

$w_{T1,s} = h_1 - h_{3s}$

$s_{3s} = s_1$

3s: $x_{3s} = (6.2828 - 2.2165)/4.3067 = 0.9442 \quad \Rightarrow$

$h_{3s} = 798.6 + 0.9442 \times 1986.2 = 2673.9 \quad \Rightarrow \quad w_{T1,s} = 269.2$ kJ/kg

$w_{T1,AC} = 0.87 \times 269.2 = 234.2$,

$h_{3,AC} = 2708.9 = 798.6 + x_{3AC} \times 1986.2 \quad => \; x_{3AC} = 0.9618$

$s_{3AC} = 2.2165 + 0.9618 \times 4.3067 = 6.3586$,

$s_{genT1} = 6.3586 - 6.2828 = 0.0758$ kJ/kg K

CV T2: $w_{T2,s} = h_2 - h_{4s}$, $s_{4s} = s_2 = 6.7240$

4s: $T_{4s} = 226.7°C$, $h_{4s} = 2881.1$, $w_{T2,s} = 517.2$, $w_{T2,AC} = 450.0$

$h_{4,AC} = 2948.3$, $s_{4AC} = 6.8546$,

$s_{genT2} = 6.8546 - 6.7240 = 0.1306$ kJ/kg K

C.V mixer: $\dot{m}_{T1}h_{3AC} + \dot{m}_{T2}h_{4,AC} = (\dot{m}_{T1} + \dot{m}_{T2})h_5$

$\Rightarrow \; (\dot{m}_{T1}/\dot{m}_{Tot})(h_{3,AC} - h_{4,AC}) = h_5 - h_{4,AC}$

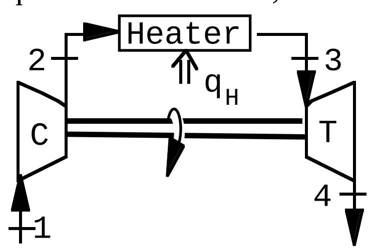
$(\dot{m}_{T1}/\dot{m}_{Tot}) = 0.683$, $\quad (\dot{m}_{T2}/\dot{m}_{tot}) = 0.317$

C.V. Total: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = 20\text{ MW} + \dot{m}_{tot} h_5$

$\dot{m}_{tot} \times 302.598 = 20\text{MW} \quad \Rightarrow \quad \dot{m}_{tot} = 66.094$ kg/s

$\dot{m}_{tot}s_{gen} = \dot{m}_{tot}s_5 - \dot{m}_{T1}s_3 - \dot{m}_{T2}s_4 = 0.00747\,\dot{m}_{tot} =$ **0.494 kW/K**

9.73 A heat-powered portable air compressor consists of three components: (a) an adiabatic compressor; (b) a constant pressure heater (heat supplied from an outside source); and (c) an adiabatic turbine. The compressor and the turbine each have an isentropic efficiency of 85%. Ambient air enters the compressor at 100 kPa, 300 K, and is compressed to 600 kPa. All of the power from the turbine goes into the compressor, and the turbine exhaust is the supply of compressed air. If this pressure is required to be 200 kPa, what must the temperature be at the exit of the heater?



$P_1 = 100$ kPa $T_1 = 300$ K $P_2 = 600$ kPa

$P_4 = 200$ kPa $\eta_{s_c} = 0.85$ $\eta_{s_t} = 0.85$

$$T_{2s} = T_1\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = 300(6)^{0.286} = 500.8 \text{ K}$$

$$-w_{s_c} = C_{P_0}(T_{2s} - T_1) = 1.004(500.8 - 300) = 201.5$$

$$-w_c = (-w_{s_c}/\eta_{s_c}) = (201.5/0.85) = 237.1 = w_T$$

$$w_{sT} = (w_T/\eta_{sT}) = (237.1/0.85) = 278.9 = C_{P_0}(T_3 - T_{4s})$$

$$T_{4s} = T_3(P_4/P_3)^{\frac{k-1}{k}} = T_3(200/600)^{0.286} = 0.7304\ T_3$$

$278.9 = 1.004\ T_3(1 - 0.7304)$ => $T_3 =$ **1030.9 K**

9.74 Assume an actual compressor has the same exit pressure and specific heat transfer as the ideal isothermal compressor in Problem 9.4 with an isothermal efficiency of 80%. Find the specific work and exit temperature for the actual compressor.

$w_{AC} = w_s/\eta = -22.8/0.8 = 28.5$ kJ/kg

$h_e = h_i + q - w_{AC} = 403.4 + (-27.83) + 28.5 = 404.07$

$T_{e,AC} \approx 6°C$ $P_e = 294$ kPa

9.75 A watercooled air compressor takes air in at 20°C, 90 kPa and compresses it to 500 kPa. The isothermal efficiency is 80% and the actual compressor has the same heat transfer as the ideal one. Find the specific compressor work and the exit temperature.

Ideal isothermal compressor exit 500 kPa, 20 °C

$$q = T(s_e - s_i) = T[s^o_{Te} - s^o_{T1} - R\ln(P_e/P_i)]$$

$$= -TR\ln(P_e/P_i) = -0.287 \times 293.15 \ln(500/90) = -144.3 \text{ kJ/kg}$$

As $h_e = h_i \Rightarrow w = q = -144.3$ => $w_{AC} = w/\eta = -180.3$ kJ/kg, $q_{AC} = q$

$q_{AC} + h_i = h_e + w_{AC} \Rightarrow$

$h_e - h_i = q_{AC} - w_{Ac} = -144.3 - (-180.3) = 36$ kJ/kg $\approx Cp(T_e - T_i)$

$T_e = T_i + 36/1.004 =$ **55.9°C**

9.76 Repeat Problem 9.33 when the compressor has an isentropic efficiency of 80%.

C.V.: Compressor $\eta_s = 0.8$, R-134a

inlet: $T_1 = 5^oC$, $x_1 = 0.965$

$s_1 = s_f + x_1 s_{fg} = 1.0243 + 0.965*0.6995 = 1.6993$ kJ/kg K,

$h_1 = h_f + x_1 h_{fg} = 206.8 + 0.965*194.6 = 394.6$ kJ/kg

exit: $P_2 = 3$ MPa

For ideal process $s_{2s} = s_1 = 1.6993$ kJ/kg K; $T_{2s} = 90^oC$, $h_{2s} = 436.2$ kJ/kg

1st Law: $q_c + h_1 = h_2 + w_c$; $q_c = 0$

$w_{cs} = h_1 - h_{2s} = -41.6$ kJ/kg => $w = w_s/\eta_s = 52.0$ kJ/kg

$h_2 = h_1 - w = 446.6$ kJ/kg

C.V.: Tank; $V_T = 2\ m^3$, $P_T = 3$ MPa

1st Law: $Q_{CV} + m_i h_i = m_2 u_2 - m_1 u_1 + m_e h_e + W_{CV}$;

$Q_{CV} = 0$, $W_{CV} = 0$, $m_e = 0$

$m_1 = 0$, $m_2 = m_i$; $u_2 = h_i = 446.6$ kJ/kg

$P_f = 3$ MPa, $u_2 = 446.6$ kJkg ‡ $T_f = 110^oC$, $v_f = 0.007339 m^3/kg$

$m_T = V_T/v_f = 272.5$ kg; $W_c = m_T w_c =$ **14197 kJ**

9.77 Saturated vapor R-22 enters an insulated compressor with an isentropic efficiency of 75% and the R-22 exits at 3.5 MPa, 120°C. Find the compressor inlet temperature by trial and error.

C.V.: Compressor, Insulated, $\eta_s = 0.75$, R-22

Inlet: sat. vap., $x_i = 1.0$

Exit: $T_e = 120^oC$, $P_e = 3.5$ MPa, $h_e = 311.1$ kJ/kg, $s_e = 0.9552$ kJ/kg-K

1st Law: $q + h_i = h_e + w$, $q = 0$, $w = h_i - h_e$

Ideal: $s_{es} = s_i$, $w_s = h_i - h_{es}$; Real: $s_e > s_i$, $w = h_i - h_e$, $\eta_s = w_s/w$

$\eta_s = \dfrac{h_i - h_{es}}{h_i - h_e}$, $s_i < s_e$ ‡ $T_i > -17^oC$

Trial & Error Solution

Assume $T_i = 5^oC$ ‡ $h_i = 251.731$ kJ/kg, $s_i = 0.9197$ kJ/kg-K

$P_e = 3.5$ MPa, $s_{es} = s_i = 0.9197$ ‡ $h_{es} = 297.4$ kJ/kg

$\dfrac{h_i - h_{es}}{h_i - h_e} = 0.769 = \eta_s$, **$T_i = 5^oC$**

9.78 Air enters an insulated turbine at 50°C, and exits the turbine at - 30°C, 100 kPa. The isentropic turbine efficiency is 70% and the inlet volumetric flow rate is 20 L/s. What is the turbine inlet pressure and the turbine power output?

C.V.: Turbine, $\eta_s = 0.7$, Insulated

Air: $C_p = 1.004$ kJ/kg-K, $R = 0.287$ kJ/kg-K, $k = 1.4$

Inlet: $T_i = 50^oC$, $\dot{V}_i = 20$ L/s $= 0.02\ m^3/s$

Exit: $T_e = -30^oC$, $P_e = 100$ kPa

a) 1^{st} Law SSSF: $q_T + h_i = h_e + w_T$; $q_T = 0$

Assume Constant Specific Heat

$w_T = h_i - h_e = C_p(T_i - T_e) = 80.3$ kJ/kg

$w_{Ts} = w/\eta = 114.7$ kJ/kg, $w_{Ts} = C_p(T_i - T_{es})$

Solve for $T_{es} = 208.9$ K

Isentropic Process: $P_e = P_i\,(T_e / T_i)^{\frac{k}{k-1}}$ => $\mathbf{P_i = 461\ kPa}$

b) $\dot{W}_T = \dot{m}w_T$; $\dot{m} = P\dot{V}/RT = 0.099$ kg/s => $\dot{W}_T = \mathbf{7.98\ kW}$

9.79 Repeat Problem 9.43 for a pump/compressor isentropic efficiency of 70%.

C.V.: Pump/Compressor, $\dot{m} = 0.5$ kg/s, R-134a

a) State 1: Table B.5.1, $T_1 = -10^oC$, $x_1 = 1.0$ Saturated vapor

$P_1 = P_g = 202$ kPa, $h_1 = h_g = 392.3$ kJ/kg, $s_1 = s_g = 1.7319$ kJ/kg K

First do ideal Compressor is Isentropic, $s_{2s} = s_1 = 1.7319$ kJ/kg-K

$h_{2s} = 425.7$ kJ/kg, $T_{2s} = 45^oC$

1^{st} Law: $q_c + h_1 = h_2 + w_c$; $q_c = 0$

$w_{cs} = h_1 - h_2 = -33.4$ kJ/kg; => $w_{c\ ac} = w_{cs}/\eta = -33.4/0.7 = -47.7$ kJ/kg

$h_2 = h_1 - w_{c\ ac} = 440$ kJ/kg, 1 MPa => $T_{2\ ac} = 59^oC$

$\dot{W}_C = \dot{m}w_C = \mathbf{-23.85\ kW}$

b) State 1: $T_1 = -10^oC$, $x_1 = 0$ Saturated liquid. This is a pump.

$P_1 = 202$ kPa, $h_1 = h_f = 186.72$ kJ/kg, $v_1 = v_f = 0.000755\ m^3/kg$

Assume Pump is isentropic and the liquid is incompressible:

$w_{ps} = -\int v\,dP = -v_1(P_2 - P_1) = -0.6$ kJ/kg => $w_p = w_{ps}/\eta = -0.86$ kJ/kg

$h_2 = h_1 - w_p = 186.72 - (-0.86) = 187.58$ kJ/kg, $P_2 = 1$MPa

Assume State 2 is a saturated liquid => $\mathbf{T_2 \cong -9.7^oC}$

$\dot{W}_P = \dot{m}w_P = \mathbf{-0.43\ kW}$

9.80 A certain industrial process requires a steady 0.5 kg/s supply of compressed air at 500 kPa, at a maximum temperature of 30°C. This air is to be supplied by installing a compressor and aftercooler. Local ambient conditions are 100 kPa, 20°C. Using an isentropic compressor efficiency of 80%, determine the power required to drive the compressor and the rate of heat rejection in the aftercooler.

Air: R = 0.287 kJ/kg-K, C_p = 1.004 kJ/kg-K, k = 1.4

State 1: $T_1 = T_o = 20^oC$, $P_1 = P_o = 100$ kPa, $\dot{m} = 0.5$ kg/s

State 2: $P_2 = P_3 = 500$ kPa

State 3: $T_3 = 30^oC$, $P_3 = 500$ kPa

Assume η_s = 80 % (Any value between 70%-90% is OK)

Compressor: Assume Isentropic

$$T_{2s} = T_1 \left(P_2/P_1\right)^{\frac{k-1}{k}}, \quad T_{2s} = 464.6 \text{ K}$$

1st Law: $q_c + h_1 = h_2 + w_c$; $q_c = 0$, assume constant specific heat

$$w_{cs} = C_p(T_1 - T_{2s}) = -172.0 \text{ kJ/kg}$$

$$\eta s = w_{cs}/w_c, \quad w_c = w_{cs}/\eta s = -215, \quad \dot{W}_C = \dot{m}w_C = \mathbf{-107.5\ kW}$$

$$w_c = C_p(T_1 - T_2), \text{ solve for } T_2 = 507.5 \text{ K}$$

Aftercooler:

1st Law: $q + h_2 = h_3 + w$; $w = 0$, assume constant specific heat

$$q = C_p(T_3 - T_2) = 205 \text{ kJ/kg}, \quad \dot{Q} = \dot{m}q = \mathbf{-102.5\ kW}$$

9.81 The turbo charger in Problem 9.24 has isentropic efficiencies of 70% for both the compressor and the turbine. Repeat the questions when the actual compressor has the same flow rate as the ideal but a lower exit pressure.

a) CV: Ideal turbine

$$s_4 = s_3 \rightarrow T_4 = T_3(P_4/P_3)^{\frac{k-1}{k}} = 923.2\left(\frac{100}{170}\right)^{0.286} = \mathbf{793.2\ K}$$

$$w_T = C_{P0}(T_3 - T_4) = 1.004(923.2 - 793.2) = 130.5\ \text{kJ/kg}$$

$$\dot{W}_T = \dot{m}w_T = \mathbf{13.05\ kW}$$

b) $-w_C = w_T = 130.5 = C_{P0}(T_2 - T_1) = 1.004(T_2 - 303.2)$

$T_2 = \mathbf{433.2\ K}$

$$s_2 = s_1 \rightarrow P_2 = P_1(T_2/T_1)^{\frac{k}{k-1}} = 100\left(\frac{433.2}{303.2}\right)^{3.5} = \mathbf{348.7\ kPa}$$

c) $\eta_{ST} = 0.85$ and $\eta_{SC} = 0.80$

As in a), $T_{4S} = 793.2$ K & $w_{ST} = 130.5$ kJ/kg

$w_T = 0.85 \times 130.5 = 110.9 = C_{P0}(T_3 - T_4) = 1.004(923.2 - T_4)$

$\rightarrow$ $T_4 = \mathbf{812.7\ K}$

$\dot{W}_T = \dot{m}w_T = \mathbf{11.09\ kW}$

$-w_C = w_T = 110.9 = C_{P0}(T_2 - T_1) = 1.004(T_2 - 303.2)$

$T_2 = \mathbf{413.7\ K}$

$-w_{CS} = 0.8 \times 110.9 = 88.7 = C_{P0}(T_{2S} - T_1) = 1.004(T_{2S} - 303.2)$

$\rightarrow$ $T_{2S} = 391.6$ K

$$s_{2S} = s_1 \rightarrow P_2 = P_1\left(\frac{T_{2S}}{T_1}\right)^{\frac{k}{k-1}} = 100\left(\frac{391.6}{303.2}\right)^{3.5} = \mathbf{244.9\ kPa}$$

9.82 In a heat-powered refrigerator, a turbine is used to drive the compressor using the same working fluid. Consider the combination shown in Fig. P9.82 where the turbine produces just enough power to drive the compressor and the two exit flows are mixed together. List any assumptions made and find the ratio of mass flow rates $\dot{m}_3/\dot{m}_1$ and T_5 (x_5 if in two-phase region) if

a. The turbine and the compressor are reversible and adiabatic

b. The turbine and the compressor both have an isentropic efficiency of 70%

a) turbine & compressor both isentropic

CV: compressor

$s_{2S} = s_1 = 0.7082 \rightarrow T_{2S} = 52.6°C$

$w_{SC} = h_1 - h_{2S} = 178.61 - 212.164 = -33.554$

CV: turbine

$s_{4S} = s_3 = 0.6444 = 0.2767 + x_{4S} \times 0.4049 \quad => \quad x_{4S} = 0.9081$

$h_{4S} = 76.155 + 0.9081 \times 127.427 = 191.875$

$w_{ST} = h_3 - h_{4S} = 209.843 - 191.875 = 17.968 \text{ kJ/kg}$

As $\dot{w}_{TURB} = -\dot{w}_{COMP}$, $\dot{m}_3/\dot{m}_1 = -\dfrac{w_{SC}}{w_{ST}} = \dfrac{33.554}{17.968} = \mathbf{1.867}$

CV: mixing portion

$\dot{m}_1 h_{2S} + \dot{m}_3 h_{4S} = (\dot{m}_1 + \dot{m}_3) h_5$

$1 \times 212.164 + 1.867 \times 191.875 = 2.867\ h_5$

$\Rightarrow h_5 = 198.980 = 76.155 + x_5 \times 127.427 \quad => \quad x_5 = \mathbf{0.9639}$

b) Both $\eta_S = 0.70$ & $\eta_{SC} = 0.70$

$\Rightarrow w_C = w_{SC}/\eta_{SC} = -33.554/0.70 = -47.934$

$w_T = \eta_{ST} w_{ST} = 0.70 \times 17.968 = 12.578$

$\dot{m}_3/\dot{m}_1 = -w_C/w_T = 47.934/12.578 = \mathbf{3.811}$

Comp: $h_2 = h_1 - w_C = 178.61 + 47.934 = 226.544$

Turb: $h_4 = h_3 - w_T = 209.843 - 12.578 = 197.265$

Mix: $1 \times 226.544 + 3.811 \times 197.265 = 4.811\ h_5$

$h_5 = 203.351 = 76.155 + x_5 \times 127.427 \quad => \quad x_5 = \mathbf{0.9982}$

Advanced Problems.

9.83 An air turbine with inlet conditions 1200 K, 1 MPa and exhaust pressure of 100 kPa pulls a sledge over a leveled plane surface, T = 20°C. The turbine work overcomes the friction between the sledge and the surface. Find the total entropy generation per kilogram of air through the turbine.

Assume an adiabatic reversible turbine

Energy Eq.: $w_T = h_i - h_e$, Entropy Eq.: $s_i = s_e$

Exit state: P_e , $s_e = s_i$ Table A.7

$\Rightarrow P_{re} = P_{ri}P_e/P_i = 191.174 \times 100/1000 = 19.117$

$\Rightarrow T_e = 665$ K, $h_e = 676$, $w_T = 1277.8 - 676 = 602$ kJ/kg

The work is dissipated at the surface as frictional heat

$s_{gen} = w_T/T_{surf} = 602 / 293.15 =$ **2.05 kJ/kg K**

9.84 Consider the scheme shown in Fig. P9.84 for producing fresh water from salt water. The conditions are as shown in the figure. Assume that the properties of salt water are the same as for pure water, and that the pump is reversible and adiabatic.

a. Determine the ratio $(\dot{m}_7/\dot{m}_1)$, the fraction of salt water purified.

b. Determine the input quantities, w_P and q_H.

c. Make a second law analysis of the overall system.

C.V. Flash evaporator: SSSF, no external q, no work.

Energy Eq.: $\dot{m}_1h_4 = (\dot{m}_1 - \dot{m}_7)h_5 + \dot{m}_7h_6$

Table B.1.1 or $632.4 = \left(1 - (\dot{m}_7/\dot{m}_1)\right) 417.46 + (\dot{m}_7/\dot{m}_1)\ 2675.5$

$\Rightarrow \dot{m}_7/\dot{m}_1 =$ **0.0952**

C.V. Pump SSSF, incompressible liq.:

$w_P = -\int vdP \approx -v_1(P_2 - P_1) = -0.001001(700 - 100) =$ **-0.6 kJ/kg**

$h_2 = h_1 - w_P = 62.99 + 0.6 = 63.6$

C.V. Heat exchanger: $h_2 + (\dot{m}_7/\dot{m}_1)h_6 = h_3 + (\dot{m}_7/\dot{m}_1)h_7$

$63.6 + 0.0952 \times 2675.5 = h_3 + 0.0952 \times 146.68 \Rightarrow h_3 = 304.3$ kJ/kg

C.V. Heater: $q_H = h_4 - h_3 = 632.4 - 304.3 =$ **328.1 kJ/kg**

CV: entire unit (SSSF) entropy equation per unit mass flow rate at state 1

$S_{C.V.,gen} = -q_H/T_H + \left(1 - (\dot{m}_7/\dot{m}_1)\right)s_5 + (\dot{m}_7/\dot{m}_1)s_7 - s_1$

$= (-328.1/473.15) + 0.9048 \times 1.3026 + 0.0952 \times 0.5053 - 0.2245$

$= 0.3088$ kJ/K kg m_1

9.85 A cylinder/piston containing 2 kg of ammonia at −10°C, 90% quality is brought into a 20°C room and attached to a line flowing ammonia at 800 kPa, 40°C. The total restraining force on the piston is proportional to the cylinder volume squared. The valve is opened and ammonia flows into the cylinder until the mass inside is twice the initial mass and the valve is closed. An electrical current of 15 A is passed through a 2-Ω resistor inside the cylinder for 20 min. It is claimed that the final pressure in the cylinder is 600 kPa. Is this possible?

$$T_1 = -10°C, \quad x_1 = 0.90 \quad \rightarrow \quad P_1 = 290.7 \text{ kPa}$$

$$v_1 = 0.001534 + 0.9 \times 0.41655 = 0.37669$$

$$u_1 = 133.96 + 0.9 \times 1175.2 = 1191.8$$

$$s_1 = 0.5408 + 0.9 \times 4.9265 = 4.9750$$

CV: cylinder

$$V_1 = mv_1 = 2 \times 0.37669 = 0.75338 \text{ m}^3 \quad => \quad m_2 = 2m_1 = 4 \text{ kg}$$

Claim: $P_2 = 600$ kPa   Process: $\quad P = CV^2 = \left[P_1/(V_1)^2\right]V^2$

$$V_2 = V_1(P_2/P_1)^{1/2} = 0.75338\left(\frac{600}{290.7}\right)^{1/2} = 1.08235 \text{ m}^3$$

$$\left.\begin{array}{l} v_2 = (V_2/m_2) = 0.27059 \\ P_2 = 600 \text{ kPa} \end{array}\right\} \rightarrow \begin{array}{l} T_2 = 71.9°C \\ u_2 = 1447.9 \end{array} \quad s_2 = 5.7226$$

At $P_i = 800$ kPa, $T_i = 40°C \quad \rightarrow \quad h_i = 1520.9, \quad s_i = 5.3171$

$$W_{BDRY} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{600 \times 1.08235 - 290.7 \times 0.75338}{1 - (-2)} = 143.5 \text{ kJ}$$

1st law: $Q_{CV} = m_2u_2 - m_1u_1 - m_ih_i + W_{BDRY} + W_{ELEC}$

$$= 4 \times 1447.9 - 2 \times 1191.8 - 2 \times 1520.9$$

$$+ 143.5 - \frac{30 \times 15}{1000} \times 60 \times 20 = -30.3 \text{ kJ}$$

$$\Delta S_{CV} = S_2 - S_1 = 4 \times 5.7226 - 2 \times 4.9750 = +12.940 \text{ kJ/K}$$

$$\Delta S_{SURR} = -\frac{Q_{CV}}{T_0} - m_is_i = \frac{+30.3}{293.2} - 2 \times 5.3171 = -10.531 \text{ kJ/K}$$

$\Delta S_{NET} = +12.940 - 10.531 =$ **+2.409 kJ/K**

9.86 A certain industrial process requires a steady stream of saturated vapor water at 200 kPa at a rate of 2 kg/s. There are two alternatives for supplying this steam from ambient liquid water at 20°C, 100 kPa. Assume pump efficiency of 80%.

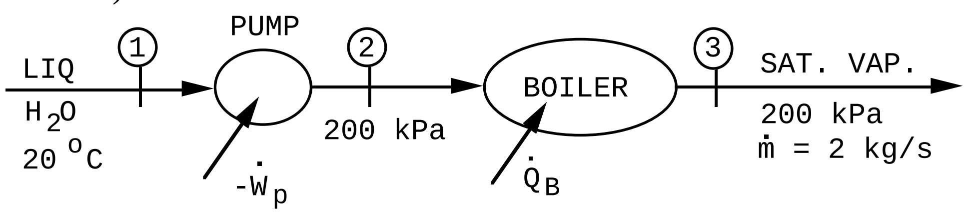
1. Pump the water to 200 kPa and feed it to a steam generator (heater).

2. Pump the water to 5 MPa, feed it to a steam generator and heat to 450°C, then expand it through a turbine from which the steam exhausts at the desired state.

a. Compare these two alternatives in terms of heat transfer and work terms. Is the turbine isentropic efficiency reasonable?

b. What is the total entropy generation for each alternative?

1)



P_1 = 100 kPa, T_1 = 20°C, v_1 = 0.001002

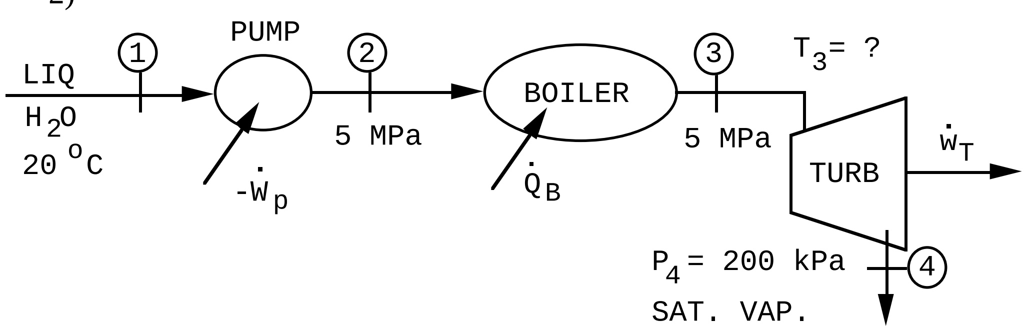
$-w_s \approx v_1(P_2 - P_1) = 0.001002\ (200 - 100) = 0.1$ kJ

$\Rightarrow -w_P = \dfrac{0.1}{0.8} = 0.125$ kJ, $-\dot{W}_P = \dot{m}(-w) =$ **0.25 kW**

$q_B = h_3 - h_2$, $h_2 = h_1 - w_P = 83.96 + 0.13 = 84.1$

$q_B = 2706.7 - 84.1 = 2622.6$, $\dot{Q}_B =$ **5245.2 kW**

2)



$h_4 = 2706.7$, $s_4 = 7.1271$

$-w_{SP} \approx 0.001002\ (5000 - 100) = 4.91$ kJ

$\Rightarrow -w_P = \dfrac{4.91}{0.8} = 6.14$ kJ; $-\dot{W}_P =$ **12.3 kW**

$h_2 = 83.96 + 6.14 = 90.1$

For given $T_3 = 450°C \rightarrow h_3 = 3316.2$, $s_3 = 6.8186$

$$\text{From}\ \left.\begin{array}{l} s_{4S} = s_3 = 6.8186 \\ P_4 = 200 \text{ kPa} \end{array}\right\} \rightarrow \begin{array}{l} x_{4S} = 0.9449 \\ h_{4S} = 2585.2 \end{array}$$

$$\eta_{ST} = \frac{h_3\text{-}h_4}{h_3\text{-}h_{4S}} = \frac{609.5}{731.0} = \mathbf{0.834} \quad \textbf{OK}$$

$\Rightarrow T_3 = 450°C$ OK. $q_B = h_3\text{-}h_2 = 3316.2 - 90.1 = 3226.1$

$\dot{Q}_B = \mathbf{6452.2\ kW}$, $\dot{W}_T = 2 \times 609.5 = \mathbf{1219\ kW}$

1. $\dot{W}_P = -0.25$ kW, $\dot{Q}_B = 5245.2$ kW
2. $\dot{W}_P = -12.3$ kW, $\dot{Q}_B = 6452.2$ kW, $\dot{W}_T = 1219$ kW

b) 1. $dS_{NET}/dt = \dot{m}(s_3\text{-}s_1) - \dot{Q}_B/T_0$

$= 2(7.1271 - 0.2966) - 5245.2/(120.2 + 273.2)$

(120.2 = min. temp.)

$= 13.661 \ -13.333 = \mathbf{0.328\ kW/K}$

2. $$dS_{NET}/dt = 13.661 + \frac{-6452.2}{450 + 273.2} = \mathbf{4.739\ kW/K}$$

(450.0 = min. temp.)

9.87 Ammonia enters a nozzle at 800 kPa, 50°C, at a velocity of 10 m/s and at the rate of 0.1 kg/s. The nozzle expansion is assumed to be a reversible, polytropic SSSF process. Ammonia exits the nozzle at 200 kPa; the rate of heat transfer to the nozzle is 8.2 kW. Verify that the exit temperature is close to -10°C. What is the velocity of the ammonia exiting the nozzle?

Process: $P_i v_i^n = P_e v_e^n$; $q = \dot{Q}/\dot{m} = 8.2 / 0.1 = 82$ kJ/kg

$$0 = -\int_i^e v dP + (KE_i - KE_e) \quad \text{or} \quad 0 = -\frac{n}{n-1}(P_e v_e - P_i v_i) + (KE_i - KE_e)$$

$$q + h_i + KE_i = h_e + KE_e = 82 + 1547.0 + \frac{10^2}{2\times1000} = 1629.1$$

Assume $T_e = -10°C \rightarrow v_e = 0.619\,26$, $h_e = 1440.6$

$800 \times 0.18465^{\,n} = 200 \times 0.61926^{\,n}$ or $(3.3537)^n = 4.0$

$n = [\ln(4)/\ln(3.3537)] = 1.1456$

$$KE_e = -\frac{1.1456}{0.1456}(200 \times 0.61926 - 800 \times 0.18465) + 0.05$$

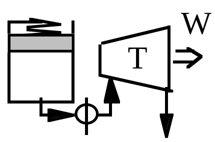
$= 187.8$ ($\mathbf{V}_e \sim 613$ m/s)

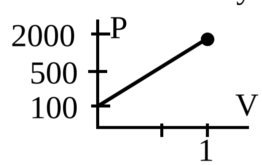
1st law: $h_e + KE_e = 1440.6 + 187.8 = 1628.5 \approx 1629.1$

OK $\mathbf{V_e = 613\ m/s}$

9.88 A cylinder fitted with a spring-loaded piston serves as the supply of steam for a steam turbine. Initially, the cylinder pressure is 2 MPa and the volume is 1.0 m3. The force exerted by the spring is zero at zero cylinder volume, and the top of the piston is open to the ambient. The cylinder temperature is maintained at a constant 300°C by heat transfer from a source at that temperature. A pressure regulator between the cylinder and turbine maintains a steady 500 kPa, 300°C at the turbine inlet, such that when the cylinder pressure drops to 500 kPa, the process stops. The turbine process is reversible and adiabatic, and the exhaust is to a condenser at 50 kPa.

a) What is the total work output of the turbine during the process?
b) What is the turbine exhaust temperature (or quality)?
c) What is the total heat transfer to the cylinder during the process?





T = Constant, P_o = 100 kPa

When $V_o = 0$, $F_{spr} = 0$

C.V. Cylinder:

State 1: $v_1 = 0.12547\ m^3/kg$, $u_1 = 2772.6$ kJ/kg, $h_1 = 3023.5$ kJ/kg,

$m_1 = V_1/v_1 = 7.97$ kg

Linear P-V relation: $V_2 - V_0 = (V_1 - V_0) \times (P_2 - P_0) / (P_1 - P_0)$

=> $V_2 = 0.2105\ m^3$

State 2: $T_2 = 300^oC$, $P_2 = 500$ kPa, $v_2 = 0.52256\ m^3/kg$, $u_2 = 2802.9$ kJ/kg,

$h_2 = 3064.2$ kJ/kg, => $m_2 = V_2/v_2 = 0.403$ kg

a) C.V. Turbine, Assume that the process is isentropic

Inlet: $T_i = 300^oC$, $P_i = 500$ kPa; $h_i = 3064.2$ kJ/kg, $s_i = 7.4598$ kJ/kg-K

Exit: $P_e = 50$ kPa, $m_e = m_i = m_1 - m_2$

b) $s_{e,s} = s_i = 7.4598$ kJ/kg K, $x_{e,s} = (7.4598-1.091)/6.5029 = 0.9794$

$h_{e,s} = 340.47 + 0.9794 \times 2305.4 = 2598.4$ kJ/kg, ‡ $\mathbf{T_e = 81.3^oC}$

1^{st} Law: $q_t + h_i = h_e + w_t$; $q_t = 0$

$w_{t,s} = h_{e,s} - h_i = 465.8$ kJ/kg => $W_{t,} = (m_1 - m_2) \times w_{t,} =$ **3524.7 kJ**

c) C.V. Cylinder, this is USUF.

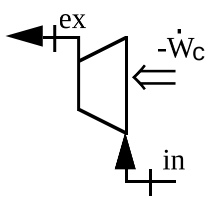
1^{st} Law ${}_1Q_2 + m_i h_i = m_2 u_2 - m_1 u_1 + m_e h_e + {}_1W_2$; $m_i = 0$

$m_e = m_1 - m_2$, $h_e = (h_1 + h_2)/2 = (3023.5 + 3064.2)/2 = 3043.85$ kJ/kg

${}_1W_2 = \int P\, dV = (1/2)(P_1 + P_2)(V_2 - V_1) = -986.9$ kJ

${}_1Q_2 = m_2 u_2 - m_1 u_1 + (m_1 - m_2) h_e + {}_1W_2$ **= 1077.9 kJ**

9.89 Supercharging of an engine is used to increase the inlet air density so that more fuel can be added, the result of which is an increased power output. Assume that ambient air, 100 kPa and 27°C, enters the supercharger at a rate of 250 L/s. The supercharger (compressor) has an isentropic efficiency of 75%, and uses 20 kW of power input. Assume that the ideal and actual compressor have the same exit pressure. Find the ideal specific work and verify that the exit pressure is 175 kPa. Find the percent increase in air density entering the engine due to the supercharger and the entropy generation.



C.V.: Air in compressor (SSSF)

Cont: $\dot{m}_{in} = \dot{m}_{ex} = \dot{m} = \dot{V}/v_{in} = 0.29$ kg/s

Energy: $\dot{m}h_{in} - \dot{W} = \dot{m}h_{ex}$ Assume: $\dot{Q} = 0$

Entropy: $\dot{m}s_{in} + \dot{S}_{gen} = \dot{m}s_{ex}$

$\eta_c = w_{C\,s}/w_{C\,ac} \Rightarrow \quad -\dot{W}_S = -\dot{W}_{AC} \times \eta_c = 15$ kW

$-w_{C\,s} = -\dot{W}_S/\dot{m} = 51.724, \quad -w_{C\,ac} = 68.966$

Table A.7: $\quad h_{ex\,s} = h_{in} - w_{C\,s} = 300.62 + 51.724 = 352.3$

$\Rightarrow T_{ex\,s} = 351.5$ K $\quad P_{r\,ex} = 1.9423$

$P_{ex} = P_{in} \times P_{r\,ex}/P_{r\,in} = 100 \times 1.9423/1.1165 =$ **174 kPa**

The actual exit state is

$h_{ex\,ac} = h_{in} - w_{C\,ac} = 369.6 \;\Rightarrow\; T_{ex\,ac} = 368.6$ K

$v_{in} = RT_{in}/P_{in} = 0.8614, \quad v_{ex} = RT_{ex}/P_{ex} = 0.608$ m^3/kg

$\rho_{ex}/\rho_{in} = v_{in}/v_{ex} = 0.8614/0.608 =$ **1.417 or 41.7 %**

$s_{gen} = s_{ex} - s_{in} = 7.0767 - 6.8693 - 0.287 \ln(174/100)] =$ **0.0484 kJ/kg K**

9.90 A jet-ejector pump, shown schematically in Fig. P9.90, is a device in which a low-pressure (secondary) fluid is compressed by entrainment in a high-velocity (primary) fluid stream. The compression results from the deceleration in a diffuser. For purposes of analysis this can be considered as equivalent to the turbine-compressor unit shown in Fig. P9.82 with the states 1, 3, and 5 corresponding to those in Fig. P9.90. Consider a steam jet-pump with state 1 as saturated vapor at 35 kPa; state 3 is 300 kPa, 150°C; and the discharge pressure, P_5, is 100 kPa.

a. Calculate the ideal mass flow ratio, $\dot{m}_1/\dot{m}_3$.

b. The efficiency of a jet pump is defined as $\eta = (\dot{m}_1/\dot{m}_3)_{actual} / (\dot{m}_1/\dot{m}_3)_{ideal}$ for the same inlet conditions and discharge pressure. Determine the discharge temperature of the jet pump if its efficiency is 10%.

a) ideal processes (isen. comp. & exp.)

$$\left.\begin{array}{l}\text{expands } 3\text{-}4s \\ \text{comp } \quad 1\text{-}2s\end{array}\right\} \text{then mix at const. P}$$

$s_{4s} = s_3 = 7.0778 = 1.3026 + x_{4s} \times 6.0568 \quad => \quad x_{4s} = 0.9535$

$h_{4s} = 417.46 + 0.9535 \times 2258.0 = 2570.5$

$s_{2s} = s_1 = 7.7193 \rightarrow \ T_{2s} = 174°C \ \ \& \ \ h_{2s} = 2823.8$

$\dot{m}_1(h_{2s} - h_1) = \dot{m}_3(h_3 - h_{4s})$

$$\Rightarrow (\dot{m}_1/\dot{m}_3)_{IDEAL} = \frac{2761.0 - 2570.5}{2823.8 - 2631.1} = \mathbf{0.9886}$$

b) real processes with jet pump eff. = 0.10

$\Rightarrow (\dot{m}_1/\dot{m}_3)_{ACTUAL} = 0.10 \times 0.9886 = 0.09886$

1st law $\quad \dot{m}_1 h_1 + \dot{m}_3 h_3 = (\dot{m}_1 + \dot{m}_3) h_5$

$0.09886 \times 2631.1 + 1 \times 2761.0 = 1.09896\, h_5$

State 5: $h_5 = 2749.3$ kJ/kg, $P_5 = 100$ kPa $\quad => \quad T_5 = \mathbf{136.5\ ^oC}$

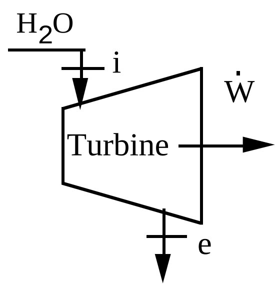
English Unit Problems

9.91E Steam enters a turbine at 450 lbf/in.2, 900 F, expands in a reversible adiabatic process and exhausts at 2 lbf/in.2. Changes in kinetic and potential energies between the inlet and the exit of the turbine are small. The power output of the turbine is 800 Btu/s. What is the mass flow rate of steam through the turbine?

C.V. Turbine, SSSF, single inlet and exit flows. Adiabatic: $\dot{Q} = 0$.

Mass: $\dot{m}_i = \dot{m}_e = \dot{m}$, Energy Eq.: $\dot{m}h_i = \dot{m}h_e + \dot{W}_T$,

Entropy Eq.: $\dot{m}s_i + \emptyset = \dot{m}s_e$ (Reversible $\dot{S}_{gen} = 0$)



Inlet state: Table C.8 $h_i = 1468.3$, $s_i = 1.7113$

Exit state: $s_e = 1.7113$, $P_e = 2$ lbf/in^2 $\Rightarrow$ saturated

$x_e = 0.8805$, $h_e = 993.99$

$w = h_i - h_e = 474.31$ Btu/lbm

$\dot{m} = \dot{W} / w = 800 / 474.31 =$ **1.687 lbm/s**

9.92E In a heat pump that uses R-134a as the working fluid, the R-134a enters the compressor at 30 lbf/in.^{2}, 20 F at a rate of 0.1 lbm/s. In the compressor the R-134a is compressed in an adiabatic process to 150 lbf/in.^{2}. Calculate the power input required to the compressor, assuming the process to be reversible.

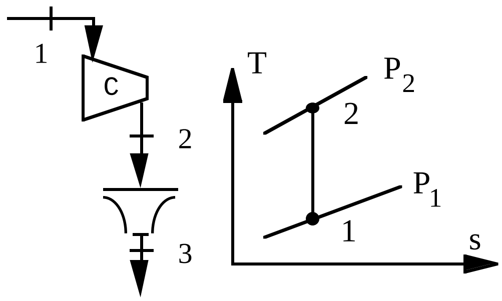
C.V.: Compressor (SSSF reversible: $\dot{S}_{gen} = 0$ & adiabatic: $\dot{Q} = 0$.)

Inlet state: $h_1 = 168.68$ $s_1 = 0.42071$, $s_2 = s_1$

Exit state: $P_2 = P_{g\text{ at }100°F} = 138.93$ & $s_2 \Rightarrow h_2 = 186.68$ Btu/lbm

$\dot{W}_c = \dot{m}w_c = \dot{m}(h_1 - h_2) = 0.1\ (168.68 - 186.68) =$ **-1.8 Btu/s**

9.93E Air at 1 atm, 60 F is compressed to 4 atm, after which it is expanded through a nozzle back to the atmosphere. The compressor and the nozzle are both reversible and adiabatic and kinetic energy in/out of the compressor can be neglected. Find the compressor work and its exit temperature and find the nozzle exit velocity.



SSSF separate control volumes around compressor and nozzle. For ideal compressor we have inlet : 1 and exit : 2

Adiabatic : $q = 0$.

Reversible: $s_{gen} = 0$

Energy Eq.: $h_1 + 0 = w_C + h_2$;

Entropy Eq.: $s_1 + 0/T + 0 = s_2$

$$- w_C = h_2 - h_1 , \quad s_2 = s_1$$

State 1: Table C.6, 519.67 R, h = 124.3, $P_{r1} = 0.9745$

$$\Rightarrow \; P_{r2} = P_{r1} \times P_2/P_1 = 0.9745 \times 4/1 = 3.898$$

State 2: $T_2 = 771$ R $\quad h_2 = 184.87$

$$\Rightarrow \quad -w_C = 184.87 - 124.3 = 60.57 \text{ Btu/lbm}$$

The ideal nozzle then expands back down to state 1 (constant s) so energy equation gives:

$$\frac{1}{2}\mathbf{V}^2 = h_2 - h_1 = -w_C = 60.57 \text{ Btu/lbm} \qquad \text{(remember conversion to lbf-ft)}$$

$$\Rightarrow \quad \mathbf{V} = \sqrt{2*60.57*32.174*778} = \mathbf{1741\ ft/s}$$

9.94E Analyse the steam turbine described in Problem 6.86. Is it possible?

C.V. Turbine. SSSF and adiabatic.

Continuity: $\dot{m}_1 = \dot{m}_2 + \dot{m}_3$; $\qquad$ Energy: $\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_3 h_3 + \dot{W}$

Entropy: $\dot{m}_1 s_1 + \dot{S}_{gen} = \dot{m}_2 s_2 + \dot{m}_3 s_3$

States from Table C.8.2: $s_1 = 1.6398$, $s_2 = 1.6516$,

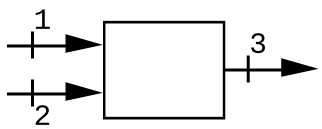
$$s_3 = s_f + x\, s_{fg} = 0.283 + 0.95 \times 1.5089 = 1.71$$

$\dot{S}_{gen} = 40 \times 1.6516 + 160 \times 1.713 - 200 \times 1.6398 =$ **12.2 Btu/s ·R**

Since it is positive => possible.

Notice the entropy is increasing through turbine: $s_1 < s_2 < s_3$

9.95E Two flowstreams of water, one at 100 lbf/in.^{2}, saturated vapor, and the other at 100 lbf/in.^{2}, 1000 F, mix adiabatically in a SSSF process to produce a single flow out at 100 lbf/in.2, 600 F. Find the total entropy generation for this process.



$h_1 = 1187.8 \quad s_1 = 1.6034$

$h_2 = 1532.1 \quad s_2 = 1.9204$

$h_3 = 1329.3 \quad s_3 = 1.7582$

Cont.: $\dot{m}_3 = \dot{m}_1 + \dot{m}_2$, Energy Eq.: $\dot{m}_3 h_3 = \dot{m}_1 h_1 + \dot{m}_2 h_2$

=> $\dot{m}_1/\dot{m}_3 = (h_3 - h_2) / (h_1 - h_2) = 0.589$

Entropy Eq.: $\dot{m}_3 s_3 = \dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{S}_{gen}$ =>

$$\dot{S}_{gen}/\dot{m}_3 = s_3 - (\dot{m}_1/\dot{m}_3)\, s_1 - (\dot{m}_2/\dot{m}_3)\, s_2$$

$$= 1.7582 - 0.589 \times 1.6034 - 0.411 \times 1.9204 = \mathbf{0.0245\ \frac{Btu}{lbm\ R}}$$

9.96E A diffuser is a steady-state, steady-flow device in which a fluid flowing at high velocity is decelerated such that the pressure increases in the process. Air at 18 lbf/in.^{2}, 90 F enters a diffuser with velocity 600 ft/s and exits with a velocity of 60 ft/s. Assuming the process is reversible and adiabatic what are the exit pressure and temperature of the air?

C.V. Diffuser, SSSF single inlet and exit flow, no work or heat transfer.

Energy Eq.: $h_i + \mathbf{V}_i^2/2g_c = h_e + \mathbf{V}_e^2/2g_c$, => $h_e - h_i = C_{Po}(T_e - T_i)$

Entropy Eq.: $s_i + \int dq/T + s_{gen} = s_i + 0 + 0 = s_e$ (Reversible, adiabatic)

Energy equation then gives:

$$C_{Po}(T_e - T_i) = 0.24(T_e - 549.7) = (600^2 - 60^2)/2\times32.2\times778$$

$$T_e = \mathbf{579.3\ R}$$

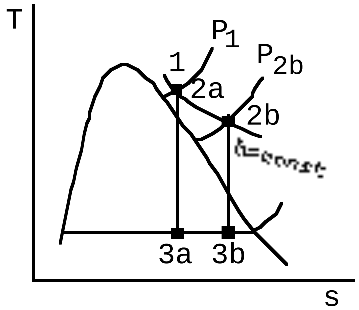
$$P_e = P_i(T_e/T_i)^{\frac{k}{k-1}} = 18\left(\frac{579.3}{549.7}\right)^{3.5} = \mathbf{21.6\ lbf/in^2}$$

9.97E One technique for operating a steam turbine in part-load power output is to throttle the steam to a lower pressure before it enters the turbine, as shown in Fig. P9.16. The steamline conditions are 200 lbf/in.^{2}, 600 F, and the turbine exhaust pressure is fixed at 1 lbf/in.^{2}. Assuming the expansion inside the turbine to be reversible and adiabatic, determine

a. The full-load specific work output of the turbine

b. The pressure the steam must be throttled to for 80% of full-load output

c. Show both processes in a *T–s* diagram.



a) C.V. Turbine full-load, reversible.

$s_{3a} = s_1 = 1.6767 = 0.132\,66 + x_{3a} \times 1.8453$

$x_{3a} = 0.8367$

$h_{3a} = 69.74 + 0.8367 \times 1036.0 = 936.6$

$w = h_1 - h_{3a}$

$= 1322.1 - 936.6 =$ **385.5 Btu/lbm**

b) $w = 0.80 \times 385.5 = 308.4 = 1322.1 - h_{3b} \quad \Rightarrow \quad h_{3b} = 1013.7$

$1013.7 = 69.74 + x_{3b} \times 1036.0 \;\Rightarrow\; x_{3b} = 0.9112$

$s_{3b} = 0.13266 + 0.9112 \times 1.8453 = 1.8140$

$$\left.\begin{array}{l} s_{2b} = s_{3b} = 1.8140 \\ h_{2b} = h_1 = 1322.1 \end{array}\right\} \rightarrow \begin{array}{l} P_2 = \mathbf{56.6\ lbf/in^2} \\ T_2 = \mathbf{579\ F} \end{array}$$

9.98E Air at 540 F, 60 lbf/in.^{2} with a volume flow 40 ft3/s runs through an adiabatic turbine with exhaust pressure of 15 lbf/in.2. Neglect kinetic energies and use constant specific heats. Find the lowest and highest possible exit temperature. For each case find also the rate of work and the rate of entropy generation.

$T_i = 540 \text{ F} = 1000 \text{ R}$

$v_i = RT_i/P_i = 53.34 \times 1000/60\ 144 = 6.174 \text{ ft / lbm}$

$\dot{m} = \dot{V}/v_i = 40/6.174 = 6.479 \text{ lbm/s}$

a. lowest exit T, this must be reversible for maximum work out.

$T_e = T_i(P_e/P_i)^{\frac{k-1}{k}} = 1000\ (15/60)^{0.286} =$ **673 R**

$w = 0.24\ (1000 – 673) = 78.48;\ \dot{W} = \dot{m}w = 508.5 \text{ Btu/s}$

$\dot{S}_{gen} =$ **0**

b. Highest exit T, for no work out. $\quad T_e = T_i =$ **1000 R**

$\dot{S}_{gen} = \dot{m}\,(s_e – s_i) = - \dot{m}R \ln (P_e / P_i) = - 6.479 \times \frac{53.34}{778} \ln (15/60)$

$=$ **0.616 Btu/s ·R**

9.99E A supply of 10 lbm/s ammonia at 80 lbf/in.^{2}, 80 F is needed. Two sources are available one is saturated liquid at 80 F and the other is at 80 lbf/in.^{2}, 260 F. Flows from the two sources are fed through valves to an insulated SSSFmixing chamber, which then produces the desired output state. Find the two source mass flow rates and the total rate of entropy generation by this setup.

Cont.: $\dot{m}_1 + \dot{m}_2 = \dot{m}_3$ Energy Eq.: $\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$

$h_1 = 131.68$ $s_1 = 0.2741$ $h_2 = 748.5$ $s_2 = 1.4604$

$h_3 = 645.63$ $s_3 = 1.2956$

$\dot{m}_1 h_1 + (\dot{m}_3 - \dot{m}_1) h_2 = \dot{m}_3 h_3$

$\dot{m}_1 = \dot{m}_3 \times (h_3 - h_2) / (h_1 - h_2) = 10 \times (-102.87)/(-616.82) = 1.668$ lbm/s

$\Rightarrow$ $\dot{m}_2 = \dot{m}_3 - \dot{m}_1 = 8.332$ lbm/s

$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2$

$= 10 \times 1.2956 - 1.668 \times 0.2741 - 8.332 \times 1.46 =$ **0.331 Btu/s · R**

9.100E Air from a line at 1800 lbf/in.^{2}, 60 F, flows into a 20-ft^3 rigid tank that initially contained air at ambient conditions, 14.7 lbf/in.^{2}, 60 F. The process occurs rapidly and is essentially adiabatic. The valve is closed when the pressure inside reaches some value, P_2. The tank eventually cools to room temperature, at which time the pressure inside is 750 lbf/in.^{2}. What is the pressure P_2? What is the net entropy change for the overall process?

CV: tank. Fill to P_2, then cool to $T_3 = 520$, $P_3 = 750$

$m_1 = P_1V/RT_1 = 14.7 \times 144 \times 20/53.34 \times 520 = 1.526$ lbm

$m_3 = P_3V/RT_3 = 750 \times 144 \times 20/53.34 \times 520 = 77.875$ lbm $= m_2$

$m_i = m_2 - m_1 = 77.875 - 1.526 = 76.349$ lbm

$Q_{CV} + m_ih_i = m_2u_3 - m_1u_1 = m_2h_3 - m_1h_1 - (P_3 - P_1)V$

But, since $T_i = T_3 = T_1$, $m_ih_i = m_2h_3 - m_1h_1$

$\Rightarrow Q_{CV} = -(P_3 - P_1)V = -(750 - 14.7) \times 20 \times 144/778 = -2722$ Btu

$\Delta S_{NET} = m_3s_3 - m_1s_1 - m_is_i - Q_{CV}/T_0 = m_3(s_3 - s_i) - m_1(s_1 - s_i) - Q_{CV}/T_0$

$$= 77.875\left[0 - \frac{53.34}{778}\ln\left(\frac{750}{1800}\right)\right] - 1.526\left[0 - \frac{53.34}{778}\ln\left(\frac{14.7}{1800}\right)\right]$$

$+ 2722/520 =$ **9.406 Btu/R**

1-2 heat transfer = 0 so 1st law: $m_ih_i = m_2u_2 - m_1u_1$

$m_iC_{P0}T_i = m_2C_{V0}T_2 - m_1C_{V0}T_1$

$T_2 = 76.349 \times 0.24 + 1.526 \times 0.171) \times 520 / (77.875 \times 0.171) = 725.7$ R

$P_2 = m_2RT_2/V = 77.875 \times 53.34 \times 725.7 / (144 \times 20) =$ **1047 lbf/in^2**

9.101E An old abandoned saltmine, 3.5×106 ft^3 in volume, contains air at 520 R, 14.7 lbf/in.^{2}. The mine is used for energy storage so the local power plant pumps it up to 310 lbf/in.^{2} using outside air at 520 R, 14.7 lbf/in.^{2}. Assume the pump is ideal and the process is adiabatic. Find the final mass and temperature of the air and the required pump work. Overnight, the air in the mine cools down to 720 R. Find the final pressure and heat transfer.

C.V. = Air in mine + pump (USUF) Cont: $m_2 - m_1 = m_{in}$

Energy: $m_2u_2 - m_1u_1 = {}_1Q_2 - {}_1W_2 + m_{in}h_{in}$

Entropy: $m_2s_2 - m_1s_1 = \int dQ/T + {}_1S_{2\,gen} + m_{in}s_{in}$

Process: ${}_1Q_2 = 0$, ${}_1S_{2\,gen} = 0$, $s_1 = s_{in}$

$\Rightarrow$ $m_2s_2 = m_1s_1 + m_{in}s_{in} = (m_1 + m_{in})s_1 = m_2s_1$ $\Rightarrow$ $s_2 = s_1$

Const. s $\Rightarrow P_{r2} = P_{r1}P_2/P_1 = 0.9767 \times 310/14.7 = 20.597$

$\Rightarrow T_2 = \mathbf{1221\ R}$, $u_2 = 213.09$

$$m_1 = P_1V_1/RT_1 = \frac{14.7 \times 3.5\times10^6 \times 144}{53.34 \times 520} = 2.671\times10^5 \text{ lbm}$$

$$m_2 = P_2V_2/RT_2 = \frac{310 \times 3.5\times10^6 \times 144}{53.34 \times 1221} = 2.4\times10^6 \text{ kg}$$

$\Rightarrow$ $m_{in} = m_2 - m_1 = \mathbf{2.1319\times10^6\ lbm}$

${}_1W_2 = m_{in}h_{in} + m_1u_1 - m_2u_2 = 2.1319\times10^6 \times 124.38 + 2.671\times10^5$

$\times 88.73 - 2.4\times10^6 \times 213.09 = -2.226\times10^8$ Btu = -pump work

${}_2W_3 = \emptyset$, $P_3 = P_2T_3/T_2 = 310\times720/1221 = \mathbf{182.8\ lbf/in^2}$

${}_2Q_3 = m_2(u_3 - u_2) = 2.4\times10^6(123.17 - 213.09) = \mathbf{-2.158\times10^8\ Btu}$

9.102E A rigid 35 ft^3 tank contains water initially at 250 F, with 50 % liquid and 50% vapor, by volume. A pressure-relief valve on the top of the tank is set to 150 lbf/in.^{2} (the tank pressure cannot exceed 150 lbf/in.^{2} - water will be discharged instead). Heat is now transferred to the tank from a 400 F heat source until the tank contains saturated vapor at 150 lbf/in.^{2}. Calculate the heat transfer to the tank and show that this process does not violate the second law.

C.V. Tank. $v_{f1} = 0.017$ $\quad v_{g1} = 13.8247$

$m_{LIQ} = V_{LIQ} / vf1 = 0.5 \times 35/0.017 = 1029.4$ lbm

$m_{VAP} = V_{VAP} / vg1 = 0.5 \times 35/13.8247 = 1.266$ lbm

$m = 1030.67$

$x = m_{VAP} / (m_{LIQ} + m_{VAP}) = 0.001228$

$u = u_f + x\ u_{fg} = 218.48 + 0.001228 \times 869.41 = 219.55$

$s = s_f + x\ s_{fg} = 0.3677 + 0.001228 \times 1.3324 = 0.36934$

state 2: $v_2 = v_g = 3.2214$ $\qquad u_2 = 1110.31 \quad h_2 = 1193.77$

$s_2 = 1.576$ $\qquad m_2 = V/v_2 = 10.865$ lbm

$Q = m_2 u_2 - m_1 u_1 + m_e h_e + W$

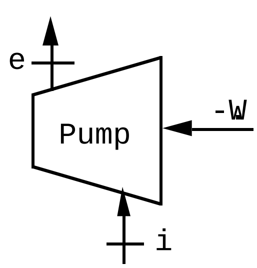
$= 10.865 \times 1110.31 - 1030.67 \times 219.55 + 1019.8 \times 1193.77 = 1003187$ Btu

$\dot{S}_{gen} = m_2 s_2 - m_1 s_1 - m_e s_e - {}_1Q_2 / T_{source}$

$= 10.865 \times 1.576 - 1030.67 \times 0.36934 + 1019.8 \times 1.57 - 1003187/860$

$=$ **77.2 Btu/s · R**

9.103E Liquid water at ambient conditions, 14.7 lbf/in.^{2}, 75 F, enters a pump at the rate of 1 lbm/s. Power input to the pump is 3 Btu/s. Assuming the pump process to be reversible, determine the pump exit pressure and temperature.



$-\dot{W} = 3$ Btu/s, $\quad P_i = 14.7$

$T_i = 75$ F $\quad \dot{m} = 1$ lbm/s

$$w_P = \frac{\dot{W}_P}{\dot{m}} = \frac{-3}{1} = -3 \text{ Btu/lbm}$$

$$= -\int v dP \approx -v_i(P_e - P_i)$$

$$3 \cong 0.01606(P_e - 14.7) \times \frac{144}{778} \Rightarrow P_e = \mathbf{1023.9\ lbf/in^2}$$

$h_e = h_i - w_P = 43.09 + 3 = 46.09$ Btu/lbm

$\cong h_f(T_e) \Rightarrow T_e =$ **78 F**

9.104E A fireman on a ladder 80 ft above ground should be able to spray water an additional 30 ft up with the hose nozzle of exit diameter 1 in. Assume a water pump on the ground and a reversible flow (hose, nozzle included) and find the minimum required power.

$$-w_p = \Delta PE_{13} = \frac{g\,\Delta Z}{g_C} = \frac{32.2 \times 130}{32.2 \times 778} = 0.167 \text{ Btu/lbm}$$

Nozzle: $\quad KE = -\Delta PE_{23} = \dfrac{32.2 \times 30}{32.2 \times 778} = \dfrac{\mathbf{V}_2^2}{2 \times 32.2 \times 778}$

$\mathbf{V}_2^2 = 2 \times 32.2 \times 30 = 1932, \qquad \mathbf{V} = 43.95$ ft/s

$A = (\pi/4) \times (1^2/144) = 0.00545 \text{ ft}^2$

Assume: $\quad v = v_{F,70F} = 0.01605 \text{ ft}^3\text{/lbm}$

$\dot{m} = A\mathbf{V}/v = 0.00545 \times 43.95 / 0.01605 = 14.935$ lbm/s

$\dot{W}_{pump} = \dot{m}w_p = 14.935 \times 0.167 \times (3600/2544) =$ **3.53 hp**

9.105E Saturated R-134a at 10 F is pumped/compressed to a pressure of 150 lbf/in.^{2} at the rate of 1.0 lbm/s in a reversible adiabatic SSSF process. Calculate the power required and the exit temperature for the two cases of inlet state of the R-134a:

a) quality of 100 %.
b) quality of 0 %.

$w_{cs\,s} = h_1 - h_{2s}; \qquad s_2 - s_1 = S_{gen} + \int dq/T = \varnothing$

Ideal rev. $\Rightarrow$ $S_{gen} = \varnothing$ $\quad$ Adiabatic $q = \varnothing$

a. Inlet $\qquad h_1 = 168.06 \qquad s_1 = 0.414$

Exit $\qquad s_2 = s_1 \quad \Rightarrow \quad T_2 = 116 \qquad h_2 = 183.5$

$w_{c,\,s} = 168.05 - 183.5 = -15.5$

$\dot{W} = \dot{m}\, w_{c,\,s} = 1 \times (-15.5) = -15.5 \text{ Btu} = -15.5 \times 3600/254 = -21.8\text{hp}$

b. Inlet $\qquad h_1 = 79.02 \qquad v_1 = 0.01202$

$w_e = -\int v\,dp = -v(P_2 - P_1) = -0.01202\,(150 - 26.79) = -0.27$ Btu/lbm

$\dot{W} = \dot{m}\, w_p = -0.4$ hp

$h_2 = h_1 - w_p = 79.02 + 0.27 = 79.29 \quad => \quad T_2 \approx 10.86$ F $\approx$**10.9 F**

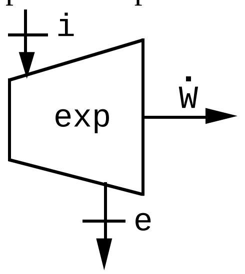
9.106E A small pump takes in water at 70 F, 14.7 lbf/in.^{2} and pumps it to 250 lbf/in.^{2} at a flow rate of 200 lbm/min. Find the required pump power input.

Assume reversible pump and incompressible flow

$w_p = -\int vdP = -v_i(P_e - P_i) = -0.016051(250 - 14.7) \times 144/788 = -0.7$ Btu/lbm

$\dot{W}_p = \dot{m}w_p = 200(-0.7)/60 =$ **-2.33 Btu/s**

9.107E Helium gas enters a steady-flow expander at 120 lbf/in.^{2}, 500 F, and exits at 18 lbf/in.^{2}. The mass flow rate is 0.4 lbm/s, and the expansion process can be considered as a reversible polytropic process with exponent, *n* = 1.3. Calculate the power output of the expander.



$P_i = 120\ \text{lbf/in}^2 \quad T_i = 500\ \text{F}$

$P_e = 18\ \text{lbf/in}^2 \quad \dot{m} = 0.4\ \text{lbm/s}$

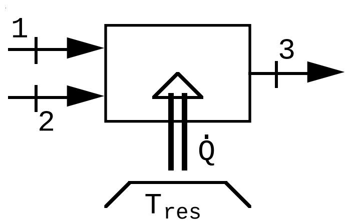
$Pv^{1.30} = \text{const.}$

$$T_e = T_i\left(\frac{P_e}{P_i}\right)^{\frac{n-1}{n}} = 960\left(\frac{18}{120}\right)^{\frac{0.3}{1.3}} = 619.6\ \text{R}$$

$$w = -\int v dP = -\frac{nR}{n-1}(T_e - T_i) = -\frac{1.3 \times 386}{0.3 \times 778}(619.6 - 960) \quad = +731.8\ \text{Btu/lbm}$$

$$\dot{W} = \dot{m}w = 0.4 \times 731.8 \times \frac{3600}{2544} = \mathbf{414.2\ hp}$$

9.108E A mixing chamber receives 10 lbm/min ammonia as saturated liquid at 0 F from one line and ammonia at 100 F, 40 lbf/in.^{2} from another line through a valve. The chamber also receives 340 Btu/min energy as heat transferred from a 100-F reservoir. This should produce saturated ammonia vapor at 0 F in the exit line. What is the mass flow rate at state 2 and what is the total entropy generation in the process?



CV: Mixing chamber out to reservoir

$\dot{m}_1 + \dot{m}_2 = \dot{m}_3$

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

$\dot{m}_1 s_1 + \dot{m}_2 s_2 + \dot{Q}/T_{res} + \dot{S}_{gen} = \dot{m}_3 s_3$

From energy equation:

$$\dot{m}_2 = [(\dot{m}_1(h_1 - h_3) + \dot{Q}]/(h_3 - h_2)$$

$$= [10(42.6 - 610.92) + 340]/(610.92 - 664.3)$$

$$= \mathbf{100.1\ lbm/min} \ \Rightarrow\ \dot{m}_3 = 110.1\ \text{lbm/min}$$

$$\dot{S}_{gen} = \dot{m}_3 s_3 - \dot{m}_1 s_1 - \dot{m}_2 s_2 - \dot{Q}/T_{res}$$

$$= 110.1\times1.3332 - 10\times0.0967 - 100.1\times1.407 - 340/559.67 = \mathbf{4.37\ Btu/R\ min}$$

9.109E A compressor is used to bring saturated water vapor at 150 lbf/in.^{2} up to 2500 lbf/in.^{2}, where the actual exit temperature is 1200 F. Find the isentropic compressor efficiency and the entropy generation.

Inlet: $h_i = 1194.9 \quad s_i = 1.5704$

IDEAL EXIT: $P_e,\ s_{e,s} = s_i \Rightarrow h_{e,s} = 1523.8$

$w_s = h_i - h_{e,s} = 1194.9 - 1523.8 = -328.9$ Btu/lbm

ACTUAL EXIT: $h_{e,AC} = 1587.7, \quad s_{e,AC} = 1.6101$

$w_{AC} = h_i - h_{e,ac} = 1194.9 - 1587.7 = -392.8$ Btu/lbm

$\eta_c = w_s/w_{AC} = 328.9/392.8 = \mathbf{0.837}$

$s_{GEN} = s_{e,AC} - s_i = 0.0397$ Btu/lbm R

9.110E A small air turbine with an isentropic efficiency of 80% should produce 120 Btu/lbm of work. The inlet temperature is 1800 R and it exhausts to the atmosphere. Find the required inlet pressure and the exhaust temperature.

C.V. Turbine actual:

$w = h_i - h_{e,ac} = 449.794 - h_{e,ac} = 120 \Rightarrow h_{e,ac} = 329.794, \;\; T_e = \mathbf{1349.2\ R}$

C.V. Ideal turbine:

$w_s = w/\eta_s = 120/0.8 = 150 = h_i - h_{e,s} \Rightarrow h_{e,s} = 299.794$

$T_{e,s} = 1233$ R $\quad s_i = s_{e,s} \Rightarrow P_e/P_i = P_{re}/P_{ri}$

$P_i = P_e\, P_{ri}/P_{re} = 14.7 \times 91.6508/21.3428 = \mathbf{63.125\ lbf/in^2}$

9.111E Air enters an insulated compressor at ambient conditions, 14.7 lbf/in.^{2}, 70 F, at the rate of 0.1 lbm/s and exits at 400 F. The isentropic efficiency of the compressor is 70%. What is the exit pressure? How much power is required to drive the compressor?

Compressor: $P_i = 14.7,\ T_i = 70$ F, $T_e = 400$ F, $\eta_{s\,C} = 0.70$

Real: $-w = C_{P0}(T_e - T_i) = 0.24(400 - 70) = 79.2$ Btu/lbm

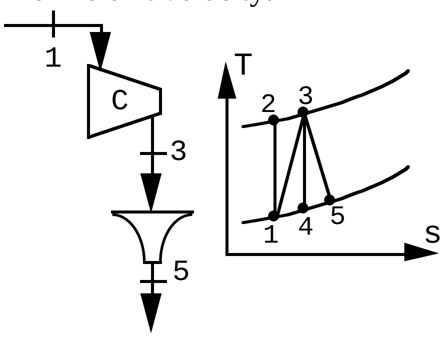
Ideal: $-w_s = -w \times \eta_s = 79.2 \times 0.7 = 55.4$ Btu/lbm

$55.4 = C_{P0}(T_{es} - T_i) = 0.24(T_{es} - 530), \quad T_{es} = 761$ R

$P_e = P_i(T_{es}/T_i)^{\frac{k}{k-1}} = 14.7(761/530)^{3.5} = \mathbf{52.1\ lbf/in^2}$

$-\dot{W}_{REAL} = \dot{m}(-w) = (0.1 \times 79.2 \times 3600)/2544 = \mathbf{11.2\ hp}$

9.112E Air at 1 atm, 60 F is compressed to 4 atm, after which it is expanded through a nozzle back to the atmosphere. The compressor and the nozzle both have efficiency of 90% and kinetic energy in/out of the compressor can be neglected. Find the actual compressor work and its exit temperature and find the actual nozzle exit velocity.



SSSF seperate control volumes around compressor and nozzle.
Assume both adiabatic.

Ideal compressor: $w_c = h_1 - h_2 \quad s_2 = s_1$

$\Rightarrow\ P_{r2} = P_{r1} \times P_2/P_1 = 0.9745 \times 4/1 = 3.898$

State 2: $T_2 = 771\text{ R} \quad h_2 = 184.87$

$\Rightarrow\ w_{c,s} = 124.3 - 184.87 = -60.57$

Actual compressor: $w_{c,AC} = w_{c,s}/\eta_c = -67.3 = h_1 - h_3$

$\Rightarrow\ h_3 = h_1 - w_{c,AC} = 124.3 + 67.3 = 191.6$

$T_3 = 799\text{ R} \quad P_{r3} = 4.4172$

Ideal nozzle: $s_4 = s_3 \Rightarrow P_{r4} = P_{r3} \times 1/4 = 1.1043$

$\Rightarrow\ T_4 = 539\text{ R} h_4 = 128.84$

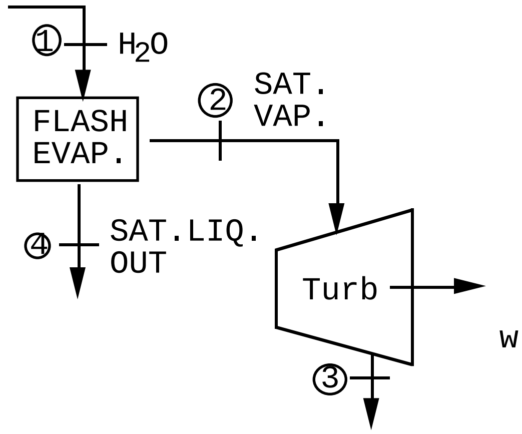
$\mathbf{V}_s^2/2 = h_3 - h_4 = 191.6 - 128.84 = 62.76$

$\mathbf{V}_{AC}^2/2 = \mathbf{V}_s^2 \times \eta_{NOZ}/2 = 62.76 \times 0.9 = 56.484$

$\mathbf{V}_{AC}^2 = 2 \times 56.484 \times 32.174 \times 778 = 2.828\times10^6$

$\mathbf{V}_{AC} =$ **1681.6 ft/s**

9.113E A geothermal supply of hot water at 80 lbf/in.^{2}, 300 F is fed to an insulated flash evaporator at the rate of 10,000 lbm/h. A stream of saturated liquid at 30 lbf/in.^{2} is drained from the bottom of the chamber and a stream of saturated vapor at 30 lbf/in.^{2} is drawn from the top and fed to a turbine. The turbine has an isentropic efficiency of 70% and an exit pressure of 2 lbf/in.^{2}. Evaluate the second law for a control volume that includes the flash evaporator and the turbine.



CV: flash evap.

$h_1 = 269.73 = 218.93 + x \times 945.4$

$x = \dot{m}_{VAP}/\dot{m}_1 = 0.0537$

$\Rightarrow \dot{m}_{VQP} = 537$ lbm/h

$\dot{m}_{LIQ} = 9463$ lbm/h

Turbine:

$s_{3s} = s_2 = 1.6996$

$= 0.17499 + x_{3s} \times 1.7448$

$=> \quad x_{3s} = 0.8738$

$=> \quad h_{3s} = 94.02 + 0.8738 \times 1022.1 = 987.1$

$w_s = h_2 - h_{3s} = 1164.3 - 987.1 = 177.2$ Btu/lbm

$w = \eta_s w_s = 0.7 \times 177.2 = 124.0$ Btu/lbm

$h_3 = h_2 - w = 1164.3 - 124.0 = 1040.3 = 94.01 + x_3 \times 1022.1$

$\Rightarrow \quad x_3 = 0.9258, \;\; s_3 = 0.17499 + 0.9258 \times 1.7448 = 1.7904$

$\dot{S}_{gen} = \dot{S}_{NET} = \dot{S}_{SURR} = m_4 s_4 + m_3 s_3 - m_1 s_1 - \dot{Q}_{CV}/T_0$

$= 9463 \times 0.3682 + 537 \times 1.7904 - 10000 \times 0.4372 - 0$

$= \mathbf{+73.7\ Btu/h\ R} > 0$

9.114E Redo Problem 9.104 if the water pump has an isentropic efficiency of 85% (hose, nozzle included).

$$-w_p = \Delta PE_{13} = \frac{g\,\Delta Z}{g_C} = \frac{32.2 \times 130}{32.2 \times 778} = 0.167 \text{ Btu/lbm}$$

Nozzle: $\quad KE = -\Delta PE_{23} = \dfrac{32.2 \times 30}{32.2 \times 778} = \dfrac{\mathbf{V}_2^2}{2 \times 32.2 \times 778}$

$\mathbf{V}_2^2 = 2 \times 32.2 \times 30 = 1932, \qquad \mathbf{V} = 43.95$ ft/s

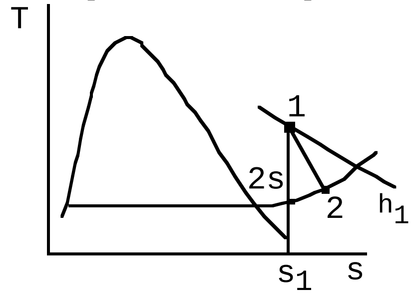
$A = (\pi/4) \times (1^2/144) = 0.00545 \text{ ft}^2$

Assume: $\quad v = v_{F,70F} = 0.01605 \text{ ft}^3/\text{lbm}$

$\dot{m} = A\mathbf{V}/v = 0.00545 \times 43.95 / 0.01605 = 14.935$ lbm/s

$\dot{W}_{pump} = \dot{m} w_p/\eta = 14.935 \times 0.167 \times (3600/2544)/0.85 = \mathbf{4.15\ hp}$

9.115E A nozzle is required to produce a steady stream of R-134a at 790 ft/s at ambient conditions, 14.7 lbf/in.^{2}, 70 F. The isentropic efficiency may be assumed to be 90%. What pressure and temperature are required in the line upstream of the nozzle?



$KE_2 = 790^2/2 \times 32.174 \times 778 = 12.466$ Btu/lbm

$KE_{2s} = KE_2/\eta = 13.852$

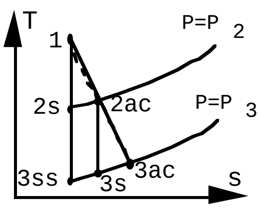
$h_1 = h_2 + KE_2 = 180.981 + 12.466$
$= 193.447$ Btu/lbm

$h_{2s} = h_1 - KE_{2s} = 193.447 - 13.852$
$= 179.595$ Btu/lbm

2s: $P_2, h_{2s} \Rightarrow T_{2s} = 63.12, s_{2s} = 0.4485$

1: $h_1, s_1 = s_{2s} \Rightarrow T_1 =$ **137.25 F** $\quad P_1 =$ **55 lbf/in^2**

9.116E A two-stage turbine receives air at 2100 R, 750 lbf/in.^{2}. The first stage exit at 150 lbf in.^{2} then enters stage 2, which has an exit pressure of 30 lbf/in.^{2}. Each stage has an isentropic efficiency of 85%. Find the specific work in each stage, the overall isentropic efficiency, and the total entropy generation.



C.V. around each turbine for first the ideal and then the actual produces for stage 1:

Ideal T1: $P_{r2} = P_{r1}P_2/P_1 = 170.413 \times (150/780) = 34.083$

$h_{2s} = 341.92 \quad w_{T1,s} = h_1 - h_{2s} = 532.57 - 341.92 = 190.65$

Actual T1: $w_{T1,AC} = \eta_{T1}w_{T1,s} =$ **162.05** $= h_1 - h_{2AC}$

$h_{2AC} = 370.52 \quad P_{r2,AC} = 45.448$

Ideal T2, has inlet from actual T1, exit state 2,AC

$P_{r3} = P_{r2,AC}P_3/P_2 = 45.448(30/150) = 9.0896$

$h_{3s} = 235.39 \quad w_{T2,s} = h_{2AC} - h_{3s} = 370.52 - 235.39 = 135.13$

$w_{T2,AC} = \eta_{T2}w_{T2,s} =$ **114.86** $= h_{2AC} - h_{3AC}$

$h_{3AC} = 255.66 \quad s^\circ_{T3,AC} = 1.8036$

For the overall isentropic efficiency we need the isentropic work:

$P_{r3,ss} = P_{r1}P_3/P_1 = 170.413 \times (30/750) = 6.8165$

$h_{3ss} = 216.86 \Rightarrow \quad w_{ss} = h_1 - h_{3ss} = 315.71$

$\eta = (w_{T1,AC} + w_{T2,AC})/w_{ss} =$ **0.877**

$s_{GEN} = s_{3AC} - s_1 = s^\circ_{T3,AC} - s^\circ_{T1} - R \ln (P_3/P_1)$

$= 1.8036 - 1.9846 - \frac{53.34}{778} \times \ln \frac{30}{750} =$ **0.0397 Btu/lbm R**

9.117E A watercooled air compressor takes air in at 70 F, 14 lbf/in.^{2} and compresses it to 80 lbf/in.^{2}. The isothermal efficiency is 80% and the actual compressor has the same heat transfer as the ideal one. Find the specific compressor work and the exit temperature.

$$q = T(s_e - s_i) = T[s^o_{Te} - s^o_{T1} - R \ln(P_e / P_i)]$$

$$= - TR \ln (P_e / P_i) = - (460 + 70) \frac{53.34}{778} \ln \frac{80}{14} = - 63.3 \text{ Btu/lbm}$$

As $h_e = h_i \Rightarrow w = q = - 63.3$ => $w_{AC} = w/\eta = - 79.2$ Btu/lbm, $q_{AC} = q$

$q_{AC} + h_i = h_e + w_{AC} \Rightarrow$

$h_e - h_i = q_{AC} - w_{Ac} = - 63.3 - (- 79.2) = 15.9 \text{ Btu/lbm} \approx C_p (T_e - T_i)$

$T_e = T_i + 15.9/0.24 =$ **136 F**

9.118E Repeat Problem 9.105 for a pump/compressor isentropic efficiency of 70%.

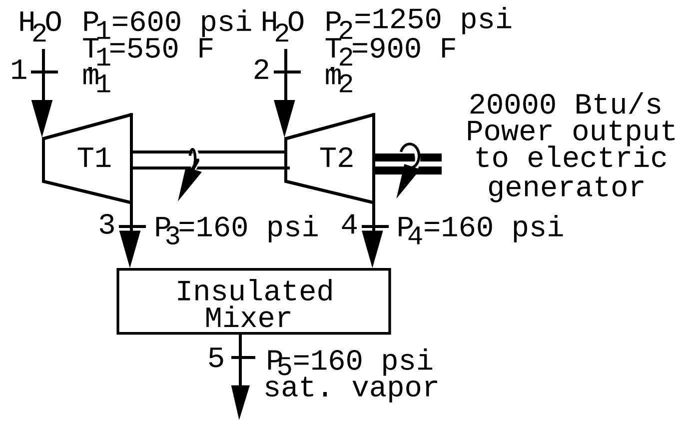
a. $w_{c,\,s} = - 15.5$, $w_{c,\,AC} = - 22.1 = h_1 - h_{2\,AC}$

$h_{2,\,AC} = 168.06 + 22.1 = 190.2 \Rightarrow T_2 = 141.9$ F

b. $w_{c,\,s} = - 0.27$, $w_{c,\,AC} = - 0.386$

$h_{2,\,AC} = h_1 - wp = 79.4 \Rightarrow T_2 =$ **11.2 F**

9.119E A paper mill has two steam generators, one at 600 lbf/in.^{2}, 550 F and one at 1250 lbf/in.^{2}, 900 F. The setup is shown in Fig. P9.72. Each generator feeds a turbine, both of which have an exhaust pressure of 160 lbf/in.^{2} and isentropic efficiency of 87%, such that their combined power output is 20000 Btu/s. The two exhaust flows are mixed adiabatically to produce saturated vapor at 160 lbf/in.^{2}. Find the two mass flow rates and the entropy produced in each turbine and in the mixing chamber.



Inlet States:

$h_1 = 1255.4$

$s_1 = 1.499$

$h_2 = 1438.4$

$s_2 = 1.582$

Ideal & Actual T1:

$s_{3s} = s_1 \;\Rightarrow$

$x_{3s} = 0.9367$

$h_{3s} = 1141.55$

$w_{T1,s} = h_1 - h_{3s} = 113.845 \;=>\; w_{T1,AC} = \eta_{T1}w_{T1,s} = 99.05 = h_1 - h_{3,AC}$

$h_{3,AC} = 1156.35 \qquad s_{3,AC} = 1.517$

Ideal & Actual T2: $\quad s_{4s} = s_2 \;\Rightarrow\; h_{4s} = 1210.17$

$w_{T2,s} = h_2 - h_{4s} = 228.23, \quad w_{T2,AC} = \eta_{T2}w_{T2,s} = 198.56 = h_2 - h_{4,AC}$

$h_{4,AC} = 1239.84 \qquad s_{4,AC} = 1.6159$

C.V. Mixing Chamber: $\quad \dot{m}_{T1}h_{3,AC} + \dot{m}_{T2}h_{4,AC} = (\dot{m}_{T1} + \dot{m}_{T2})h_5$

$$\frac{\dot{m}_{T1}}{\dot{m}_{tot}} = \frac{h_5 - h_{4,AC}}{h_{3,AC} - h_{4,AC}} = \frac{1196 - 1239.84}{1156.35 - 1239.84} = 0.525, \quad \frac{\dot{m}_{T2}}{\dot{m}_{tot}} = 0.475$$

C.V. Shaft: $\quad \dot{m}_{T1}w_{T1,AC} + \dot{m}_{T2}w_{T2,AC} = \dot{m}_{tot} \times 146.317$

$= 20000$ Btu/s $\Rightarrow\; \dot{m}_{TOT} = 136.69$ lbm/s

$\dot{m}_{T1} = 71.76$ lbm/s $\qquad \dot{m}_{T2} = 64.93$ lbm/s

$\dot{s}_{GEN\ T1} = \dot{m}_{T1}(s_{3,AC} - s_1) = 71.76(1.517 - 1.499) = 1.292$ Btu/s R

$\dot{s}_{GEN\ T2} = \dot{m}_{T2}(s_{4,AC} - s_2) = 64.93(1.6159 - 1.582) = 2.201$ Btu/s R

$\dot{s}_{GEN\ MIX} = \dot{m}_{TOT}s_5 - \dot{m}_{T1}s_{3,AC} - \dot{m}_{T2}s_{4,AC} = 136.69 \times 1.5651$

$- 71.76 \times 1.517 - 64.93 \times 1.6159 =$ **0.153 Btu/s R**