Introduction to Thermodynamics and Heat Transfer (ECE 309)
Suggested Problems for Chapter 3

1. A 4 m × 5 m × 7 m room is heated by the radiator of a steam-heating system as shown in Fig. 1. The seam radiator transfers heat at a rate of 10,000 kJ /h, and a 100 W fan is used to distribute the warm air in the room. The rate of heat loss from the room is estimated to be about 5000 kJ /h. If the initial temperature of the room air is 10 °C, determine how long it will take for the air temperature to rise to 20°C. Assume constant specific heats at room temperature.

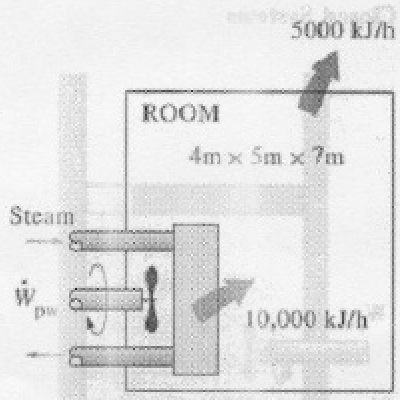
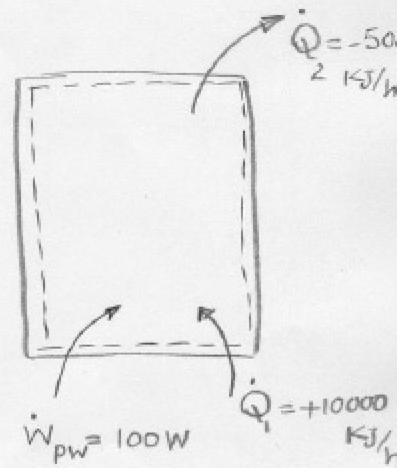


Fig. 1



$T_i = 10°C$

$\Delta t = ?$ for $T = 20°C$

$$\dot{Q}_{net} - \dot{W}_{net} = \frac{dE}{dt} = \frac{dU}{dt} \quad \text{or} \quad (\dot{Q}_{net} - \dot{W}_{net})\Delta t = \Delta U$$

$$dU = mc_v dT \quad \text{or} \quad \Delta U = m C_v \Delta T$$

$$m = \frac{PV}{RT_1} = \frac{(100\,kPa)(4\times5\times7)m^3}{(0.287\,kPa\,m^3)(10+273)K} = 172.4\,kg$$

$$C_v = .718\,kJ/kg°C \quad (\text{Table A-2a})$$

$$\therefore \left[(10000-5000)/3600 - (-.1)\right]\Delta t = 172.4 \times 0.718 \times (20-10)$$

$$\Rightarrow \boxed{\Delta t = 831.4\ Sec}$$

2. A piston-cylinder device contains 0.8 kg of nitrogen initially at 100 kPa and 27 °C. The nitrogen is now compressed slowly in a polytropic process during which $PV^{1.3} = C$ until the volume is reduced by one-half. Determine the work done and the heat transfer for this process.

$m = 0.8 \text{ Kg}$

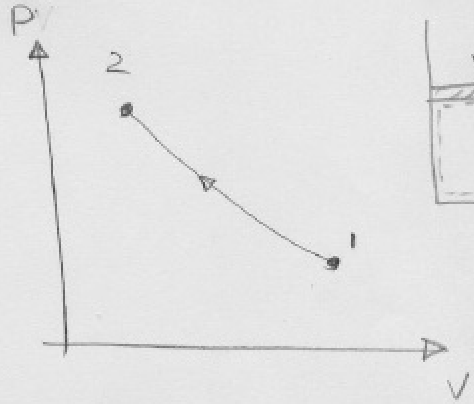
$P_1 = 100 \text{ KPa}$

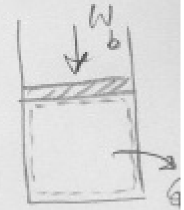
$T = 27°C$

$PV^{1/3} = C$

$V_2 = \frac{1}{2} V_1$

$\left\{ \begin{array}{l} W = ? \\ Q = ? \end{array} \right.$





$$W_b = \int_1^2 p\,dV = \cdots = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{m R (T_2 - T_1)}{1-n}$$

$$P_1 V_1^{1.3} = P_2 V_2^{1.3} = C \Rightarrow P_2 = P_1 \left(\frac{V_1}{V_2}\right)^{1.3} = 100\left(\frac{2}{1}\right)^{1.3} = 246.2 \text{ K}$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \Rightarrow T_2 = T_1\left(\frac{P_2V_2}{P_1V_1}\right) = (27+273)\left[\frac{246.2 \times 1}{100 \times 2}\right]$$

$$T_2 = 369.3 \text{ K} = 96.3 \text{ °C} \leftarrow$$

$$W_b = \frac{0.8 \text{ Kg} \times .2968 \frac{\text{KJ}}{\text{KgK}} \times (96.3 - 27)\text{K}}{1 - 1.3} = -54.8 \text{ KJ} \leftarrow$$

$$\boxed{W_b = -54.8 \text{ KJ}}$$

$$Q - (W_b + \overset{0}{W_{other}}) = \Delta U$$

$$Q = \Delta U + W_b = m C_v^* (T_2 - T_1) + W_b$$

$$= 0.8 \times (.744)(96.3 - 27) - 54.8$$

$$\boxed{Q = -13.55 \text{ KJ}} \leftarrow$$

3. A rigid tank containing 0.4 m^3 of air at 400 kPa and 30 °C is connected by a valve to a piston-cylinder device with zero clearance (Fig. 2). The mass of the piston is such that a pressure of 200 kPa is required to raise the piston. The valve is now opened slightly, and air is allowed to flow into the cylinder until the pressure in the tank drops to 200 kPa. During this process, heat is exchanged with the surroundings such that the entire air remains at 30 °C at all times. Determine the heat transfer for this process.

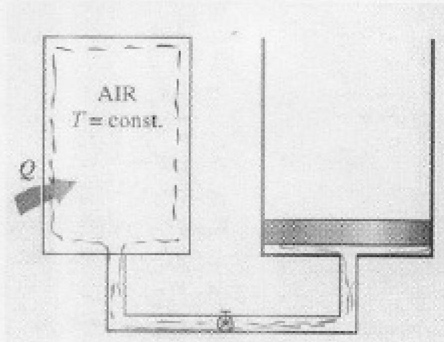


Fig. 2

$P_1 = 400\ kPa$, $T_1 = 30°C$ $V_1 = .4\,m^3$

$P_2 = 200\ kPa$ $T_2 = T_1 = 30°C$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \quad \text{or } P_1V_1 = P_2V_2 \quad \text{or } PV = cte \text{ or } P = \frac{c}{V}$$

$$V_2 = \left(\frac{P_1}{P_2}\right)V_1 = \left(\frac{400}{200}\right) \times .4 = .8\,m^3 \leftarrow$$

$$W_b = \int_1^2 p\,dV = c \ln\frac{V_2}{V_1} = P_1V_1 \ln\frac{V_2}{V_1} = (400 \times .4) \ln\frac{.8}{.4}$$

$$\boxed{W_b = 110.9\ KJ}$$

$$Q - (W_b + \cancel{W_{other}}) = \cancel{\Delta U} \quad \text{since } \Delta T = 0$$

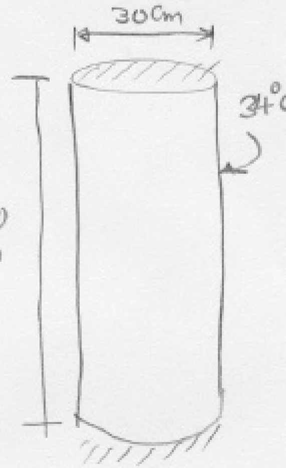
$$Q = W_b = 110.9\ KJ$$

4. It is well known that wind makes cold air feel much colder as a result of the wind-chill effect, which is due to the increase in the convection heat transfer coefficient as a result of the increase in air velocity. The wind-chill effect is usually expressed in terms of the wind-chill factor, which is the difference between the actual air temperature and the equivalent calm-air temperature. For example, a wind-chill factor of 20 °C for an actual air temperature of 5 °C means that the windy air at 5 °C feels as cold as the still air at -15 °C. In other words, a person will lose as much heat to air at 5 °C with a wind-chill factor of 20 °C as he or she would in calm air at –15 °C.

For heat transfer purposes, a standing naked man can be modeled as a 30-cm-diameter, 170-cm-long vertical cylinder with both the top and bottom surfaces insulated and with the side surface at an average temperature of 34 °C. For a convection heat transfer coefficient of 15 W/(m².°C), determine the rate of heat loss from this man by convection in still air at 20 °C. What would your answer be if the convection heat transfer coefficient was increased to 50 W/(m².°C) as a result of winds? What is the wind-chill factor in this case?

$h_1 = 15\ W/m^2{}^\circ C$

$\dot{Q} = ?$



$T_f = 20^\circ C$

(a) $\dot{Q}_1 = hA(T_s - T_f) = 15 \times (\pi \times .3 \times 1.7)(34 - 20)$

$\dot{Q}_1 = 336.5\ W$

(b) for windy condition

$\dot{Q}_2 = hA(T_s - T_f) = 50 \times (\pi \times 0.3 \times 1.7) \times (34 - 20) = 1121.55\ (W)$

(c) $1121.5 = 15 \times (\pi \times .3 \times 1.7)(34 - T_{eff})$

$T_{eff} = -12.7^\circ C$

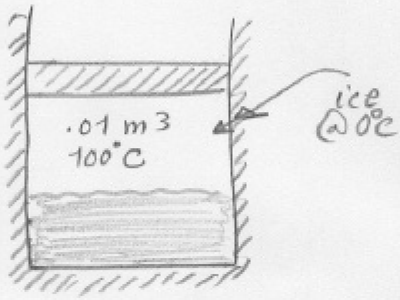
on windchill factor $= 20 - (-12.7) = 32.7^\circ C$

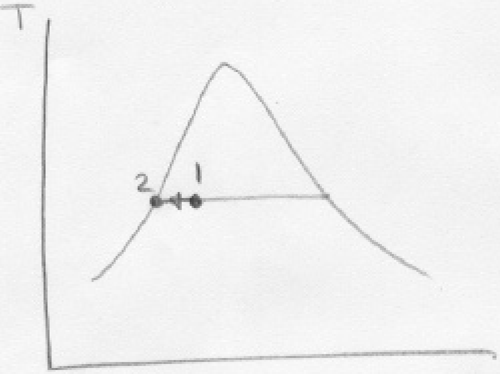
5. An insulated piston-cylinder device initially contains 0.01 m^3 of saturated liquid-vapor mixture with a quality of 0.2 at 100 °C. Now some ice at 0 °C is added into the cylinder. If the cylinder contains saturated liquid at 100 °C when thermal equilibrium is established, determine the amount of ice added. The melting temperature and the heat of fusion of ice at atmospheric pressure are 0 °C and 333.7 kJ/(kg.°C), respectively.

$V_1 = 0.01\ m^3$

$x_1 = 0.2$

$T = 100°C$





$v_f = .001044\ (m^3/kg)$

$v_g = 1.6729\ (m^3/kg)$

$h_f = 419.04\ (kJ/kg)$

$h_g = 2676.1\ (kJ/kg)$

$v_1 = v_f + x v_{fg} = .001044 + .2(1.6729 - .001044) = .3354\ m^3/kg$ ✓

$h_1 = h_f + x h_{fg} = 419.04 + .2(2676.1 - 419.04) = 870.4\ kJ/kg$

$h_2 = h_f = 419.04$

$$m_1 = \frac{V_1}{v_1} = \frac{.01}{.3354} = .0298\ kg$$

$\Delta h = (870.4 - 419.04) = 451.36\ kJ/kg$

or $\Delta H = 451.36 \times .0298 = 13.45\ kJ$

$\Delta H = m_{ice} C_{ice} (\Delta T)_{ice} + m_{ice} h_{fus}$

$= m_{ice} [C_{ice} \Delta T + h_{fus}]$

$13.45 = m_{ice} [4.184 \times 100 + 333.7]$

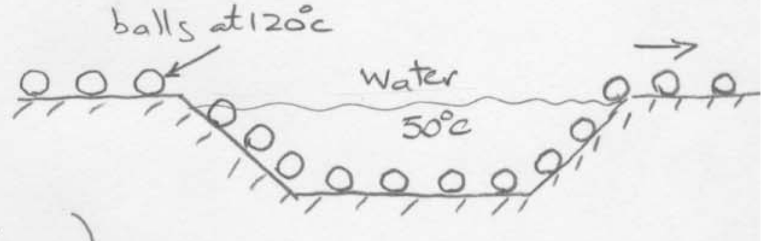
$m_{ice} = .0179\ kg$ or $\boxed{17.9\ kg}$

ch. 3

Problem 6

Assumptions

- thermal properties of the balls are constant
- balls are at a uniform temp before and after quenching
- $\Delta KE = \Delta PE \approx 0$



$\rho_{Al} = 2700$ (kg/m³)

$C_{P_{Al}} = 0.959$ (kJ/kg C)

Solution

We take a single ball as the system. The energy balance for this closed system is,

$$\underbrace{E_{in} - E_{out}}_{\text{net energy transfer by heat, work, and mass}} = \underbrace{\Delta E_{system}}_{\text{changes in internal, kinetic, potential, etc.}}$$

$$-Q_{out} = \Delta U_{ball} = m\,(u_2 - u_1)$$

$$Q_{out} = mc\,(T_1 - T_2)$$

the total amount of heat transfer from a ball is;

$$m = \rho V = \rho \frac{\pi D^3}{6} = 2700\,(\text{kg}/\text{m}^3)\,\frac{\pi\,(0.05\text{m})^3}{6} = 0.1767\,(\text{k}$$

$$Q_{out} = mc\,(T_1 - T_2) = 0.1767\,(\text{kg})\;0.959\,(\text{kJ}/\text{kgc})(120-74^{\circ}$$

$$= 7.80\;(\text{kJ}/\text{ball})$$

Then the rate of heat transfer from the balls to the water becomes

$$\dot{Q}_{total} = n^{o}_{ball}\ Q_{ball} = 100\ \text{ball}/\text{min} \times 7.80\ \text{kJ}/\text{ball}$$

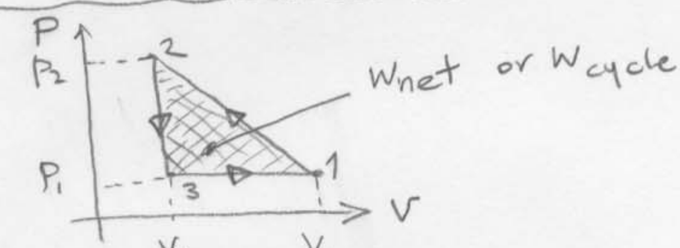
$$= 780\ \text{kJ}/\text{min}$$

Therefore, heat must be removed from the water at a rate of $780\ \text{kJ}/\text{min}$ in order to keep its temp constant at $50°C$.

Since energy input must be equal to energy output for a system whose energy level remains constant.

$$E_{in} = E_{out} \quad \text{when} \quad \Delta E_{system} = 0$$

Problem 7



$$W_{cycle} = W_{12} + W_{23} + W_{31}$$

$$\begin{cases} W_{12} = -\int_1^2 p\,dV = -\left(\frac{P_1+P_2}{2}\right)(V_2 - V_1) = \left(\frac{P_1+P_2}{2}\right)(V_1 - V_2) \\ W_{23} = -\int_2^3 p\,dV = 0 \qquad \text{Since } dV = 0 \\ W_{31} = -\int_3^1 p\,dV = -P_1\,(V_1 - V_3) = -P_1\,(V_1 - V_2) \end{cases}$$

$$W_{cycle} = \left(\frac{P_1+P_2}{2}\right)(V_1 - V_2) - P_1\,(V_1 - V_2)$$

Note that is equal to the cross_hatched area in the p-v diagram. Also, in such a cyclic process,

$$\underline{\Delta U = \Delta T = \Delta P = \Delta(\text{any property}) = 0}$$