Dec 2001 + Solutions

THE UNIVERSITY OF MANITOBA

1:30 p.m. 8 December 20 01 FINAL EXAMINATION

PAPER NO.: 142

PAGE NO.: 1 of 3

DEPARTMENT & COURSE NO.: 130.112

TIME: 3 HOURS

EXAMINATION: Thermal Sciences

EXAMINER: Dr. S.J. Ormiston

Values

Instructions:

1. You are permitted to use the textbooks for the course and a calculator.
2. Clear, systematic solutions are required. Marks will not be assigned for problems that require unreasonable (in the opinion of the instructor) effort for the marker to decipher.
3. Ask for clarification if any problem statement is unclear to you.
4. You may need to interpolate in the property tables. Use linear interpolation between table entries.
5. There are five questions on this exam. The weight of each problem is indicated. The exam will be marked out of 100.

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[9] **1.** A Carnot refrigerator removes energy at a rate of 112.0 [kW] from a cold storage room at -13 [$°C$] and adds energy to the atmosphere (outdoors) at 30 [$°C$]. As shown in Figure 1, the refrigerator is driven by a Carnot engine that takes heat from a reservoir at 327 [$°C$] and rejects energy to the atmosphere (outdoors) at 30 [$°C$].

4 (a) Determine the power required to drive the refrigerator.

5 (b) Determine the total rate of heat rejected to the atmosphere by the combined devices.

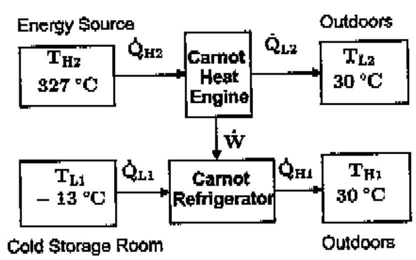

Figure 1: Figure for problem 1.

[21] **2.** A room that has a volume of 130 [m^3] contains atmospheric air at 99 [kPa] with a dry bulb temperature of 30 [$°C$] and a wet bulb temperature of 23 [$°C$].

In the calculations below do not use the psychrometric chart unless specifically asked to do so. Keep 4 significant figures in your calculations (and keep the same number of figures on properties as they appear in the tables).

6 (a) Determine the specific humidity.

2 (b) Determine the relative humidity.

2 (c) Determine the specific enthalpy of the air in [kJ/kg dry air].

9 (d) Determine the mass of water that must be removed from the atmospheric air in a dehumidification process (during which the total pressure is unchanged and the room temperature remains constant at 30 [$°C$]) to achieve a final relative humidity of 30%.

2 (e) *Using the psychrometric chart* (assume that the pressure is approximately one atmosphere for these purposes), estimate the specific volume in [m^3/kg dry air].

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[32] **3.** Figure 2 shows a cogeneration plant made up of a steam (water) power cycle and a refrigerant (R-134a) power cycle. In the steam cycle superheated vapour enters the turbine with a mass flow rate of 5.0 [kg/s] at a pressure of 4 [MPa] and a temperature of 400 [$°C$]. The exhaust (exit flow) from the steam turbine is at 150 [kPa] with a quality of 95%. Forty percent of the mass flow leaving the steam turbine (i.e. 2.0 [kg/s]) is extracted and used for industrial process heating. The rest of the turbine exhaust flow passes through a heat exchanger which serves as the condenser of the steam cycle and the boiler of the R-134a cycle. The exit of the water side of the heat exchanger is saturated liquid water at 150 [kPa], which is combined in a mixing chamber with the return flow from the industrial process (which is at 60 [$°C$] and 150 [kPa]), before being pumped (in pump 1) up to the steam generator pressure. The exit flow from pump 1 is at a temperature of 92 [$°C$].

In the R-134a cycle, the refrigerant enters the turbine at 1.6 [MPa] and 80 [$°C$]. The exhaust of the R-134a turbine is at 700 [kPa] and 50 [$°C$]. The R-134a is in saturated liquid state at the exit from its condenser (state 9). The refrigerant enters the heat exchanger at 1.6 [MPa] and 27.5 [$°C$]. In this analysis it may be assumed that the turbines and pumps are adiabatic, and that the heat exchanger is well-insulated.

4 (a) Determine the rate of heat transfer to the boiler, $\dot{Q}_B$, in [kW].

10 (b) Determine the **net** power output of the steam cycle, in [kW].

10 (c) Determine the **net** power output of the R-134a cycle, in [kW].

8 (d) On two separate T-v (temperature–specific volume) diagrams, draw process representations with respect to the vapour dome for each of the power cycles. On the diagrams, clearly indicate the labelled state points, the process paths (use a dashed line if the path is unknown), and the constant pressure lines that pass through the state points.

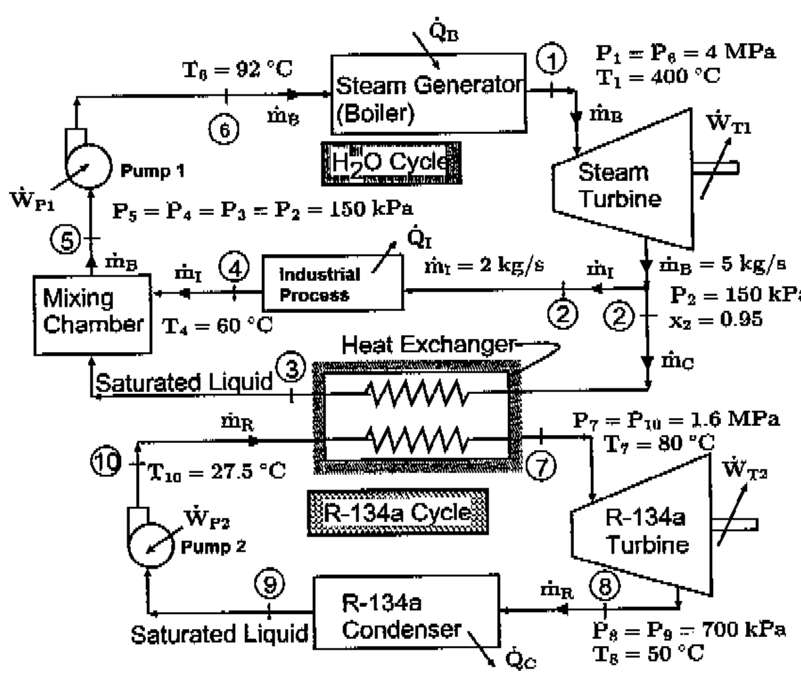

Figure 2: Schematic diagram for problem 3.

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[21] **4**. The frictionless piston-cylinder closed system shown in Figure 3 below contains an ideal gas mixture composed of 5.00 [kg] of argon (**Ar**), 4.00 [kg] of ethane ($\mathbf{C_2H_6}$), and 3.5 [kg] of nitrogen ($\mathbf{N_2}$). Initially, the system has a pressure of $P_1 = 600$ [kPa] and a temperature of $T_1 = 400$ [$°C$], and the linear spring is just touching the piston but not exerting any force on it. Heat is added to the system until the final volume of the mixture is 4.02 [m^3] (state 2). The spring constant, k, is 180 [kN/m], and the cross-sectional area of the piston, A, is 0.6 [m^2].

5 (a) Calculate the initial volume of the mixture, V_1 in [m^3].

5 (b) Determine the final pressure, P_2, in [kPa].

2 (c) Calculate the work done by the system in the process, W_{12}, in [kJ].

6 (d) Calculate the heat transfer to the system in the process, Q_{12}, in [kJ].

3 (e) Show the process on a P–V (pressure–volume) diagram. Clearly identify the states and show the process path with respect to constant temperature lines.

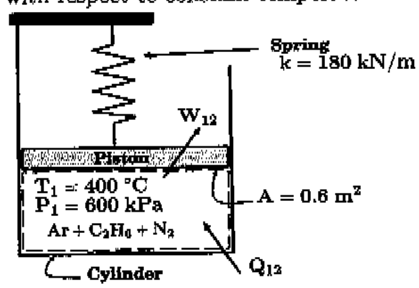

Figure 3: Figure for problem 4.

[17] **5**. The wall of a toilet tank is a composite wall made of porcelain tank material (k_p=0.11 [W/m · K]) and a foam insulating liner (k_f=0.050 [W/m · K]) as shown in Figure 4. The outside of the tank is exposed to convection with room air and the foam is exposed to convection with the cold water in the tank. The total wall surface area is 0.375 [m^2].
On a humid summer day the convection heat transfer coefficients are h_o=4.0 [W/m^2 · K] for the room-side surface of the wall and h_i=25.0 [W/m^2 · K] for the water-side surface of the wall. The room air temperature, T_o, is 25 [$°C$], and the water temperature, T_i is 5 [$°C$]. The thicknesses of the porcelain and foam insulation are shown in the figure.

7 (a) Calculate the total rate of heat transfer, in [W], through the composite wall shown.

4 (b) Determine the temperature at the outside surface of the tank, T_1, in [$°C$].

6 (c) If the relative humidity in the room is 60%, what thickness of foam insulation, L_f, is required to prevent condensation on the outside surface of the tank (keeping k_p, k_f, L_p, T_i, h_i, T_o, and h_o the same)?

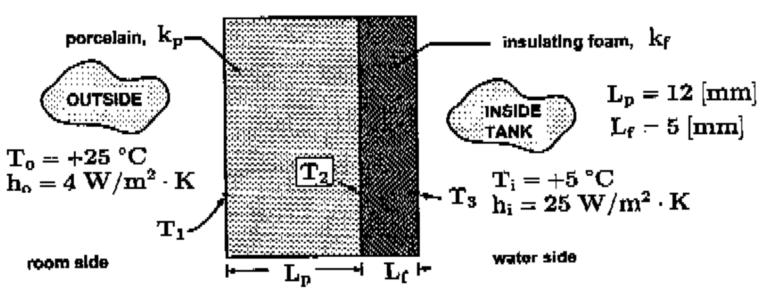

Figure 4: Schematic diagram for problem 5.

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1. (a) Carnot Refrigerator $COP_{R,rev} = \dfrac{1}{\left(\frac{T_{H1}}{T_{L1}} - 1\right)}$

$$COP_{R,rev} = \frac{1}{\frac{(30+273)}{(-13+273)} - 1} = 6.0465$$

$$\dot{W} = \frac{\dot{Q}_{L1}}{COP_{R,rev}} = \frac{112.0}{6.0465} = 18.523\ [kW]$$

(b) $\dot{Q}_{rejected} = \dot{Q}_{H1} + \dot{Q}_{L2}$

$$\dot{Q}_{H1} = \dot{Q}_{L1} + \dot{W} = 112.0 + 18.523 = 130.523\ [kW]$$

Carnot Heat Engine $\eta_{th,rev} = 1 - \dfrac{T_{L2}}{T_{H2}} = 1 - \dfrac{(30+273)}{(327+273)}$

$$\eta_{th,rev} = 0.495$$

$$\eta_{th} = \frac{\dot{W}}{\dot{Q}_{H_2}} \Rightarrow \dot{Q}_{H_2} = \frac{\dot{W}}{\eta_{th,rev}} = \frac{18.523}{0.495} = 37.420\ [kW]$$

$$\dot{Q}_{L2} = \dot{Q}_{H_2} - \dot{W} = 37.420 - 18.523 = 18.897\ (kW)$$

$$\dot{Q}_{rejected} = 130.523 + 18.897 = 149.42\ [kW]$$

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(2) (a) $\forall_m = 130\ [m^3]$ $\quad T_1 = T_{db} = 30\ [°C]$

$P_m = 99\ [kPa]$ $\quad T_2 = T_{wb} = 23\ [°C]$

$$\omega_1 = \frac{c_p (T_2 - T_1) + \omega_2 h_{fg_2}}{h_{g_1} - h_{f_2}} \qquad \omega_2 = \frac{0.622\, P_{g_2}}{(P_2 - P_{g_2})}$$

$$P_{g_2} = P_{sat}(23\ [°C]) = 2.339 + \frac{(23-20)}{(25-20)}(3.169 - 2.339) = 2.837\ [kPa]$$

$$\omega_2 = \frac{0.622\,(2.837)}{(99.0 - 2.837)} = 0.01835 \quad \left[\frac{kg\ H_2O}{kg\ dry\ air}\right]$$

$$h_{fg_2} = h_{fg}\big|_{23[°C]} = 2454.1 + \frac{(23-20)}{(25-20)}(2442.3 - 2454.1) = 2447.0\ \left[\frac{kJ}{kg}\right]$$

$$h_{f_2} = h_f\big|_{23[°C]} = 83.96 + \frac{(23-20)}{(25-20)}(104.89 - 83.96) = 96.52\ \left(\frac{kJ}{kg}\right)$$

$$h_{g_1} = h_g\big|_{30[°C]} = 2556.3\ \ (kJ/kg)$$

$$c_{p_0} = 1.005\ [kJ/kg\,K]$$

$$\omega_1 = \frac{1.005\,(23 - 30) + (0.01835)\,2447.0}{(2556.3 - 96.52)} = 0.01539\ \left[\frac{kg\ H_2O}{kg\ dry\ air}\right]$$

(b) $$\phi_1 = \frac{\omega_1 P_1}{(0.622 + \omega_1) P_{g1}}$$

$$P_{g1} = P_{sat}(30\ [°C]) = 4.246\ (kPa)$$

$$\phi_1 = \frac{0.01539\,(99)}{(0.622 + 0.01539)\ 4.246} = 0.5630$$

$$\phi_1 = \underline{56.30\ \%}$$

2. (c) $h_1 = c_{pa} T_1 + \omega_1 h_{g1}$

$$h_1 = 1.005(30) + (0.01539)\,2556.3 = 69.49 \left[\frac{kJ}{kg\ dry\ air}\right]$$

(d) Initially $P_1 = 99\,[kPa]$ $P_{g1} = 4.246\,(kPa)$

$T_1 = 30\,[°C]$

$\phi_1 = 0.5630$

$P_{v1} = (0.5630)(4.246) = 2.3905\,(kPa)$

$$m_{v1} = \frac{P_{v1} V_m}{R_v T_1} = \frac{(2.3905)(130)}{(0.4615)(30+273)} = 2.2224\,[kg]$$

New condition (call it "3") has $\phi_3 = 0.30 = \dfrac{P_{v3}}{P_{g3}}$

if T_{db} = constant $P_{g3} = P_{g1} = 4.246\,(kPa)$

$\Rightarrow P_{v3} = (0.30)(4.246) = 1.2738\,[kPa]$

$$m_{v3} = \frac{P_{v3} V_m}{R_v T_3} = \frac{(1.2738)(130)}{(0.4615)(30+273)} = 1.1842\,[kg]$$

Mass removed $= (m_{v1} - m_{v3}) = 2.2224 - 1.1842 = 1.0382\,(kg)$ ←

(e) For the initial conditions $T_{db} = 30\,[°C]$ $T_{wb} = 23\,[°C]$

$v \simeq 0.878 \left[\frac{m^3}{kg\ dry\ air}\right]$

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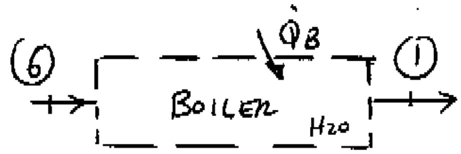
(3) (a)



1st Law for boiler (neglect $\Delta pe, \Delta ke$; $\dot{W}_{sh}=0$)

$$\dot{Q}_B = \dot{m}_B (h_1 - h_6)$$

$$h_1 = h(4\,[MPa], 400\,[°C]) = 3213.6\ [kJ/kg]$$

$$h_6 = h_f(92\,[°C]) = 376.92 + \frac{(92-90)}{(95-90)}(397.96 - 376.92)$$

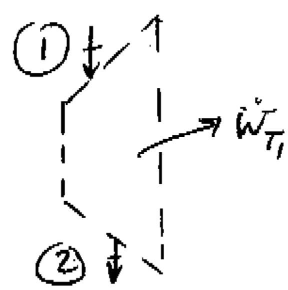
$$h_6 = 385.34\ [kJ/kg]$$

$$\dot{Q}_B = 5.0\,(3213.6 - 385.34) = 14141\ [kW]$$

(b) <u>Net</u> power output of the steam cycle is $\dot{W}_{T1} - \dot{W}_{P1}$
need 1st Law analysis on steam turbine & pump 1

- steam turbine 1st law (neglect $\Delta pe, \Delta ke$; $\dot{Q}_{12}=0$)

$$-\dot{W}_{T_1} = \dot{m}_B (h_2 - h_1)$$



$$h_2 = (1 - x_2)\, h_f|_{P_2} + x_2\, h_g|_{P_2}$$

$$h_f(0.150\,[MPa]) = 467.11\ [kJ/kg]$$
$$h_g(0.150\,[MPa]) = 2693.6\ [kJ/kg]$$

$$h_2 = (1 - 0.95)\,467.11 + (0.95)\,2693.6 = 2582.3\ [kJ/kg]$$

$$-\dot{W}_{T_1} = 5.0\,(2582.3 - 3213.6)$$

$$\dot{W}_{T_1} = 3156.5\ [kW]$$

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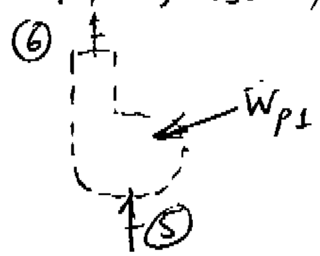
3 (b) continued

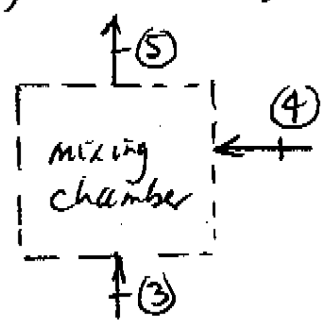
▶ Pump 1 1^{st} Law (neglect Δpe, Δke; $\dot{Q}_{56} = 0$)



note $\dot{W}_{P1}$ is assumed +VE in

$$\dot{W}_{P1} = \dot{m}_B (h_6 - h_5)$$

need h_5 → must analyze mixing chamber to get h_5



1^{st} Law on mixing chamber ($\Delta pe = 0$, $\Delta ke = 0$, $\dot{Q} = 0$, $\dot{W}_{sh} = 0$)

$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e$$

$$\dot{m}_3 h_3 + \dot{m}_4 h_4 = \dot{m}_5 h_5$$

$$h_5 = \frac{\dot{m}_3 h_3 + \dot{m}_4 h_4}{\dot{m}_5}$$

mass conservation $\dot{m}_3 + \dot{m}_4 = \dot{m}_5$ $\qquad \dot{m}_B = 5.0\ [kg/s] = \dot{m}_5$

$\dot{m}_C + \dot{m}_I = \dot{m}_B$ $\qquad \dot{m}_I = 2.0\ [kg/s] = \dot{m}_4$

$$\dot{m}_C = \dot{m}_B - \dot{m}_I = 5.0 - 2.0 = 3.0\ [kg/s] = \dot{m}_3$$

$$h_3 = h_f|_{P_3} = h_f(0.150\,(MPa)) = 467.11\ [kJ/kg]$$

$$h_4 = h_f|_{60^\circ C} = 251.13\ [kJ/kg]$$

$$h_5 = \frac{3.0(467.11) + 2.0(251.13)}{5.0} = 380.72\ [kJ/kg]$$

$$\dot{W}_{P1} = 5.0\,(385.34 - 380.72) = 23.1\ [kW]$$

$$\dot{W}_{net,H_2O} = 3156.5 - 23.1 = 3133.4\ [kW] \leftarrow$$

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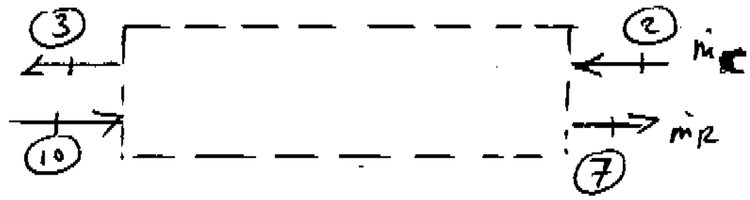
3 (c) Net power output of R134a cycle

is $\dot{W}_{T_2} - \dot{W}_{P_2}$

need $\dot{m}_R$ to do 1st Law on devices in R134a cycle

→ get $\dot{m}_R$ from 1st Law on Heat Exchanger (neglect Δpe, Δke; $\dot{Q}=0$, $\dot{W}_{sh}=0$)



$$\Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e \qquad \dot{m}_2 = \dot{m}_3 = \dot{m}_B = 5.0\ [kg/s]$$

$$\dot{m}_{10} = \dot{m}_7 = \dot{m}_R$$

$$\dot{m}_2 h_2 + \dot{m}_{10} h_{10} = \dot{m}_3 h_3 + \dot{m}_7 h_7$$

$$\dot{m}_c (h_2 - h_3) = \dot{m}_R (h_7 - h_{10})$$

$$\dot{m}_R = \dot{m}_c \frac{(h_2 - h_3)}{(h_7 - h_{10})}$$

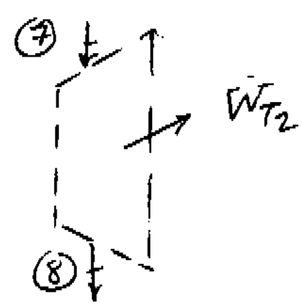
$$h_7 = h(1.6\ [MPa], 80\ [°C]) = 303.74\ [kJ/kg]$$

$$h_{10} = h_f(27.5\ [°C]) = 85.75 + \frac{(27.5-26)}{(28-26)}(88.61 - 85.75) = 87.90 \left(\frac{kJ}{kg}\right)$$

$$\dot{m}_R = 3.0 \frac{(2582.3 - 467.11)}{(303.74 - 87.90)} = 29.40\ [kg/s]$$

→ R-134a Turbine 1st Law (neglect Δpe, Δke; $\dot{Q}_{78} = 0$)

$$-\dot{W}_{T_2} = \dot{m}_R (h_8 - h_7)$$



$$h_8 = h(0.700\ [MPa], 50\ [°C])$$

$$h_8 = 286.35\ (kJ/kg)$$

$$-\dot{W}_{T_2} = 29.40\,(286.35 - 303.74)$$

$$\dot{W}_{T_2} = 511.27\ (kW)$$

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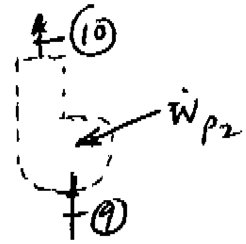
3 (c) continued

- Pump 2



1st Law

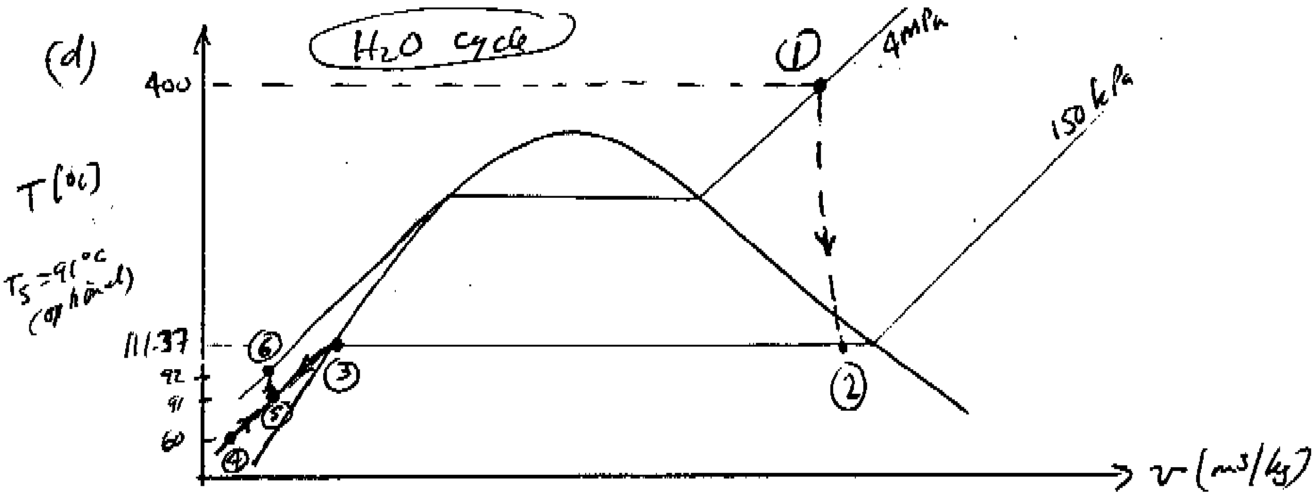
$$\dot{W}_{P2} = \dot{m}_R(h_{10} - h_9)$$

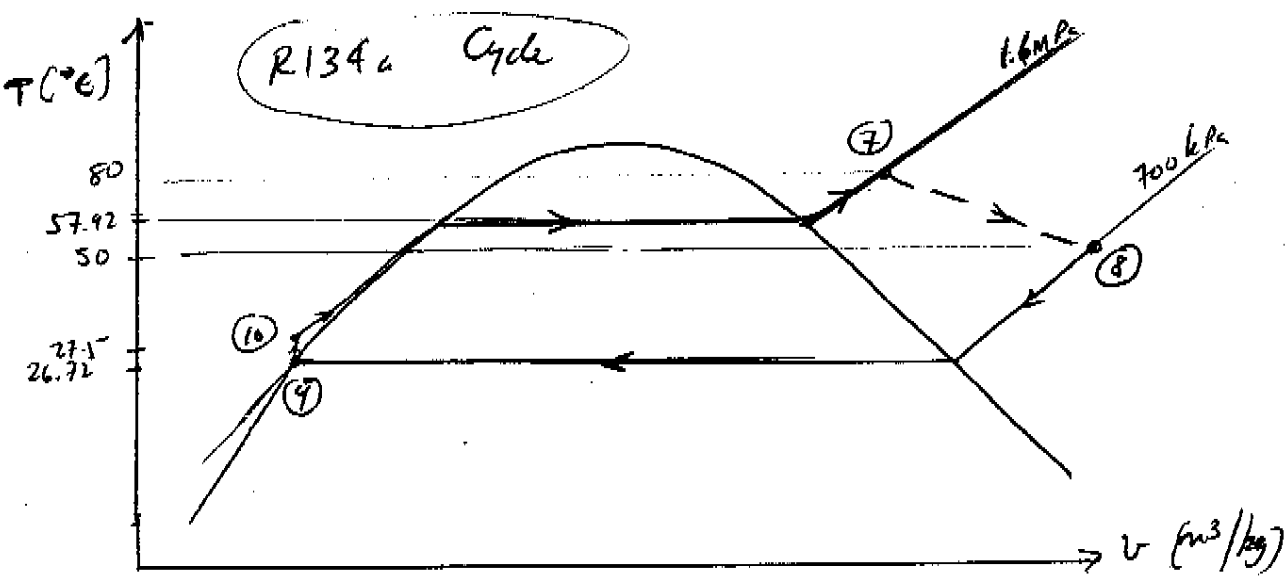
$$h_9 = h_f\big|_{P_9} = h_f(0.700\,[MPa]) = 86.78\ (kJ/kg)$$

$$\dot{W}_{P2} = 29.40\,(87.90 - 86.78) = 32.93\ [kW]$$

$$\dot{W}_{net,R134a} = 511.27 - 32.39 = 478.34\ [kW]$$

(d)





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(4) (a) $m_{Ar} = 5.00$ [kg] $M_{Ar} = 39.948$ [kg/kmol]

$m_{C_2H_6} = 4.00$ [kg] $M_{C_2H_6} = 30.070$ [kg/kmol]

$m_{N_2} = 3.50$ [kg] $M_{N_2} = 28.013$ [kg/kmol]

$$m_m = 5.00 + 4.00 + 3.50 = 12.50 \text{ [kg]}$$

$$\forall_1 = \frac{m_m R_m T_1}{P_1} \qquad R_m = \frac{R_u}{M_m} \qquad M_m = \frac{m_m}{N_m}$$

$T_1 = 400$ [°C]
$P_1 = 600$ [kPa]

$$N_{Ar} = \frac{m_{Ar}}{M_{Ar}} = \frac{5.00 \text{ [kg]}}{39.948 \text{ [kg/kmol]}} = 0.12516 \text{ [kmol]}$$

$$N_{C_2H_6} = \frac{m_{C_2H_6}}{M_{C_2H_6}} = \frac{4.00 \text{ [kg]}}{30.070 \text{ [kg/kmol]}} = 0.13302 \text{ [kmol]}$$

$$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{3.50 \text{ [kg]}}{28.013 \text{ [kg/kmol]}} = 0.12494 \text{ [kmol]}$$

$$N_m = 0.12516 + 0.13302 + 0.12494 = 0.38312 \text{ [kmol]}$$

$$M_m = \frac{12.50}{0.38312} = 32.627 \text{ [kg/kmol]}$$

$$R_m = \frac{8.314}{32.627} = 0.2548 \text{ [kJ/kg K]}$$

$$\forall_1 = \frac{(12.50)\, 0.2548\, (400 + 273)}{600} = 3.573 \text{ [m}^3\text{]} \leftarrow$$

(b) P_2 comes from linear change of P with $\forall$ (linear spring)

$$P(\forall) = a(\forall - \forall_1) + P_1 \qquad a = \frac{k}{A^2} = \frac{180}{(0.6)^2} = 500.0 \left(\frac{kPa}{m^3}\right)$$

$$P_2 = a(\forall_2 - \forall_1) + P_1$$
$$P_2 = 500.0\,(4.02 - 3.573) + 600 = 823.5 \text{ [kPa]}$$

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4 (c) $W_{12} = \frac{1}{2}(P_1 + P_2)(\forall_2 - \forall_1)$

$= \frac{1}{2}(600 + 823.5)(4.02 - 3.573) = 318.15$ [kJ]

(d) $Q_{12} - W_{12} = (U_2 - U_1) = m_m C_{v,m}(T_2 - T_1)$ (neglect ΔKE, ΔPE)

$Q_{12} = W_{12} + m_m c_{v,m}(T_2 - T_1)$

$T_2 = \frac{P_2 \forall_2}{m_m R_m} = \frac{(823.5)(4.02)}{(12.50)(0.2548)} = 1039.39\,[K] = 766.39\,[°C]$

$c_{v,m} = \sum mf_i \, c_{v_i}$

$mf_{Ar} = \frac{5.00}{12.50} = 0.400$ $\qquad c_{v_{Ar}} = 0.3122$ [kJ/kg K]

$mf_{C_2H_6} = \frac{4.00}{12.50} = 0.320$ $\qquad c_{v_{C_2H_6}} = 1.4897$ [kJ/kg K]

$mf_{N_2} = \frac{3.5}{12.50} = 0.280$ $\qquad c_{v_{N_2}} = 0.743$ [kJ/kg K]

$c_{v,m} = 0.400(0.3122) + 0.320(1.4897) + 0.280(0.743)$

$c_{v,m} = 0.8096$ [kJ/kg K]

$Q_{12} = 318.15 + (12.50)\,0.8096\,(766.39 - 400)$

$Q_{12} = 318.15 + 3707.87$

$Q_{12} = 4026.02$ [kJ] ←

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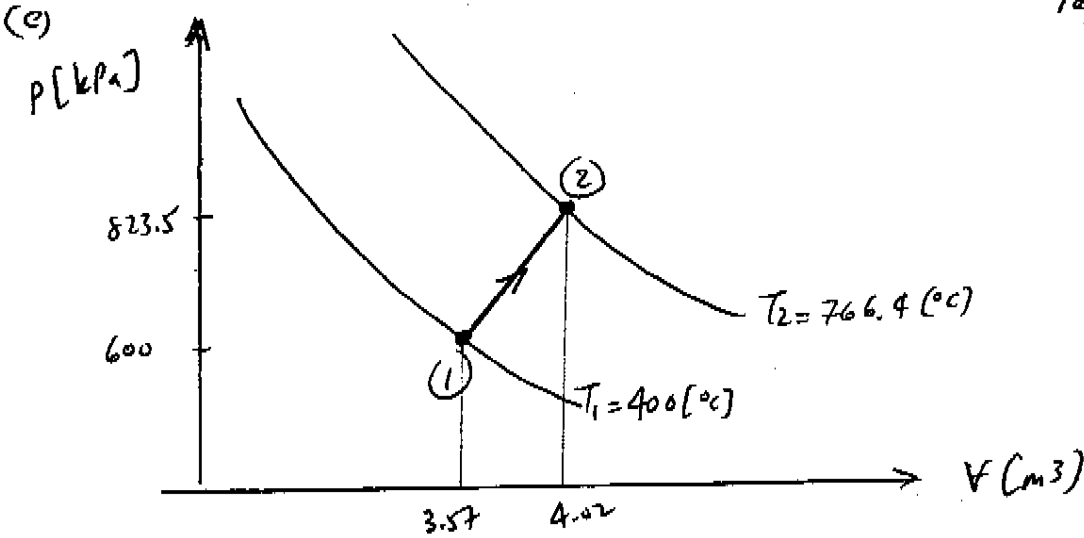
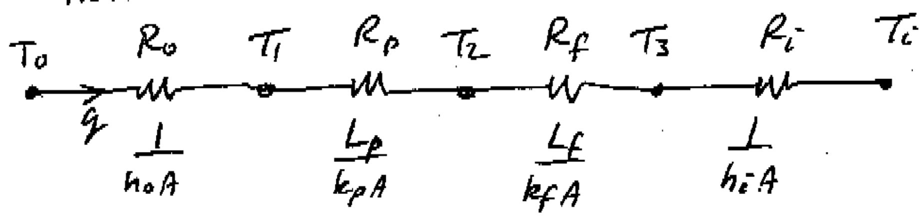
4 (e)



⑤. (a) Thermal resistance network



$A = 0.375\,[m^2]$

$L_p = 12$ mm $= 0.012$ m

$L_f = 5$ mm $= 0.005$ m

$k_p = 0.11 \left(\frac{W}{mK}\right)$

$k_f = 0.050 \left(\frac{W}{mK}\right)$

$$R_o = \frac{1}{4(0.375)} = 0.66667 \left[\frac{K}{W}\right]$$

$$R_p = \frac{0.012}{0.11(0.375)} = 0.29091 \left[\frac{K}{W}\right]$$

$$R_f = \frac{0.005}{0.050(0.375)} = 0.26667 \left[\frac{K}{W}\right]$$

$$R_i = \frac{1}{25(0.375)} = 0.10667 \left[\frac{K}{W}\right]$$

$$R_{tot} = 0.66667 + 0.29091 + 0.26667 + 0.10667 = 1.3309 \left[\frac{K}{W}\right]$$

$$q = \frac{(T_o - T_i)}{R_{tot}} = \frac{(25 - 5)}{1.3309} = 15.03\,[W] \leftarrow$$

5 (b) $T_1 = T_0 - q R_0$

$$T_1 = 25 - 15.03(0.66667) = 14.98 \, [°C]$$

(c) $\phi = 0.60$

To prevent condensation T_1 must be just above the dew point temperature. $T_{dp} = T_{sat}(P_v)$

$P_v = \phi P_g$ $\qquad P_g = P_{sat}(T_{room}) = P_{sat}(25 [°C])$

$P_g = 3.169 \, [kPa]$

$$P_v = (0.60)(3.169) = 1.9014 \, [kPa]$$

$$T_{dp} = T_{sat}(1.9014 \, [kPa])$$

$$= 13.03 + \frac{(1.9014 - 1.5)}{(2.0 - 1.5)}(17.50 - 13.03)$$

$$T_{dp} = 16.62 \, [°C]$$

Calculate new L_f that will give $T_1 = 16.7 [°C]$

new $q^{new} = \dfrac{25 - 16.7}{0.66667} = 12.45 \, [W]$ $\qquad q^{new} = \dfrac{(T_0 - T_1^{new})}{R_0}$

$q^{new} = \dfrac{(T_0 - T_i)}{R_{tot}^{new}}$ $\qquad R_{tot}^{new} = \dfrac{(25-5)}{12.45} = 1.6064 \, [\frac{K}{W}]$

$$R_f^{new} = R_{tot}^{new} - R_i - R_0 - R_p = 1.6064 - 0.10667 - 0.66667 - 0.29091$$

$$R_f^{new} = 0.54215 \, [\tfrac{K}{W}] = \frac{L_f^{new}}{k_f A}$$

$$L_f^{new} = R_f^{new} \cdot k_f A = (0.54215)(0.050)(0.375)$$

$$L_f^{new} = 0.0102 \, (m) \Rightarrow L_f^{new} = \underline{10.2 \, [mm]}$$