THE UNIVERSITY OF MANITOBA

6:00 p.m. 17 December 20 02 FINAL EXAMINATION

PAPER NO.: 514 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 to decipher.
3. Ask for clarification if any problem statement is unclear to you.
4. Use linear interpolation between table entries as necessary.
5. Retain all the significant figures of property values from tables. Keep 4 significant figures in your intermediate results. Final answers must have 3 to 5 significant figures and units.
6. Use constant specific heat. Take values at 300 $[K]$.
7. 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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[17] **1.** Perform the calculations requested in the two parts below.

Part 1: Using the formulas and the water property tables:

A room with a volume of 100 $[m^3]$ contains an air-water vapour mixture at 98 $[kPa]$ and 35 $[°C]$. The relative humidity is 66%.

3 (a) Determine the specific humidity.

3 (b) Determine the dew point temperature.

2 (c) Determine the mass of air.

2 (d) Determine the mass of vapour.

3 (e) Determine the specific enthalpy of the mixture in $[kJ/kg\,\text{dry air}]$.

Part 2: Using the psychrometric chart:

4 (f) For a wet bulb temperature of 17 $[°C]$ and relative humidity of 20%, find the dry bulb temperature, the specific enthalpy, the dew point temperature, and the specific volume.

[14] **2.** Two different fuels can be used in a heat engine operating between the fuel burning temperature and a low temperature of 77 $[°C]$. Fuel A burns at 1477 $[°C]$, delivers 56,000 $[kJ/kg]$ and costs \$1.75 per $[kg]$. Fuel B burns at 2227 $[°C]$, delivers 40,000 $[kJ/kg]$ and costs \$1.50 per $[kg]$. Demonstrate, through calculations, which is the better fuel to buy. (*Hint:* Think in terms of cost for the desired output).

[19] **3.** Two insulated tanks A and B are connected by a valve that is initially closed. Tank A has a volume of 1.75 $[m^3]$ and initially contains argon at 456 $[kPa]$ and 10.0 $[°C]$. Tank B has a volume of 2.25 $[m^3]$ and initially contains ethane at 123 $[kPa]$ and 60.0 $[°C]$. Perform the requested calculations for the two processes described below.

14 (a) First, the valve is opened and remains open until the resulting ideal gas mixture comes to a uniform state. Determine the pressure and temperature of the uniform state at the end of this process.

5 (b) Second, the insulation on the tanks is then removed and the mixture (uniformly distributed in the total volume) is cooled until the temperature reaches 20 $[°C]$. Calculate the heat transfer from the tanks during this process.

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36 4. Figure 1 shows a schematic of a nuclear power plant that uses water as the working fluid. The high temperature compressed liquid coming out of the reactor (heater) is throttled into the separator. The function of the separator is to take the mixture at state 2 conditions and split it into two streams with mass flow rates $\dot{m}_3$ of saturated vapour and $\dot{m}_4$ of saturated liquid at a pressure of 2 [MPa]. The split in mass flow rates is controlled by the quality at state 2 (i.e. $\dot{m}_3/\dot{m}_2 = x_2$). The heat transfer rate from the condenser, $\dot{Q}_C$, is 19,000 [kW]. The known property information for states in the system is given in the figure. Neglect changes in kinetic and potential energies in all the devices. Assume that the throttling valve, the separator, the turbine, the mixing chamber, and both pumps are all well insulated (i.e. adiabatic).

5 (a) Determine the quality at state 2.

8 (b) Determine the power output of the turbine, in [kW].

5 (c) Determine the rate of heat transfer to the fluid in the reactor (heater), $\dot{Q}_H$, in [kW].

8 (d) Determine T_8, in [°C].

4 (e) Calculate the cycle overall thermal efficiency.

6 (f) On a T-v (temperature–specific volume) diagram, draw process representations with respect to the vapour dome for this cycle. On the diagram, 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. On the diagram, indicate state temperature values and the values of saturation temperatures for reference as appropriate.

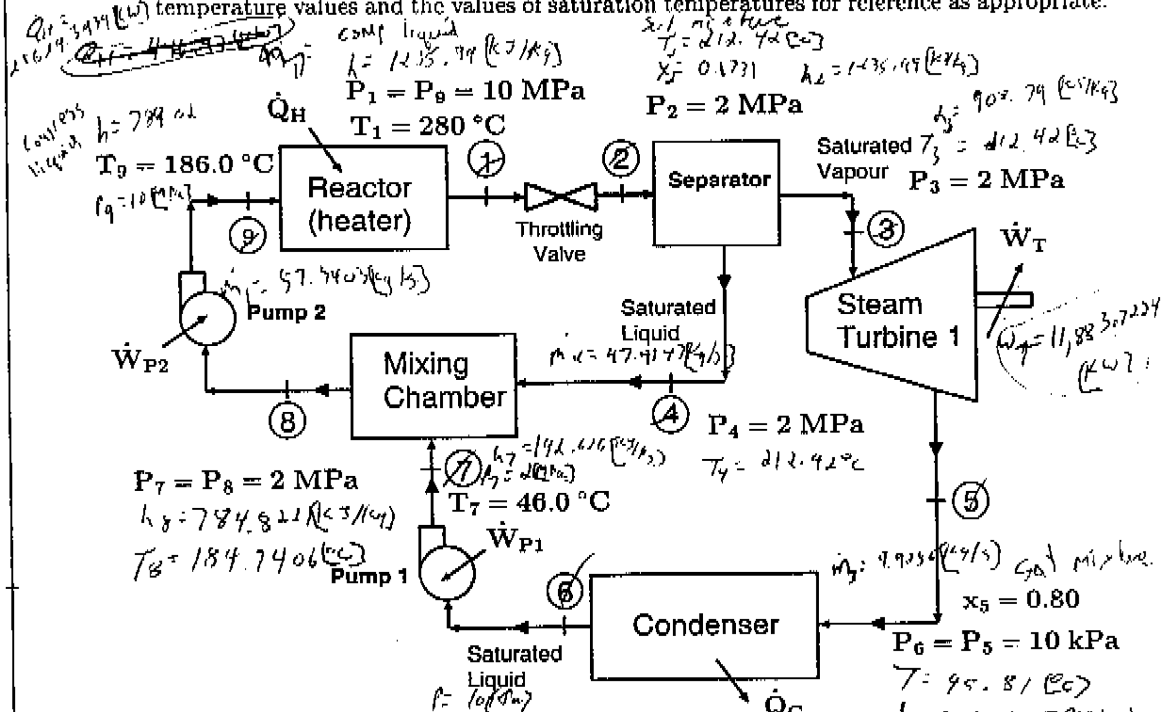

Figure 1: Schematic diagram for problem 4.

T = 45.81 [°C]
h_6 = 191.83 [kJ/kg]

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Values

14 **5.** The interior of a refrigerator is to be maintained at 4 [°C]. The walls of the refrigerator are constructed of two steel sheets 5 [mm] thick with 2 [cm] of glass-wool insulation between them, as shown schematically in Figure 2. The inside and outside heat transfer coefficients are 12.0 [W/m$^2 \cdot$ K] and 18.0 [W/m$^2 \cdot$ K], respectively. The thermal conductivities of the steel and the glass-wool insulation are known to be k_S=45.0 [W/m $\cdot$ K] and k_I=0.040 [W/m $\cdot$ K], respectively. For the purposes of this problem, the total surface area of the refrigerator walls may be taken as 4.50 [m^2]. The kitchen ambient temperature is 24 [°C].

5 (a) Calculate the total rate of heat transfer through the refrigerator walls, in [W].

2 (b) Determine the temperature on the outside surface of the refrigerator, T_4, in [°C].

3 (c) If the refrigerator COP is 2.5 and the cost of electrical energy is \$0.08 per [kWh], determine the daily cost to operate the refrigerator for the conditions corresponding to the situation in part (a) (i.e., with the door always closed).

4 (d) Determine the thickness of insulation required to reduce the heat loss to 50% of the value calculated in part (a). Assume the ambient temperatures, heat transfer coefficients, material properties, and geometric quantities (except the insulation thickness) remain the same as in part (a).

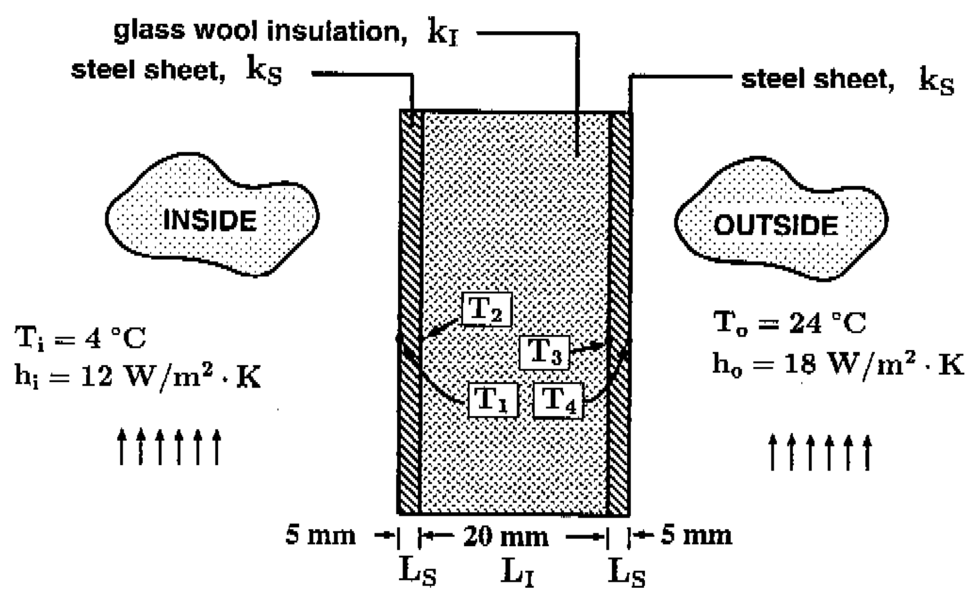


Figure 2: Schematic diagram for problem 5.

130.112 (F02) Final Exam Solution

1. Part 1

$\forall_m = 100\ [m^3] \qquad P_m = \ [kPa] \qquad T_m = 35\ [°C]$

$\phi = 0.66$

(a) $$\omega = \frac{0.622\,\phi P_g}{P - \phi P_g}$$

$$P_g = P_{sat}(T_m) = P_{sat}(35\ [°C]) = 5.628\ [kPa]$$

$$\omega = \frac{0.622\,(0.66)\,5.628}{98 - 0.66(5.628)} = 0.024504 \left[\frac{kg\ H_2O}{kg\ dry\ air}\right]$$

(b) $T_{dp} = T_{sat}(P_v)$

$$P_v = \phi P_g = 0.66(5.628) = 3.7145\ [kPa]$$

Interpolate to find T_{sat} in Table A-5

P [kPa]	T_{sat} [°C]
3.0	24.08
3.7145	T_{dp}
4.0	28.96

$$T_{dp} = 24.08 + \frac{(3.7145 - 3.0)}{(4.0 - 3.0)}(28.96 - 24.08)$$

$$T_{dp} = 27.57\ [°C] \leftarrow$$

(c) $$M_a = \frac{P_a \forall_m}{R_a T_m} \qquad R_a = 0.2870\ (kJ/kg\,K)$$

$$P_a = P - P_v = 98 - 3.7145 = 94.286\ [kPa]$$

$$M_a = \frac{94.286\,(100)}{0.2870\,(35+273)} = 106.66\ [kg]$$

2/14

1. continued

(d) $m_v = \omega m_a = (0.024504)(106.66)$

$m_v = 2.6136$ [kg]

(e) $h = c_{p_0} T + \omega h_g|_T$

$h_g|_{35[°C]} = 2565.3 \left[\frac{kJ}{kg}\right]$

$c_{p_0} = 1.005$ (kJ/kg K)

$h = (1.005)(35) + (0.024504)(2565.3) = 98.04 \left[\frac{kJ}{kg\ dry\ air}\right]$

Part 2

$T_{wb} = 17$ [°C]

$\phi = 0.20$

Read $T_{db} \simeq 32.0$ [°C]

Read $h \simeq 48.0$ [kJ/kg dry air]

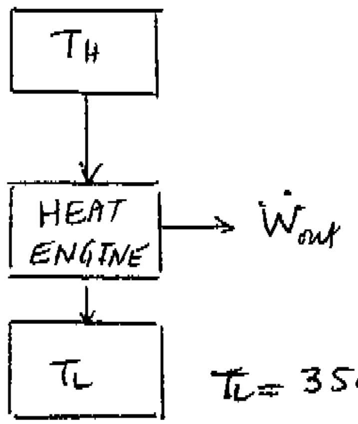
Read $T_{dp} \simeq 6.5$ [°C]

Read $v \simeq 0.873$ [m^3/kg dry air]

3/14

2-4

2. Heat Engine lower temperature: 77 [°C] = 350 [K]
higher temperature = fuel burning temperature



$T_L = 350\,[K]$

To compare the fuels, use their best possible performance
→ i.e. use Carnot efficiency

fuel A

$$\eta_{A,rev} = \left(1 - \frac{T_L}{T_{H_A}}\right)$$

$$T_{H_A} = 1477\,[°C] = 1750\,[K]$$

$$\eta_{A,rev} = \left(1 - \frac{350}{1750}\right) = 0.80$$

fuel B

$$\eta_{B,rev} = \left(1 - \frac{T_L}{T_{H_B}}\right)$$

$$T_{H_B} = 2227\,[°C] = 2500\,[K]$$

$$\eta_{B,rev} = \left(1 - \frac{350}{2500}\right) = 0.86$$

$$\frac{\text{Cost}}{s} = \frac{\text{price}}{kg} \cdot \underbrace{\frac{kg}{s}}_{\text{mass flow rate}}$$

mass flow rate comes from energy content & $\dot{Q}_H$

$$(\dot{Q}_H)_{fuel} = \dot{m}_{fuel}\,(h_c)_{fuel}$$

← heat content (energy content)

$$\eta = \frac{\dot{W}_{out}}{\dot{Q}_H}$$

$$\Rightarrow \dot{W}_{out} = \eta \cdot \dot{Q}_H$$

$$\therefore\ \dot{W}_{out_{fuel}} = \eta_{fuel} \cdot \dot{m}_{fuel}\,(h_c)_{fuel}$$

Cost per unit output

$$\frac{\frac{\text{Cost}}{s}}{\dot{W}_{out}} = \frac{\left(\frac{\text{price}}{kg}\right)_{fuel} \dot{m}_{fuel}}{\eta_{fuel} \cdot \dot{m}_{fuel} \cdot (h_c)_{fuel}} = \frac{\left(\frac{\text{price}}{kg}\right)_{fuel}}{\eta_{fuel} \cdot (h_c)_{fuel}}$$

4/14

2-21

2 (continued)

$$\frac{\text{Cost}}{kJ_{output}} = \frac{\left(\frac{\text{price}}{kg}\right)_{fuel}}{\eta_{fuel} \cdot (h_c)_{fuel}}$$

Units

$$\frac{\$}{kg \cdot \frac{kJ}{kg}} \rightarrow \frac{\$}{kJ}$$

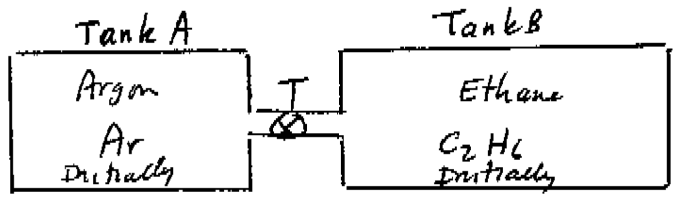
Fuel A $\left(\frac{Cost}{kJ}\right)_A = \frac{\$1.75}{(0.80)(56{,}000)} = 3.90625 \times 10^{-5} \ \frac{\$}{kJ}$

Fuel B $\left(\frac{Cost}{kJ}\right)_B = \frac{\$1.50}{(0.86)(40{,}000)} = 4.3605 \times 10^{-5} \ \frac{\$}{kJ}$

∴ Fuel A is the better choice. (lower cost per unit energy output)

5/14

3. (a) 3-4



$\forall_A = 1.75\ [m^3]$ $\qquad \forall_B = 2.25\ [m^3]$

Initially
- Insulated
- $P_{A_1} = 456\ [kPa]$ $\qquad P_{B_1} = 123\ [kPa]$

$T_{A_1} = 10.0\ [°C] = 283\ [K]$ $\qquad T_{B_1} = 60.0\ [°C] = 333\ [K]$

Process 1 → 2
- Adiabatic (insulated)
- Constant total volume (system is both tanks)
- Closed system

$$m_{Argon} = \frac{P_{A_1} \forall_A}{R_{Ar} T_{A_1}} \qquad m_{Ethane} = \frac{P_{B_1} \forall_B}{R_{Ethane} T_{B_1}}$$

$$R_{Ar} = 0.2081 \left[\frac{kJ}{kg\,K}\right] \qquad R_{ethane} = 0.2765 \left[\frac{kJ}{kg\,K}\right]$$

$$m_{Argon} = \frac{456\,(1.75)}{0.2081\,(283)} \qquad m_{ethane} = \frac{123\,(2.25)}{0.2765\,(333)}$$

$$m_{Argon} = 13.550\ [kg] \qquad m_{ethane} = 3.0057\ [kg]$$

First Law for process 1 to 2

$$\cancel{Q_{12}}^{0} - \cancel{W_{12}}^{0} = (U_2 - U_1)$$

$$U_1 = U_{1\,argon} + U_{1\,ethane}$$

$$U_2 = U_{2\,argon} + U_{2\,ethane}$$

$$(U_{2\,argon} - U_{1\,argon}) + (U_{2\,ethane} - U_{1\,ethane}) = 0$$

3 (cont'd) $\Delta U = m C_{vo} \Delta T$ 6/14

$$m_{argon} C_{vo\,argon} (T_2 - T_{A_1}) + m_{ethane} C_{vo\,ethane} (T_2 - T_{B_1}) = 0$$ 3-4

$$(m_{argon} C_{vo\,argon} + m_{ethane} C_{vo\,ethane}) T_2 = m_{argon} C_{vo\,argon} T_{A_1} + m_{ethane} C_{vo\,ethane} T_{B_1}$$

$$T_2 = \frac{(m_{argon} C_{vo\,argon} T_{A_1} + m_{ethane} C_{vo\,ethane} T_{B_1})}{(m_{argon} C_{vo\,argon} + m_{ethane} C_{vo\,ethane})}$$

$$C_{vo\,argon} = 0.3122 \ (kJ/kg\,K)$$
$$C_{vo\,ethane} = 1.4897 \ (kJ/kg\,K)$$

$$T_2 = \frac{(13.550)(0.3122)(283) + (3.0057)(1.4897)(333)}{((13.550)(0.3122) + (3.0057)(1.4897)} = 308.71 \ (K)$$

$P_{2_m} \forall_{2_m} = m_m R_m T_{2_m}$ for the mixture at state 2

$$\forall_{2_m} = \forall_A + \forall_B = 1.75 + 2.25 = 4.00 \ (m^3)$$
$$m_m = m_{argon} + m_{ethane} = 13.550 + 3.0057 = 16.556 \ (kg)$$

$$P_{2_m} = \frac{m_m R_m T_{2_m}}{\forall_{2_m}} \qquad R_m = \frac{R_u}{M_m} \qquad M_m = \frac{m_m}{N_m} \qquad N = \frac{m}{M}$$

$$M_{argon} = 39.948 \left(\frac{kg}{kmol}\right)$$
$$M_{ethane} = 30.070 \left(\frac{kg}{kmol}\right)$$

$$N_{argon} = \frac{13.550}{39.948}$$

$$N_{argon} = 0.33919 \ (kmol)$$

$$N_{ethane} = \frac{3.0057}{30.070}$$

$$N_{ethane} = 0.099957 \ (kmol)$$

$$N_m = N_{argon} + N_{ethane} = 0.33919 + 0.099957 = 0.43915 \ (kmol)$$

$$M_m = \frac{16.556}{0.43915} = 37.700 \left(\frac{kg}{kmol}\right)$$

3 (cont'd) 7/14

3-3)

$$R_m = \frac{8.31434}{37.700} = 0.22054 \left(\frac{kJ}{kg\,K}\right)$$

$$P_2 = \frac{(16.556)(0.22054)\,308.71}{4.00}$$

$$P_2 = 281.80 \; [kPa] \leftarrow$$

(b) Process 2→3 constant volume cooling

$$Q_{23} - \cancel{W}_{23} = m_m Cv_m (T_3 - T_2)$$

$$Q_{23} = m_m Cv_m (T_3 - T_2)$$

$$Cv_m = \Sigma mf_i Cv_i = \left(\frac{13.550}{16.556}\right) 0.3122 + \left(\frac{3.0057}{16.556}\right) 1.4897$$

$$Cv_m = 0.81843\,(0.3122) + 0.18155\,(1.4897)$$

$$Cv_m = 0.52597 \; (kJ/kg\,K)$$

$$Q_{23} = (16.556)(0.52597)\,(293 - 308.71)$$

$$Q_{23} = -136.80 \; [kJ]$$

Heat transfer from the tanks: $+136.80$ [kJ]

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4. (a) $h_2 = h_1$

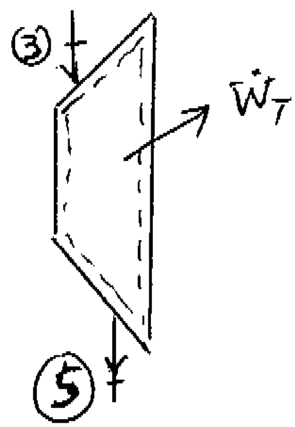
$h_1 = h(10[MPa], 280[°C]) = 1234.1 \ \left[\frac{kJ}{kg}\right]$ (Table A-7)

$h_2 = 1234.1 \ \left(\frac{kJ}{kg}\right)$ at $P_2 = 2\,[MPa]$

$h_f|_{2MPa} = 908.79 \left(\frac{kJ}{kg}\right) \qquad h_g|_{2MPa} = 2799.5 \left(\frac{kJ}{kg}\right)$

$$x_2 = \frac{1234.1 - 908.79}{(2799.5 - 908.79)} = 0.1721$$

(b) 1st Law for the turbine

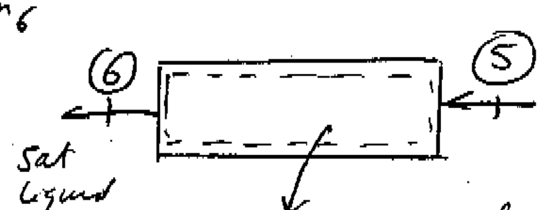


$-\dot{W}_T = \dot{m}_3 (h_5 - h_3)$

$h_3 = h_g|_{2MPa} = 2799.5 \left(\frac{kJ}{kg}\right)$

go to condenser to determine $\dot{m}_3 = \dot{m}_5 = \dot{m}_6$

1st Law for the condenser



$\dot{Q}_c = 19{,}000 (kW)$

$-\dot{Q}_c = \dot{m}_5 (h_6 - h_5)$

$$\dot{m}_5 = \frac{-\dot{Q}_c}{(h_6 - h_5)}$$

$h_f|_{10kPa} = 191.83 \left(\frac{kJ}{kg}\right)$

$h_g|_{10kPa} = 2584.7 \left(\frac{kJ}{kg}\right)$

$x_5 = 0.8 \quad P_5 = P_6 = 10\,[kPa]$

$h_5 = (1 - 0.8)191.83 + 0.8\,(2584.7)$

$h_5 = 2106.1 \ (kJ/kg)$

9/14

$$h_6 = 191.83 \ [kJ/kg]$$

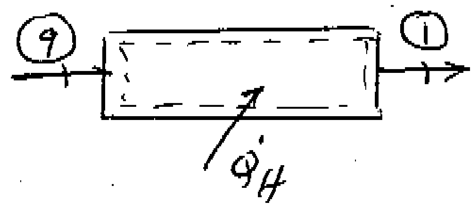
$$\dot{m}_5 = \frac{-19,000}{(191.83 - 2106.1)} = 9.925 \ [kg/s]$$

$$\dot{m}_3 = \dot{m}_5 = 9.925 \ (kg/s)$$

$$\dot{W}_T = -\dot{m}_3 (h_5 - h_3) = -9.925 (2106.1 - 2799.5)$$

$$\dot{W}_T = +6882.0 \ [kW] \leftarrow$$

(c) Reactor 1st Law



$$\dot{Q}_H = \dot{m}_1 (h_1 - h_9)$$

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

$$\frac{\dot{m}_3}{\dot{m}_2} = x_2 \Rightarrow \dot{m}_2 = \frac{\dot{m}_3}{x_2} = \frac{9.925}{0.1721} = 57.67 (kg/s)$$

$$\dot{m}_1 = 57.67 \ (kg/s)$$

$$h_9 = h(10 [MPa], 186 [°C])$$ -: Interpolate in Table A-7

P=10 [MPa]	T [°C]	h [kJ/kg]
	180	767.84
	186	h_9
	200	856.0

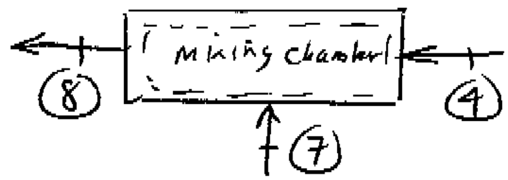
$$h_9 = 767.84 + \frac{(186 - 180)}{(200 - 180)} (856.0 - 767.84)$$

$$h_9 = 794.29 \ (kJ/kg)$$

4(c) (cont'd)

$$\dot{Q}_H = 57.67(1234.1 - 794.29) = 25{,}364\ (kW)$$

(d) To determine T_8 → need h_8 → 1st law on the mixing chamber



$$\dot{m}_4 h_4 + \dot{m}_7 h_7 = \dot{m}_8 h_8$$

$$h_8 = \frac{\dot{m}_4 h_4 + \dot{m}_7 h_7}{\dot{m}_8}$$

$$\dot{m}_8 = \dot{m}_1 = 57.67\ (kg/s)$$

$$\dot{m}_7 = \dot{m}_5 = \dot{m}_3 = 9.925\ (kg/s)$$

Mass conservation to get $\dot{m}_4$

$$\dot{m}_2 = \dot{m}_3 + \dot{m}_4$$

$$\Rightarrow \dot{m}_4 = \dot{m}_2 - \dot{m}_3 = 57.67 - 9.925 = 47.745\ (kg/s)$$

$$h_4 = h_f\big|_{2MPa} = 908.79\ (kJ/kg)$$

$$h_7 = h_f\big|_{46°C}$$

$T_{sat}(2[MPa]) = 212.42\ [°C]$

→ state 7 is compressed liquid

Table A-4

T [°C]	h_f (kJ/kg)
45	188.45
46	h_7
50	209.33

$$h_7 = 188.45 + \frac{(46-45)}{(50-45)}(209.33 - 188.45)$$

$$h_7 = 192.63\ (kJ/kg)$$

4(d) (cont'd) 11/14

$$h_8 = \frac{(47.745)\,908.79 + (9.925)\,192.63}{57.67}$$

$$h_8 = 785.54 \quad (kJ/kg)$$

$h_f|_{2MPa} = 908.79$ (kJ/kg) $\Rightarrow$ State 8 is compressed liquid ($h_8 < h_f(P_8)$)

Interpolate for T_8

T [°C]	h_f [kJ/kg]
185	785.37
T_8	785.54
190	807.62

$$T_8 = 185 + \frac{(785.54 - 785.37)}{(807.62 - 785.37)} = 185.04 \ [°C]$$

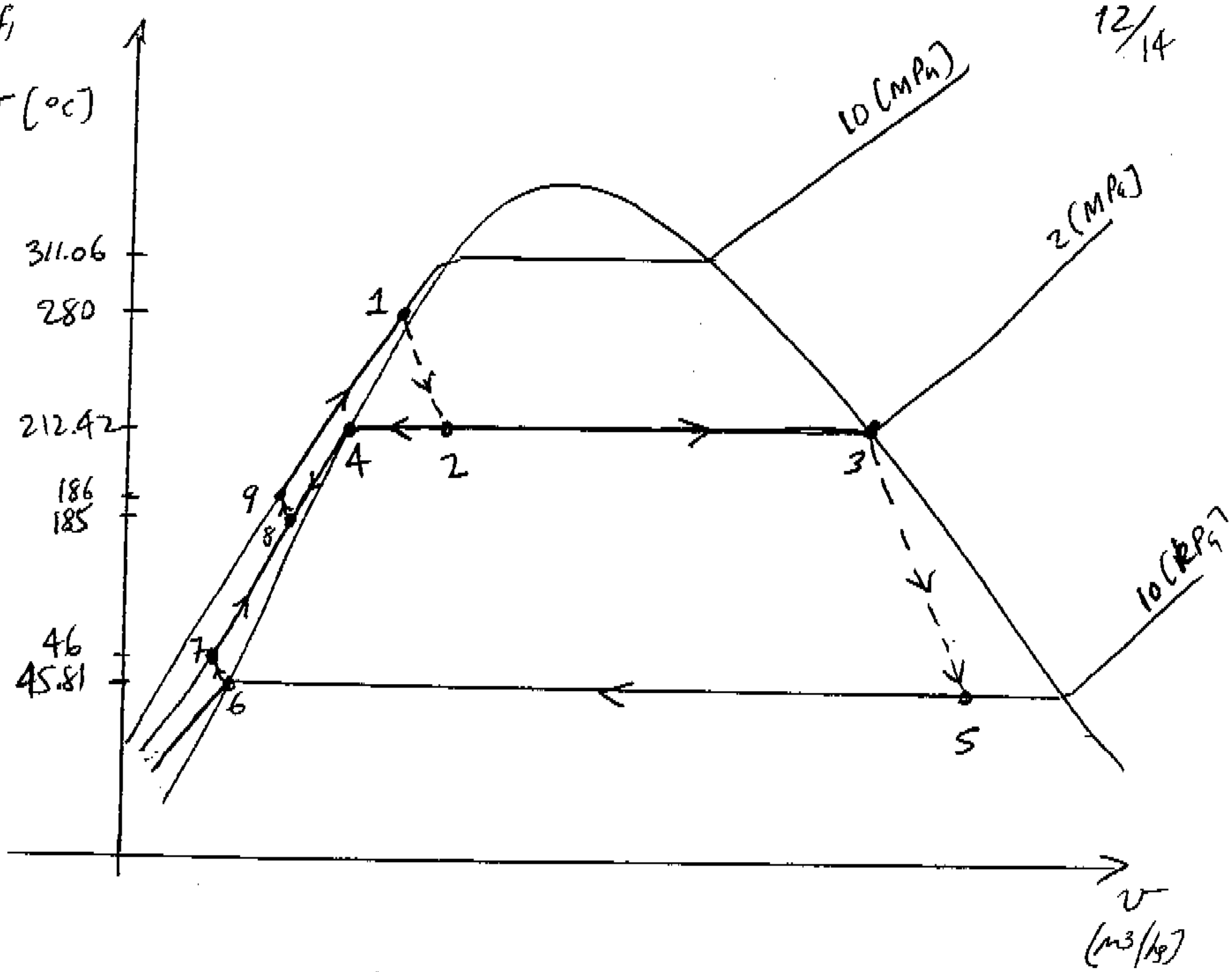
(e) $$\eta_{th} = \frac{\dot{W}_T - \dot{W}_{P_1} - \dot{W}_{P_2}}{\dot{Q}_H}$$

$$\dot{W}_{P_1} = \dot{m}_7 (h_7 - h_6) = 9.925(192.63 - 191.83) = 7.94 \ [kW]$$

$$\dot{W}_{P_2} = \dot{m}_9 (h_9 - h_8) = 57.67(794.29 - 785.54) = 504.61 \ [kW]$$

$$\eta_{th} = \frac{6882.0 - 7.94 - 504.61}{25{,}364} = 0.2511$$

4 (f) 12/14



$T_{sat}(10\,(MPa)) = 311.06\ (°C)$

$T_{sat}(10\,(kPa)) = 45.81\ (°C)$

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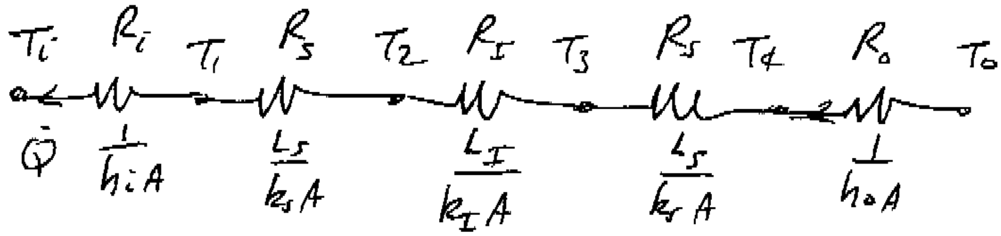
5. (a) Thermal resistance network



$$\dot{Q} = \frac{(T_0 - T_i)}{R_{tot}}$$

$$R_i = \frac{1}{12(4.50)} = 0.018519 \left[\frac{K}{W}\right]$$

$$R_S = \frac{0.005}{(45.0)(4.50)} = 2.4691 \times 10^{-5} \left(\frac{K}{W}\right)$$

$$R_I = \frac{0.020}{(0.040)(4.50)} = 0.11111 \left(\frac{K}{W}\right)$$

$$R_o = \frac{1}{18(4.50)} = 0.012346 \left(\frac{K}{W}\right)$$

$$R_{tot} = 0.018519 + 2.4691 \times 10^{-5} + 0.11111 + 2.4691 \times 10^{-5} + 0.012346$$

$$R_{tot} = 0.14202 \left[\frac{K}{W}\right]$$

$$\dot{Q} = \frac{(24-4)}{0.14202} = 140.83 \,[W]$$

(b) $T_4 = T_o - \dot{Q} R_o$

$= 24 - 140.83(0.012346) = 22.26 \,[°C]$

5 (c) $COP_R = \frac{\dot{Q}_L}{\dot{W}_{in}}$ 14/14

$\dot{Q}_L$ is the rate of energy removed from the refrigerated space — it must be equal to $\dot{Q}$ (energy added to the refrigerator through the walls (to keep the space maintained at 4 [°C])).

$$\dot{W}_{in} = \frac{\dot{Q}_L}{COP_R} = \frac{140.83}{2.5} = 56.33\ [W]$$

$$\text{Daily cost} = \dot{W}_{in}(kW)\,24\,(h) \cdot \text{cost per kWh}$$

$$= \left(\frac{56.33}{1000}\right)(24)\ \$0.08 = \$0.108/\text{day}$$

$\boxed{\frac{10.8\ ¢}{\text{day}}}$

(d) $\dot{Q}^{new} = 0.5\ \dot{Q}^{old} = 0.5(140.83) = \underline{70.415 (W)}$

$$R_{tot}^{new} = \frac{\Delta T}{\dot{Q}^{new}} = \frac{(24-4)}{70.415} = 0.28403\ \left(\frac{K}{W}\right)$$

$$R_{tot}^{new} = R_i + 2R_s + R_I^{new} + R_o$$

$$R_I^{new} = R_{tot}^{new} - R_i - 2R_s - R_o$$

$$R_I^{new} = 0.28403 - 0.018519 - 2(2.4691 \times 10^{-5}) - 0.012346$$

$$R_I^{new} = 0.25312\ \left(\frac{K}{W}\right)$$

$$R_I^{new} = \frac{L_I^{new}}{k_I A} \qquad L_I^{new} = R_I^{new} \cdot k_I \cdot A$$

$$L_I^{new} = 0.25312\,(0.040)(4.50) = 0.04556\ (m)$$

$$L_I^{new} = \underline{45.56}\ (mm)$$