Dec. 2000 + Solutions

THE UNIVERSITY OF MANITOBA

9:00 a.m. 14 December 20 00 FINAL EXAMINATION

NO.: 350

EPARTMENT & COURSE NO.: 130.112

TIME: 3 HOURS

EXAMINATION: Thermal Sciences

EXAMINER: Dr. S.J. Ormiston

Instructions:

1. You are permitted to use the textbook 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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[25] **1.** A closed system containing an ideal gas mixture composed of 3.5 [kg] of nitrogen (N_2), 1.5 [kg] of helium (He), and 4.0 [kg] of methane (CH_4), initially at a pressure of $P_1 = 120$ [kPa] and a temperature of $T_1 = 60$ [°C], undergoes two quasi-equilibrium processes, one after the other.

The first process (state 1 to state 2), is a polytropic compression until the pressure and temperature are $P_2 = 505$ [kPa] and $T_2 = 150$ [°C]. The second process (state 2 to state 3) is an adiabatic expansion process until the pressure and temperature are $P_3 = 200$ [kPa] and $T_3 = -10$ [°C].

8 (a) Calculate the value of the polytropic exponent, n, for the first process (state 1 to state 2).

4 (b) Calculate the work done by the system in the first process, W_{12}, in [kJ].

5 (c) Calculate the heat transfer to the system in the first process, Q_{12}, in [kJ].

3 (d) Calculate the work done by the system in the second process, W_{23}, in [kJ].

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

[11] **2.** A Carnot heat pump is used to heat a house and maintain the house temperature at 20 [°C]. On a day when the average outdoor temperature is constant at -2 [°C], the house is estimated to lose energy to the outdoors at an average rate of 90,000 [kJ/h]. The heat pump consumes 9 [kW] of electrical power while it is operating.

7 (a) What length of time, in hours, did the heat pump run that day (24 hour period)?

2 (b) Calculate the total heating cost for the day if the electricity to supply the heat pump power costs \$0.065 per [kWh].

2 (c) Calculate the total heating cost for the day if all the heating of the home is provided by electrical resistance heaters (instead of the heat pump). Use the same electrical energy cost as in part (b).

[18] **3.** A room that has a volume of 150 [m^3] contains atmospheric air at 100 [kPa] and 30 [°C] with a relative humidity of 60%. In the calculations below do not use the psychrometric chart unless specifically asked to do so.

4 (a) Determine the specific humidity.

3 (b) Determine the enthalpy of the air in [kJ/kg dry air].

2 (c) Determine the dew point temperature.

3 (d) *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].

6 (e) If 0.9 [kg] of water is then removed from the atmospheric air in a dehumidification process (during which the total pressure was unchanged and the room temperature remained constant at 30 [°C]), determine the final relative humidity.

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4. Figure 1 shows a cogeneration plant providing turbine power and steam for process heating. The boiler supplies 6.0 [kg/s] of steam at 4 [MPa] and 400 [°C] to the first of two turbines. Steam at the exit of the first turbine is at 200 [kPa] and 150 [°C]. Some of the steam leaving the first turbine is extracted at a rate of $\dot{m}_E$. Part of the extracted steam is supplied at a rate of $\dot{m}_P = 2.4$ [kg/s] to the process heat load, which returns condensate at 50 [°C] and 100 [kPa] (state 6). Due to condensate losses, only 50% of the condensate at state 6 returns from the process and flows into the open feed water heater (i.e. $\dot{m}_R = 0.5\,\dot{m}_P$). Make-up water enters the open feed water heater at a temperature of 20 [°C] and a pressure of 100 [kPa]. The remainder of the extracted steam, $\dot{m}_V$, goes through a throttling valve and then flows into the feed water heater at such a rate that saturated liquid at 100 [kPa] exits the feed water heater (state 9). Steam flows at a rate $\dot{m}_{T2}$ through the second turbine and exits at the condenser pressure of 10 [kPa] with a quality of 95%. Table 1 gives a summary of all the state information provided in this problem. In this analysis it may be assumed that the turbines are adiabatic.

6 (a) Determine the power output of the first turbine, $\dot{W}_{T1}$, in [kW].

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

6 (c) Using only mass conservation equations, determine the mass flow rate of make-up water, $\dot{m}_W$, in [kg/s].

13 (d) Determine the mass flow rate through the throttling valve, $\dot{m}_V$, in [kg/s].

6 (e) Determine the power output of the second turbine, $\dot{W}_{T2}$, in [kW].

Table 1: State summary for Problem 4.

State	P [kPa]	T [°C]	x	State	P [kPa]	T [°C]	x
1	4000	400.00	N/A	6	100	50.00	N/A
2	200	150.00	N/A	7	100		
3	10	45.81	0.95	8	100	20.00	N/A
4	10	45.81	0.0	9	100	99.63	0.0
5	100	46.00	N/A	10	4000	101.00	N/A

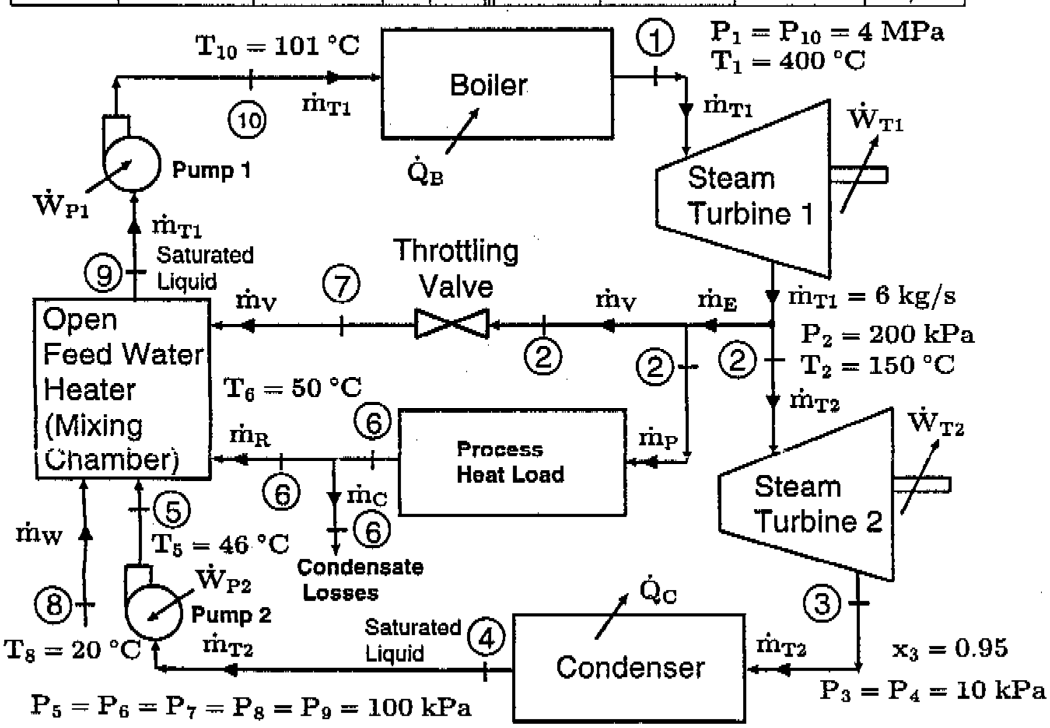

Figure 1: Schematic diagram for problem 4.

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11 **5.** A house has a composite wall made of a plaster board (k_p=0.25 [W/m · K]), glass fibre blanket (k_b=0.030 [W/m · K]), and plywood siding (k_s=0.12 [W/m · K]), as shown in Figure 2.

On a cold winter day the convection heat transfer coefficients are h_i=10.0 [W/m^2 · K] for the inside surface of the wall and h_o=30.0 [W/m^2 · K] for the outside surface of the wall. The total wall surface area is 10 [m^2]. The room inside air temperature, T_i, is 22 [$°C$], and the outdoor air temperature, T_o is −15 [$°C$]. The thicknesses of the plaster board, the glass fibre, and the plywood siding are L_p=10 [mm], L_b=100 [mm], and L_s=20 [mm], as shown in the figure.

6 (a) Calculate the total rate of heat transfer through the wall in [W].

3 (b) Determine the temperature at the inside surface of the plaster board, T_1, in [$°C$].

2 (c) If the outdoor air temperature were to drop to −35 [$°C$] (all other conditions remaining the same), what would the value of T_1 be?

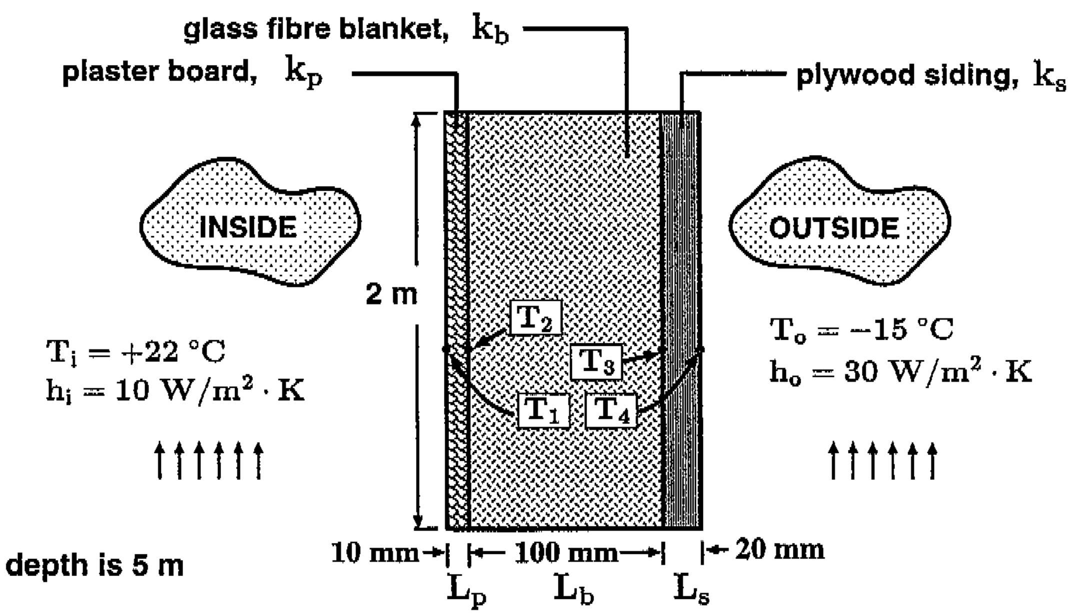


Figure 2: Schematic diagram for problem 5.

1-L

(1.) Closed system, ideal gas mixture

(a) $P_1 V_1^n = P_2 V_2^n$

$$\left(\frac{P_2}{P_1}\right) = \left(\frac{V_1}{V_2}\right)^n \Rightarrow n = \frac{\ln\left(\frac{P_2}{P_1}\right)}{\ln\left(\frac{V_1}{V_2}\right)}$$ need V_1 & V_2

$P_1 = 120\ [kPa]$
$T_1 = 60\ [°C]$
$P_2 = 505\ [kPa]$
$T_2 = 150\ [°C]$

$$P_1 V_1 = m_m R_m T_1 \quad \Rightarrow \quad \frac{P_1 V_1}{P_2 V_2} = \frac{T_1}{T_2}$$
$$P_2 V_2 = m_m R_m T_2$$

$$\left(\frac{V_1}{V_2}\right) = \left(\frac{T_1}{T_2}\right)\left(\frac{P_2}{P_1}\right) = \frac{(60+273)}{(150+273)}\frac{505}{120} = 3.31294$$

$$\frac{P_2}{P_1} = \frac{505}{120} = 4.20833$$

$$n = \frac{\ln(4.20833)}{\ln(3.31294)} = 1.1997 = 1.20$$

(b) $$W_{12} = \frac{m_m R_m (T_2 - T_1)}{1-n}$$ ideal gas, polytropic process

$$m_m = m_{N_2} + m_{He} + m_{CH_4} = 3.5 + 1.5 + 4.0 = 9.0\ (kg)$$

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

Tab6 A-1
$M_{N_2} = 28.013\ [kg/kmol]$
$M_{He} = 4.003\ [kg/kmol]$
$M_{CH_4} = 16.043\ [kg/kmol]$

$$N_{N_2} = \frac{m_{N_2}}{M_{N_2}} = \frac{3.5}{28.013} = 0.124942\ (kmol)$$
$$N_{He} = \frac{1.5}{4.003} = 0.374719\ (kmol)$$
$$N_{CH_4} = \frac{4.0}{16.043} = 0.249330\ (kmol)$$

1-2/

1(b) continued

$$N_M = 0.124942 + 0.374719 + 0.249330 = 0.748991 \text{ (kmol)}$$

$$M_m = \frac{9.0}{0.748991} = 12.0162 \text{ (kg/kmol)}$$

$$R_M = \frac{8.314}{12.0162} = 0.6919 \text{ (kJ/kg K)}$$

$$W_{12} = \frac{9.0(0.6919)(150-60)}{1-1.2} = -2802.2 \text{ [kJ]}$$

(c) $Q_{12} - W_{12} = m_m C_{v_0}(T_2 - T_1) + \cancel{\Delta KE}^{\,0} + \cancel{\Delta PE}^{\,0}$

$C_{v_0} = \sum C_{v_i} m_{f_i}$

Table A-2 (a)

$C_{v_{N_2}} = 0.743$ (kJ/kg K)

$C_{v_{He}} = 3.1156$ (kJ/kg K)

$C_{v_{CH_4}} = 1.7354$ (kJ/kg K)

$$m_{f_{N_2}} = \frac{3.5}{9.0} = 0.388889$$

$$m_{f_{He}} = \frac{1.5}{9.0} = 0.166667$$

$$m_{f_{CH_4}} = \frac{4.0}{9.0} = 0.444444$$

$$C_{v_0} = 0.388889(0.743) + 0.166667(3.1156) + 0.444444(1.7354)$$

$$C_{v_0} = 1.5795 \text{ [kJ/kg K]}$$

$$Q_{12} = -2802.2 + (9.0)\,1.5795(150-60)$$

$$Q_{12} = -1522.81 \text{ (kJ)}$$

1-3

1(d) $\bar{W}_{23} = ?$

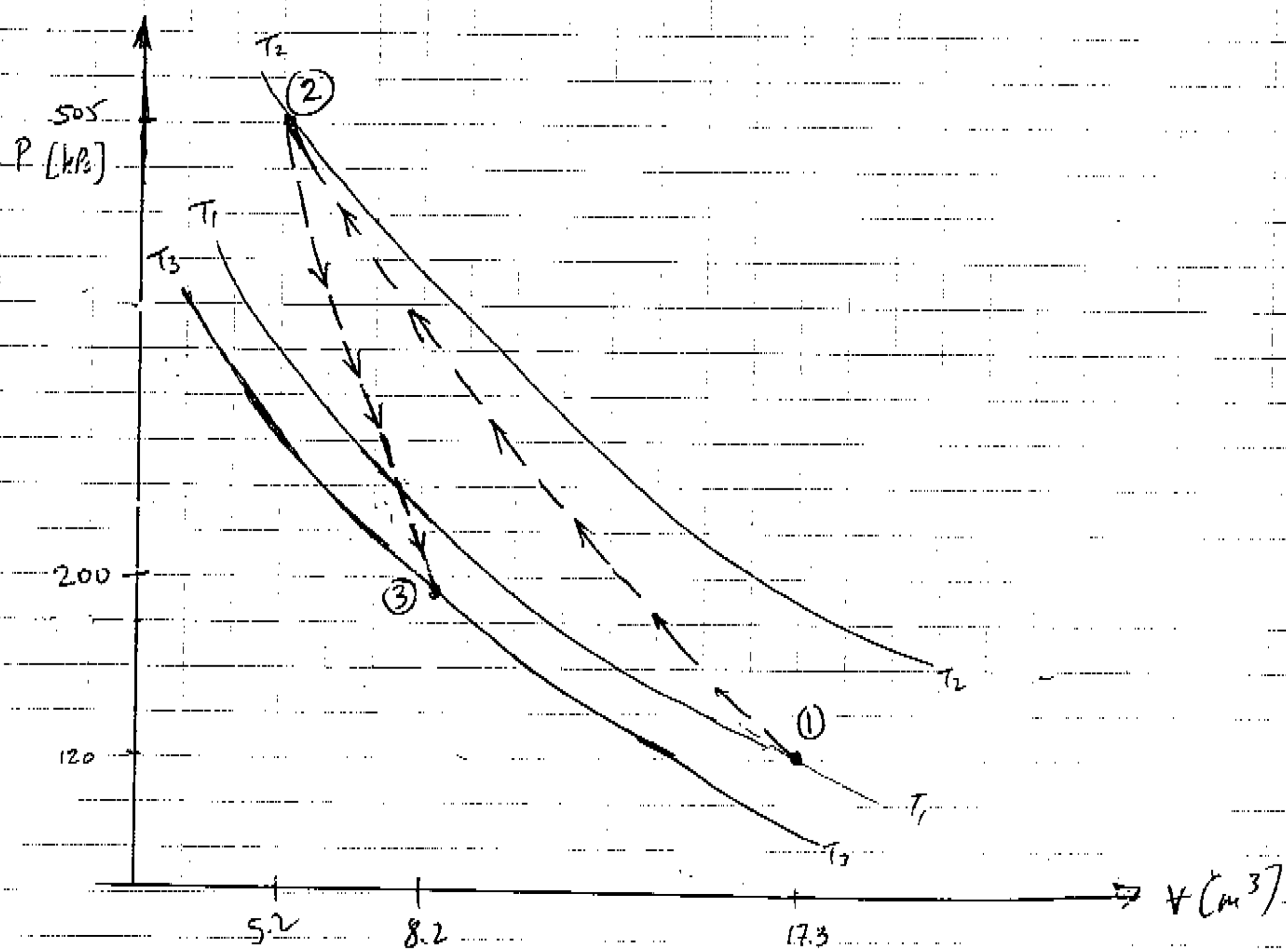
$$Q_{23} - \bar{W}_{23} = m_m C_{v_o} (T_3 - T_2)$$

$Q_{23} = 0$ (adiabatic)

$$\bar{W}_{23} = -9.0(1.5795)(-10 - 150)$$

$$\bar{W}_{23} = +2274.48 \ [kJ]$$

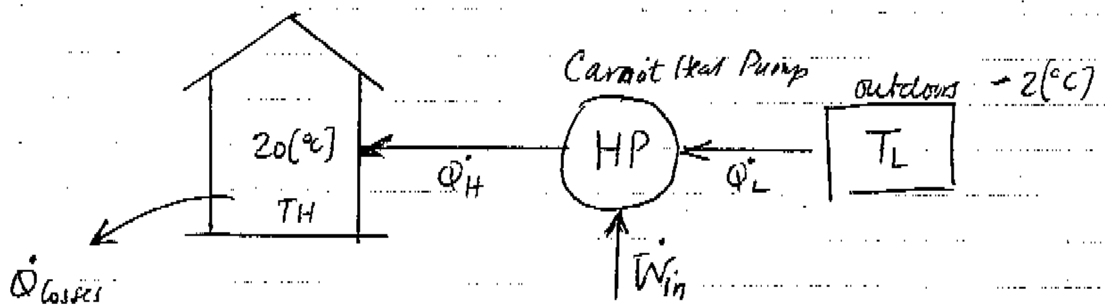
(e)



$\forall = \frac{m_m R_m T}{P}$

$T_1 = 333$ [K] $T_2 = 423$ [K] $T_3 = 263$ [K]
$P_1 = 120$ (kPa) $P_2 = 505$ (kPa) $P_3 = 200$ (kPa)
$\forall_1 = 17.28$ [m³] $\forall_2 = 5.216$ (m³) $\forall_3 = 8.189$ (m³)

(2.) 2-1/



$\dot{Q}_{losses} = 90{,}000\ [kJ/h]$ $\qquad \dot{W}_{in} = 9\ [kW]$

(a) In 24 hour period $Q_{losses} = \dot{Q}_{losses}\,\Delta t = 90{,}000 \times 24 = 2.16 \times 10^6\ [kJ]$

Carnot Heat pump operating between $T_L = 271\ [K]$
$T_H = 293\ [K]$

has a $COP_{HP,rev} = \dfrac{1}{1 - \frac{T_L}{T_H}} = \dfrac{1}{1 - \frac{271}{293}} = 13.318$

$\dot{Q}_H = COP_{HP,rev} \cdot \dot{W}_{in} = (13.318)(9) = 119.86\ [kW]$

Length of time HP ran to supply Q_{losses} is

$\tau = \dfrac{Q_{losses}}{\dot{Q}_H} = \dfrac{2.16 \times 10^6\ [kJ]}{119.86\ [\frac{kJ}{s}]} = 18{,}021\ [s]$

$\tau = 5.01$ hours

(b) Cost to power heat pump for hours

$\dfrac{\$0.065}{[kWh]} \times 9.0\ [kW] \times 5.01\ [h] = \$2.93$

(c) Cost for electric heating for all the losses

$\dfrac{\$0.065}{[kWh]} \times 2.16 \times 10^6\ kJ \times \dfrac{1\ [h]}{3600\ [s]} = \$39.00$

3-1

(3.) Room $\forall = 150 \, [m^3]$
$P = 100 \, [kPa]$
$T = 30 \, [°C] = T_{db}$
$\phi = 0.60$

(a) $\omega = \dfrac{0.622 P_v}{P - P_v}$ $\quad P_v = \phi P_g$

$P_g = P_{sat}(T) = P_{sat}(30 \, [°C])$
$P_g = 4.246 \, [kPa]$ Table A-4

$P_v = 0.6(4.246) = 2.5476 \, (kPa)$

$\omega = \dfrac{0.622(2.5476)}{(100 - 2.5476)} = 0.01626$

(b) $h = h_a + \omega h_v = C_{p_0} T + \omega h_g$ ← in degrees Celsius

$C_{p_0} = 1.005 \, (kJ/kg\,K)$ (Table A-2(a) (for air))

$h_g = h_g(30 \, [°C]) = 2556.3 \, (kJ/kg)$ (Table A-4)

$h = 1.005(30) + 0.01626(2556.3) = 71.715 \left[\dfrac{kJ}{kg \text{ dry air}}\right]$

(c) $T_{dp} = T_{sat}(P_v) = T_{sat}(2.5476 \, (kPa))$

Linear interpolation in Table A-5

P [kPa]	T_{sat}
2.5	21.08
2.5476	T_{dp}
3.0	24.08

$T_{dp} = 21.08 + \dfrac{(2.5476 - 2.5)}{(3.0 - 2.5)}(24.08 - 21.08)$

$T_{dp} = 21.37 \, [°C]$

(d) Figure A-33 $\quad T_{db} = 30 \, [°C]$, $\phi = 60\%$

Read $v = 0.88 \left[\dfrac{m^3}{kg \text{ dry air}}\right]$

3. (e) Original mass of water ?
Final mass of water

3-2

Initially $m_a = \frac{P_a \forall}{R_a T}$

$P_a = P - P_v = 100 - 2.5476$
$P_a = 97.4524 \ (kPa)$

$R_a = 0.287 \ (kJ/kg\,K)$ Table A-1

$$m_a = \frac{(97.4524)(150)}{0.287\,(30+273)} = 168.097\ (kg)$$

$$m_{v_1} = \omega_1 m_a = 0.01626\,(168.097) = 2.7333\ (kg)$$

$$m_{v_2} = m_{v_1} - (m_v)_{removed} = 2.7333 - 0.9 = 1.8333\ [kg]$$

$$\omega_2 = \frac{m_{v_2}}{m_a} = \frac{1.8333}{168.097} = 0.010906$$

Assuming P, T have not changed

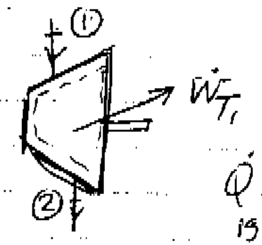
$$\phi_2 = \frac{\omega_2 P}{(0.622+\omega_2) P_g} = \frac{(0.010906)(100)}{(0.622+0.010906)\,4.246}$$

$$\phi_2 = 0.4058 \approx 0.41 = 41\ \%$$

[down from 60 % initially]

4. 4-1/

(a) 1st Law on turbine 1



$$\cancel{\dot{Q}}^{0} - \dot{W}_{T_1} = \dot{m}_{T_1}(h_2 - h_1)$$

$\dot{Q} = 0$
ignore Δpe, Δke

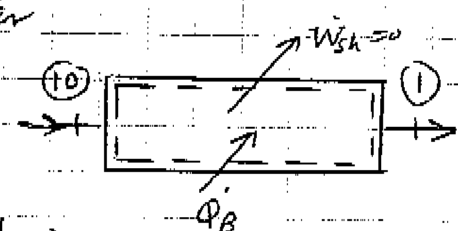
$$\dot{W}_{T1} = -\dot{m}_{T_1}(h_2 - h_1)$$

State 1 Superheated Vapor $P_1 = 4\,[MPa]$ $T_1 = 400\,[^\circ C]$
$h_1 = 3213.6\,[kJ/kg]$

State 2 Superheated vapor $P_2 = 200\,[kPa]$ $T_2 = 150\,[^\circ C]$
$h_2 = 2768.8\,[kJ/kg]$
$\dot{m}_{T_1} = 6.0\,[kg/s]$

$$\dot{W}_{T1} = -6.0\,(2768.8 - 3213.6) = +2668.8\,[kW]$$

(b) 1st Law on the Boiler



neglect Δpe Δke

$$\dot{Q}_B - \cancel{\dot{W}_{sh}}^{0} = \dot{m}_{T1}(h_1 - h_{10})$$

State 10 $P_{10} = 4\,[MPa]$ $T_{10} = 101\,[^\circ C]$
$T_{sat}(4\,[MPa]) = 250.40\,[^\circ C]$ $T < T_{sat}(P) \rightarrow$ compressed liquid

Cannot use Table A-8 → use $h_{10} = h_f\big|_{101\,[^\circ C]}$

linear interpolation in Table A-4 yields

$$h_{10} = 419.04 + \frac{(101-100)}{(105-100)}(440.15 - 419.04) = 423.26\left[\frac{kJ}{kg}\right]$$

$$\dot{Q}_B = 6.0\,(3213.6 - 423.26) = +16{,}742.0\,[kW]$$

4 (c) • Mass conservation on the Open Feed Water Heater 4-2/ (OFWR)

$$\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out}$$ steady-state, steady flow assumed.

$$\dot{m}_W + \dot{m}_{T2} + \dot{m}_R + \dot{m}_V = \dot{m}_{T1} \quad (4\text{-}1)$$

• mass conservation at the junction before the throttling valve

$$\dot{m}_E = \dot{m}_V + \dot{m}_P \quad (4\text{-}2)$$

$$\dot{m}_R = 0.5\dot{m}_P \quad (4\text{-}3) \quad \text{(Given)}$$

• mass conservation at the junction after turbine 1

$$\dot{m}_{T1} = \dot{m}_E + \dot{m}_{T2} \quad (4\text{-}4)$$

Substitute Eqs (4-2) & (4-3) into Eq (4-4)

$$\dot{m}_{T1} = (\dot{m}_V + 2\dot{m}_R) + \dot{m}_{T2} \quad (4\text{-}5)$$

Substitute Eq. (4-5) on RHS of Eq. (4-1)

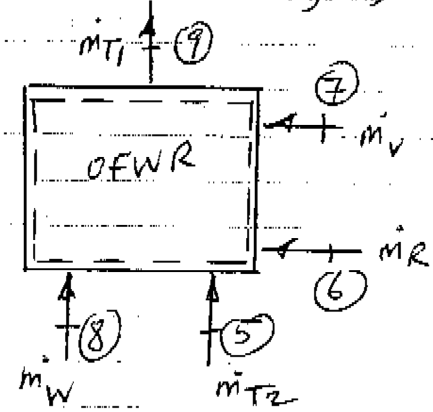
$$\dot{m}_W + \cancel{\dot{m}_{T2}} + \dot{m}_R + \cancel{\dot{m}_V} = \cancel{\dot{m}_V} + 2\dot{m}_R + \cancel{\dot{m}_{T2}}$$

$$\dot{m}_W = \dot{m}_R = 0.5\,\dot{m}_P = 0.5\,(2.4) = 1.2\ [kg/s]$$

(d) 1[st] Law on the OFWR Assumed adiabatic, neglect Δpe, Δke, $\dot{W}_{sh} = 0$

$$\Sigma \dot{m}_{in} h_{in} = \Sigma \dot{m}_{out} h_{out}$$

$$\boxed{\dot{m}_W h_8 + \dot{m}_{T2} h_5 + \dot{m}_R h_6 + \dot{m}_V h_7 = \dot{m}_{T1} h_9} \quad (4\text{-}6)$$



determine states

T_{sat}(100 [kPa]) = 99.63 [°C], so all states with $T < 99.63$ [°C] are compressed liquid.

State 5 $P_5 = 100\ [kPa]$ $T_5 = 46.00\ [°C]$ 4-3/

$$h_5 = h_f|_{46\,[°C]} = 192.63\ [kJ/kg]$$ (linear interpolation in Table A-4)

State 6 $P_6 = 100\ [kPa]$ $T_6 = 50\ [°C]$

$$h_6 = h_f|_{50\,[°C]} = 209.33\ [kJ/kg]$$ Table A-4

State 7 $P_7 = 100\ [kPa]$ $T_7 = ?$

throttling valve $\Rightarrow$ $h_7 = h_2 = 2768.8\ [kJ/kg]$

State 8 $P_8 = 100\ [kPa]$ $T_8 = 20\ [°C]$

$$h_8 = 83.96\ [kJ/kg]$$ Table A-4

State 9 $P_9 = 100\ [kPa]$ saturated liquid

$$h_9 = h_f(100\ [kPa]) = 417.46\ [kJ/kg]$$

All enthalpies are known; missing $\dot m_{T2}$ & $\dot m_V$

$\dot m_{T1} = 6.0\ [kg/s]$
$\dot m_R = 1.2\ [kg/s]$
$\dot m_W = 1.2\ [kg/s]$

From Eqs. (4-2) & (4-4)

$$\dot m_{T1} = \dot m_{T2} + \dot m_V + \dot m_P \qquad (4-7)$$

∴ Solve for $\dot m_{T2}$ in order to substitute for it in the 1st law

$$\dot m_{T2} = \dot m_{T1} - \dot m_P - \dot m_V = 6 - 2.4 - \dot m_V$$

$$\dot m_{T2} = (3.6 - \dot m_V) \qquad (4-8)$$

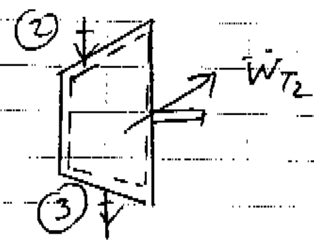
4(d) continued 4-4/

Substitute values for $\dot{m}, h, f$ Eqn (4-8) into Eq. (4-6)

$$(1.2)(83.96) + (3.6 - \dot{m}_v)\,192.63 + (1.2)\,209.33$$
$$+\ \dot{m}_v\, 2768.8 = (6)(417.46)$$

$$100.752 + 693.468 - 192.63\,\dot{m}_v + 251.196$$
$$+\ 2768.8\,\dot{m}_v = 2504.76$$
$$\Rightarrow\ 2576.17\,\dot{m}_v = 1459.344$$
$$\dot{m}_v = 0.5665\ [kg/s]$$

(e) 1st Law on turbine 2



$\dot{Q} = 0$
neglect Δpe, Δke

$$\dot{Q} - \dot{W}_{T_2} = \dot{m}_{T_2}(h_3 - h_2)$$
$$\dot{W}_{T_2} = -\dot{m}_{T_2}(h_3 - h_2)$$

State 3 $P_3 = 10\ [kPa]$
$x_3 = 0.95$
$h_f(10\ [kPa]) = 191.83\ (kJ/kg)$
$h_g(10\ (kPa)) = 2584.7\ [kJ/kg]$
$h_3 = (1-0.95)\,191.83 + (0.95)\,2584.7 = 2465.06\ [kJ/kg]$

$$\dot{m}_{T2} = 3.6 - \dot{m}_v$$
$$\dot{m}_{T2} = 3.6 - 0.5665$$
$$\dot{m}_{T_2} = 3.0335\ (kg/s)$$

$$\dot{W}_{T_2} = -3.0335\,(2465.06 - 2768.8)$$
$$\dot{W}_{T_2} = +921.40\ [kW]$$

5. 5-1

(a) Thermal resistance network

$+22\,[°C]$ $-15\,[°C]$

$T_i \xrightarrow{q} R_i \; T_1 \; R_p \; T_2 \; R_b \; T_3 \; R_s \; T_4 \; R_o \; T_o$

interior convection	plaster board	fibre blanket	siding	outside convection
$\frac{1}{h_i A}$	$\frac{L_p}{k_p A}$	$\frac{L_b}{k_b A}$	$\frac{L_s}{k_s A}$	$\frac{1}{h_o A}$

$$q = \frac{(T_i - T_o)}{R_{tot}} = \frac{(T_i - T_o)}{(R_i + R_p + R_b + R_s + R_o)}$$

$A = 10\,(m^2)$

$$R_i = \frac{1}{10(10)} = 0.010\left[\frac{K}{W}\right]$$

$$R_p = \frac{0.010}{0.25(10)} = 0.0040\left[\frac{K}{W}\right]$$

$$R_b = \frac{0.100}{0.030(10)} = 0.33333\left[\frac{K}{W}\right]$$

$$R_s = \frac{0.020}{0.12(10)} = 0.01667\left[\frac{K}{W}\right]$$

$$R_o = \frac{1}{30(10)} = 0.003333\left[\frac{K}{W}\right]$$

$$R_{tot} = 0.010 + 0.0040 + 0.33333 + 0.01667 + 0.003333$$

$$R_{tot} = 0.36733\left[\frac{K}{W}\right]$$

$$q = \frac{(22 - (-15))}{0.36733} = 100.73\,[W] \longleftarrow$$

5. (b) 5-2

$$q = \frac{(T_i - T_1)}{R_i} \qquad q R_i = T_i - T_1$$

$$T_1 = T_i - q R_i$$

$$T_1 = 22 - 100.73(0.010) = 20.99\ [°C]$$

(c) IF $T_o = -35\ [°C]$ R_{tot} the same

$$q = \frac{(22 - (-35))}{0.36733} = 155.17\ [W]$$

$$T_1 = 22 - 155.17(0.010) = 20.45\ [°C]$$