April 99 + Solutions

THE UNIVERSITY OF MANITOBA

April 19, 1:30 p.m. 19 99 — Final Examination

Paper No.: 647 — Page No.: Page 1 of 3

Dept. and Course No.: 130.112 — Time: 3 Hours

Examination: Thermal Sciences — Examiners: Professors L. Magalhaes, S. Ormiston and R. Schilling

Notes:

(i) This is an Open Textbook examination. Students are permitted to use calculators and the textbook "Thermodynamics, An Engineering Approach", 3rd (or 2nd) Edition, by Y.A. Cengel and M.A. Boles and the "Thermodynamics" excerpt by J.P. Holman. No other materials (i.e., notes, solved problems, extra pages in the text book, etc.) are allowed.

(ii) Attempt all five questions. The values are indicated in the margin.

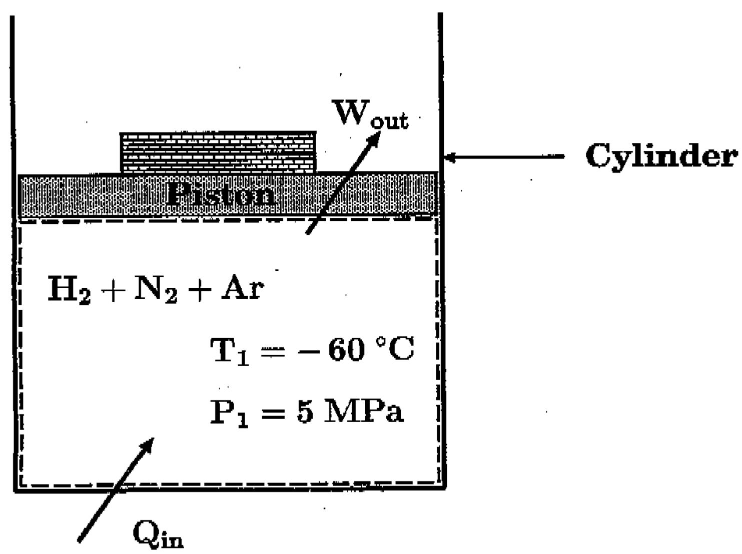
(iii) Do all of your calculations in the examination booklet provided. Include your section number and the name of your instructor on the front of the cover page of the examination booklet.

(iv) Students may use both sides of each page in the examination booklet if they wish.

Value

20 — 1. A piston-cylinder device contains 4 kg of hydrogen (H_2), 9 kg of argon (Ar) and 14 kg of nitrogen (N_2) at –60°C and 5 MPa as shown in the figure below. Heat is now transferred to the mixture in the cylinder, and it expands at constant pressure until the temperature rises to 22°C.

Determine the total heat transfer that takes place during this heating process by treating the mixture as an ideal gas.



20 — 2. A heat engine consumes fuel at the rate of 20 L /hour and produces 60 kW of output power. The fuel used in the engine has a heating value of 35,000 kJ/kg and a density of 0.8 g/cm^3.

All of the waste heat from this engine is used to heat a building.

This heat engine operates an actual refrigeration system that has a COP_R of 2.0. The refrigeration system removes heat from a low temperature reservoir at 5°C and discharges heat to the same building as the heat engine. The temperature inside the building is + 25°C.
Calculate the total amount of heat, in kJ, discharged to the building from the heat engine and the refrigeration system during a 24 hour period.

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3. Consider the devices in part of a cogeneration plant shown in the figure below. In the plant, some steam from the turbine exhaust is extracted and used in a heat exchanger in order to provide energy at a rate $\dot{Q}_I$ to an industrial process. The remaining portion of the turbine exhaust mass flow enters a condenser that transfers heat to the river water.

   The inlet state at the boiler entrance is 80°C and 4.00 MPa. Steam enters the turbine at 4.00 MPa and 450°C and the power output of the turbine is 2808 kW. The exhaust of the turbine, which is at 200 kPa and 150°C, is split in unequal portions into two streams. The stream that goes to the industrial process heat exchanger exits that heat exchanger at 52°C. The stream that goes through the condenser exits as saturated liquid at 200 kPa. The cooling water side of the condenser is at 100 kPa. River water enters at 10°C and exits at 20°C and has a mass flow rate of 106.3 kg/s. The table below gives a summary of the given state information for this problem.

   In this analysis, it may be assumed that the turbine and the condenser are well-insulated (adiabatic).

State	P, kPa	T, °C	x
1	4000	80	N/A
2	4000	450	N/A
3	200	150	N/A
4	200	120.23	0.0

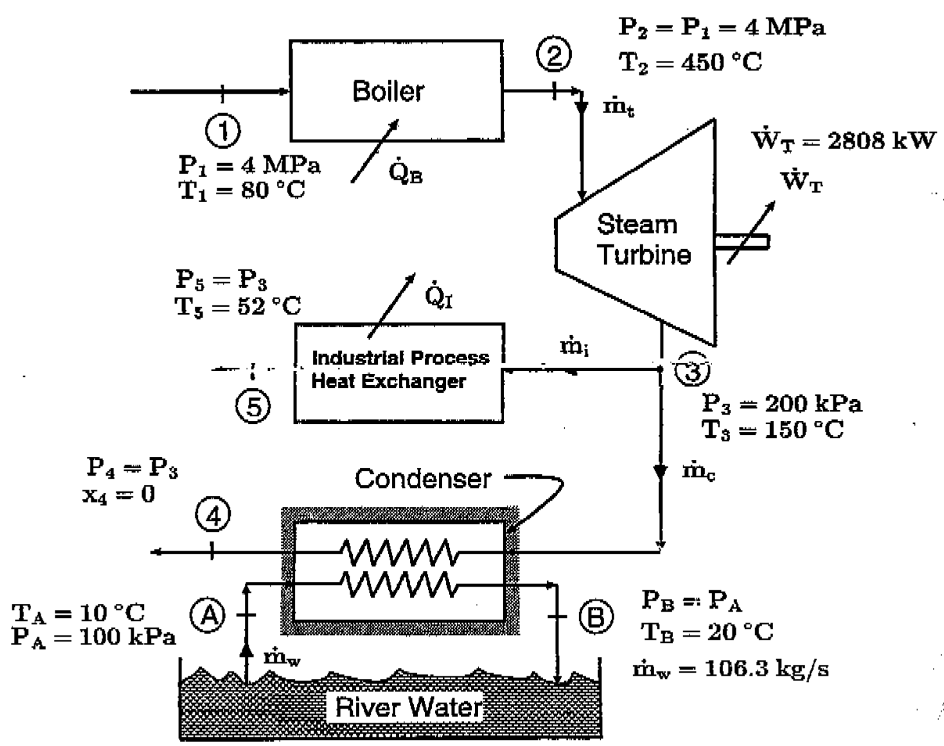
State	P, kPa	T, °C	x
5	200	52	N/A
A	100	10	N/A
B	100	20	N/A

4 (a) Calculate the mass flow rate through the turbine, $\dot{m}_t$ in kg/s.

4 (b) Calculate the ratio of turbine output power to boiler input energy rate $\dot{W}_T / \dot{Q}_B$.

6 (c) Calculate the mass flow rate through the condenser, $\dot{m}_c$, in kg/s.

6 (d) Calculate the rate of energy transfer to the industrial process, $\dot{Q}_I$, in kW.



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4. A room contains air and water vapor at a dry bulb temperature of 30°C and a total pressure of 95 kPa. The wall surface temperature in this room is 25°C and it is observed that a slight film of water has just begun to condense on the walls' surfaces. A dehumidification system inside the room is started in order to remove some of the water vapor from the atmospheric air. When the dehumidifier stops, the humidity ratio, ω, is 30% of the initial value (i.e. $\omega_{final} = 0.3\omega_{initial}$)

10 a) If the room temperature stays constant at 30°C during the dehumidification process, what is the final relative humidity in the room?

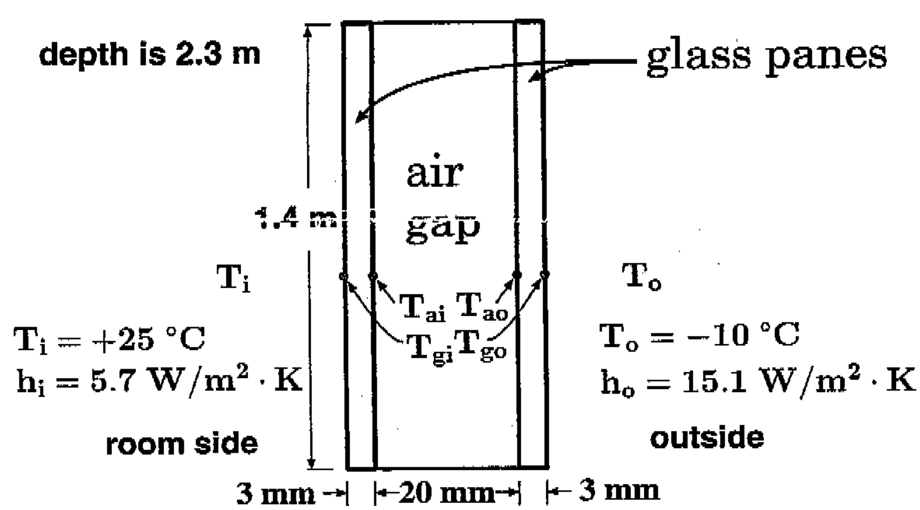
10 b) How much water, in kg, was removed from the atmospheric air if the room dimensions are 30m x 20m x 8m and the total pressure of the air and water vapor in the room was constant at 95 kPa.

5. A double-glazed window, 1.4 m high and 2.3 m wide consists of two layers of glass (each 3 mm thick) separated by an air gap 20 mm thick, as shown in the figure below. The window is installed in the outside wall of a room in which the air temperature is maintained at 25°C. The outer surface of the window (the outside of the outer pane) is exposed to the atmosphere, which has an ambient temperature of -10°C. The room-side convection heat transfer coefficient can be taken as 5.7 W/m^2·K and the convection heat transfer coefficient for the outside conditions can be taken as 15.1 W/m^2·K. The thermal conductivity of the glass is 0.76 W/m·K. Assume that the air gap contains still air (i.e. there is only conduction heat transfer through the air gap) with a thermal conductivity of 0.026 W/m·K.

14 a) Calculate the heat transfer rate, in Watts, through the double-glazed window and the room-side surface temperature of the inner glass pane, T_{gi}.

4 b) Now, calculate the heat transfer rate through a similar-sized window that has only a single pane of glass, assuming that all the remaining data (temperatures, dimensions, properties, and convection coefficients) are unchanged. For this case (single pane) also determine the room-side surface temperature of the glass.

2 c) If the dew point temperature for the conditions in the room is 13°C, discuss if there will be condensation on the inside window surface in both a) and b) cases (i.e. both the double and single pane windows).

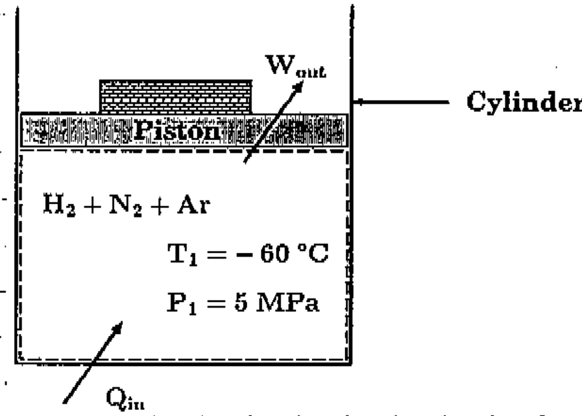


double-glazed window schematic

130.112 W99 Final Exam Solution

1. let $Q_{in} = {}_1Q_2$ Closed system Ideal Gas

$\bar{W}_{out} = {}_1W_2$



1st Law $\quad {}_1Q_2 - {}_1W_2 = m_m (u_2 - u_1)$

$${}_1Q_2 - {}_1W_2 = m_m C_{v_m} (T_2 - T_1)$$

$$m_m = \sum_{i=1}^{3} m_i = 4 + 9 + 14 = 27\ kg$$

Tables A-1 & A-2a

Mass fractions (mf_i) $\quad mf_i = \frac{m_i}{m_m}$

Molar Masses	Specific Heats
$M_{H_2} = 2.016\ \frac{kg}{kmol}$	$C_{v_{H_2}} = 10.183\ \frac{kJ}{kg\,K}$
$M_{Ar} = 39.948\ \frac{kg}{kmol}$	$C_{v_{Ar}} = 0.3122\ \frac{kJ}{kg\,K}$
$M_{N_2} = 28.013\ \frac{kg}{kmol}$	$C_{v_{N_2}} = 0.743\ \frac{kJ}{kg\,K}$

$$mf_{H_2} = \frac{4}{27} = 0.148$$

$$mf_{Ar} = \frac{9}{27} = 0.333$$

$$mf_{N_2} = \frac{14}{27} = 0.519$$

1.000 ok ✓

Mole fractions (y_i) $\quad y_i = \frac{N_i}{N_m} \quad N_i = \frac{m_i}{M_i}$

$$N_{H_2} = \frac{4\ kg}{2.016\ kg/kmol} = 1.984\ kmol \qquad y_{H_2} = \frac{1.984}{2.709} = 0.732$$

$$N_{Ar} = \frac{9}{39.948} = 0.225\ kmol \qquad y_{Ar} = \frac{0.225}{2.709} = 0.08$$

$$N_{N_2} = \frac{14}{28.013} = 0.500\ kmol \qquad y_{N_2} = \frac{0.500}{2.709} = 0.185$$

$N_m = 2.709\ kmol$

1.000 ok

Ideal gas mixture properties

$$C_{v_m} = \sum_{i=1}^{3} mf_i C_{v_i} = (0.148)\,10.183 + (0.333)\,0.3122 + (0.519)\,0.743$$

$$\Rightarrow C_{v_m} = 1.507 + 0.1040 + 0.386 = 1.997\ \frac{kJ}{kg\,K}$$

1. continued

$$R_m = \frac{R_u}{M_m} \qquad M_m = \sum_{i=1}^{3} y_i M_i = 0.732(2.016) + 0.083(39.948) + 0.185(28.013)$$

$$M_m = 1.476 + 3.316 + 5.182 = 9.974 \frac{kg}{kmol}$$

$$R_m = \frac{8.314}{9.974} = 0.8336 \frac{kJ}{kg\,K}$$

- Work done on the piston by the gas mixture (constant pressure)

$${}_1W_2 = P_1(\forall_2 - \forall_1)$$

Ideal gas behaviour

$$P\forall = m_m R_m T \qquad P_2\forall_2 = m_m R_m T_2 \qquad P_1\forall_1 = m_m R_m T_1$$

$$P_2 = P_1 \Rightarrow (\forall_2 - \forall_1) = \frac{m_m R_m (T_2 - T_1)}{P_1}$$

$$(\forall_2 - \forall_1) = \frac{(27)(0.8336)(22-(-60))}{5000} = 0.3691 \text{ m}^3$$

$${}_1W_2 = (5000)(0.3691) = 1846 \text{ kJ}$$

$${}_1Q_2 = {}_1W_2 + m_m c_{v_m}(T_2 - T_1)$$

$${}_1Q_2 = 1846 + (27)(1.997)(22-(-60))$$

$$= 1846 + 4421$$

$${}_1Q_2 = 6267 \text{ kJ} \quad \leftarrow \text{heat added to the mixture}$$

130.112 W99 Final Exam Solution

(2.)

Heat added to heat engine per hour.

$\rho = 0.8 \frac{g}{cm^3}$

$\rho = \frac{0.8 \times 1000}{1 \times 1000} = \frac{800\ g}{1000\ cm^3} = 0.8 \frac{kg}{L}$

Fuel burned / hour

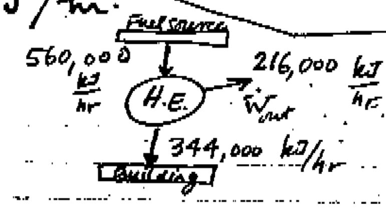
$= 20 \frac{L}{hr} \times \frac{0.8\ kg}{L} = 16 \frac{kg}{hr}$.

$\therefore$ Heat added $= 16 \times 35{,}000 = 560{,}000$ kJ/hr.

Work output $= 60$ kW $= 60 \frac{kJ}{sec}$

$= 60 \times 60 \times 60$

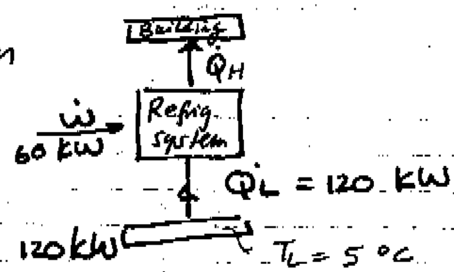
$= 216{,}000$ kJ/hr.



$\therefore$ Heat rejected to building $= 560{,}000 - 216{,}000$

$= \underline{344{,}000 \text{ kJ/hr.}}$

For the Refrigeration system



$COP_R = 2.0$

$\therefore 2.0 = \frac{\dot{Q}_L}{60}$ $\therefore \dot{Q}_L = 120$ kW

$\therefore \dot{Q}_H = 120 + 60 = 180$ kW.

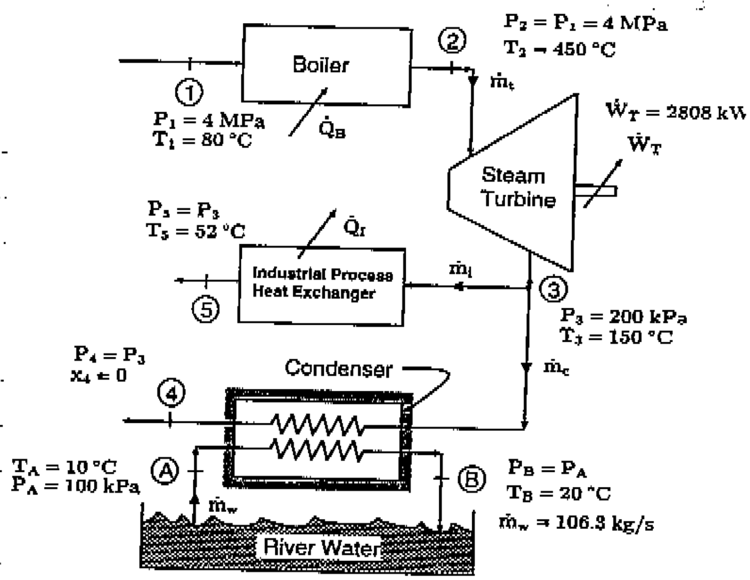
$\Rightarrow \dot{Q}_H = 180 \times 60 \times 60 = \underline{648{,}000 \text{ kJ/hr}}$

$\therefore$ Total Heat rejected to bldg

$= 344{,}000 + 648{,}000 = 992{,}000$ kJ/hr.

Heat added / day $= 992{,}000 \times 24 = 2.38 \times 10^7$ kJ/day

3. Assume • SSSF
• negligible
ΔPE ΔKE
for all devices



(a) 1st Law for the turbine (assumed adiabatic)

$$\cancel{\dot{Q}}^{\,0} - \dot{W}_T = \dot{m}_t (h_3 - h_2)$$

$$\dot{m}_t = \frac{\dot{W}_T}{(h_2 - h_3)}$$

$\dot{W}_T = 2808$ kW (given)

$$h_2 = h\Big|_{4\text{ MPa},\ 450\text{ °C}} = 3330.3 \left[\frac{kJ}{kg}\right] \quad \text{(Table A-6)}$$

$$h_3 = h\Big|_{200\text{ kPa},\ 150\text{ °C}} = 2768.8 \left(\frac{kJ}{kg}\right) \quad \text{(Table A-6)}$$

$$\dot{m}_t = \frac{2808}{(3330.3 - 2768.8)} = 5.00 \,[kg/s] \quad \leftarrow (a)$$

(b) $\dfrac{\dot{W}_T}{\dot{Q}_B} = ?$ need $\dot{Q}_B$

1st Law for Boiler: $\dot{Q}_B - \cancel{\dot{W}_{sh}}^{\,0} = \dot{m}_t (h_2 - h_1)$

$$\dot{Q}_B = \dot{m}_t (h_2 - h_1)$$

$$\dot{Q}_B = 5.00(3330.3 - 334.91) = 14{,}977 \text{ (kW)}$$

$$\boxed{\begin{gathered} h_1 = h\Big|_{4\text{ MPa},\ 80\text{ °C}} = h_f\Big|_{80\text{ °C}} \\ h_1 = 334.91 \left(\frac{kJ}{kg}\right) \quad \text{(Table A-4)} \end{gathered}}$$

$$\frac{\dot{W}_T}{\dot{Q}_B} = \frac{2808}{14{,}977} = 0.1875 \quad \leftarrow (b)$$

3 continued

(c) Condenser 1st Law (adiabatic + no shaft work)

$$\cancel{\dot{Q}}^{0} - \cancel{\dot{W}_{sh}}^{0} + \Sigma \dot{m}_i h_i = \Sigma \dot{m}_e h_e$$

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

$$\dot{m}_3 h_3 + \dot{m}_A h_A = \dot{m}_4 h_4 + \dot{m}_B h_B$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_c$$

$$\dot{m}_A = \dot{m}_B = \dot{m}_w$$

$$\dot{m}_c (h_3 - h_4) = \dot{m}_w (h_B - h_A)$$

$$\dot{m}_c = \frac{\dot{m}_w (h_B - h_A)}{(h_3 - h_4)}$$

Table A-4

$$\boxed{h_A = h_f \big|_{10°C} = 42.01 \left[\frac{kJ}{kg}\right] \quad h_B = h_f \big|_{20°C} = 83.96 \left[\frac{kJ}{kg}\right]}$$

$\dot{m}_w = 106.3$ kg/s (given)

$$\dot{m}_c = 106.3 \frac{(83.96 - 42.01)}{(2768.8 - 504.70)}$$

$$h_4 = h_f \big|_{200 kPa} = 504.70 \left(\frac{kJ}{kg}\right)$$

(Table A-5)

$$\dot{m}_c = 1.97 \ [kg/s] \leftarrow (c)$$

(d) 1st Law on Industrial process heat exchanger

$$-\dot{Q}_I + \cancel{\dot{W}_{sh}}^{0} = \dot{m}_i (h_5 - h_3)$$

$$\dot{Q}_I = \dot{m}_i (h_3 - h_5)$$

Mass conservation $\dot{m}_i + \dot{m}_c = \dot{m}_t \Rightarrow \dot{m}_i = \dot{m}_t - \dot{m}_c$

$$\dot{m}_i = 5.00 - 1.97$$

$$\dot{m}_i = 3.03 \ [kg/s]$$

$$\dot{Q}_I = 3.03 (2768.8 - 217.69)$$

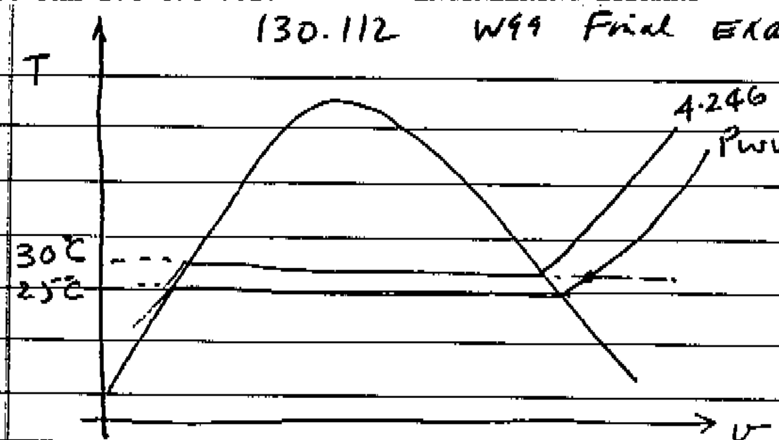
$$\dot{Q}_I = 7,730 \ [kW] \leftarrow (d)$$

$$h_5 = h_f \big|_{52°C} = 217.69 \left(\frac{kJ}{kg}\right)$$

(by linear interpolation in Table A-4)

130.112 W99 Final Exam Solution

(4)



$P_{WV_1} = P_{v_1} = P_{sat}(25°C)$

$P_{v_1} = 3.169$ kPa

$\omega_1 = \frac{0.622 P_{WV_1}}{P_{air}} = \frac{(0.622)3.169}{95 - 3.169} = 0.02146$

$\omega_2 = .3(0.02146) = 0.006438$

$\omega_2 = \frac{0.622 P_{WV_2}}{(P - P_{WV_2})} \quad \therefore 0.006438 = \frac{0.622 P_{WV_2}}{(95 - P_{WV_2})}$

$0.6116 - 0.006438 P_{WV_2} = 0.622 P_{WV_2}$

$\therefore P_{WV_2} = \frac{0.6116}{(0.622 + 0.006438)} = 0.973$ kPa

$\therefore RH_2 = \phi_2 = \frac{P_{WV_2}}{P_{MAX}} = \frac{0.973}{4.246} = 22.9\%$

Initial

Mass air in room $\left(\frac{P_a V}{RT}\right)_1 = \frac{(95 - 3.169)(30 \times 20 \times 8)}{0.287(30 + 273)}$

$P_a = (P - P_v)$

$= 5068.8$ kg.

Final mass air in room. $= \frac{PV}{RT} = \frac{(95 - 0.973)(30 \times 20 \times 8)}{0.287(303)}$

$= 5190$ kg.

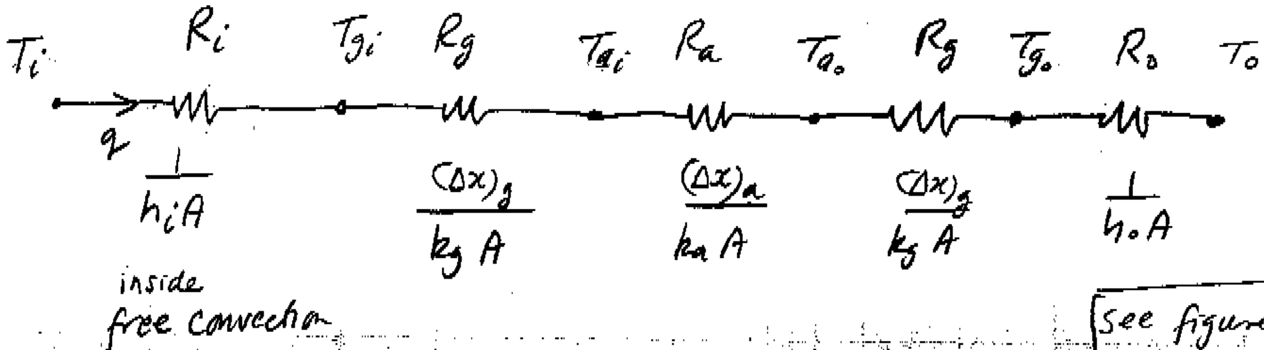
$\therefore M_{WV_1} = 5068.8(0.02146) = 108.8$

$M_{WV_2} = 5190(0.006438) = 33.4$

$\therefore$ Change in mass of water vapour $\to \Delta WV = 75.4$ kg.

5-1/2

5 (a) double-glazed window thermal resistance network



see figure on next page

$$R_i = \frac{1}{5.7(1.4)(2.3)} = 0.05448 \left[\frac{K}{W}\right]$$

$$R_g = \frac{0.003}{(0.76)(1.4)(2.3)} = 0.001226 \left[\frac{K}{W}\right]$$

$$R_a = \frac{0.020}{(0.026)(1.4)(2.3)} = 0.2389 \left[\frac{K}{W}\right]$$

$$R_o = \frac{1}{(15.1)(1.4)(2.3)} = 0.02057 \left[\frac{K}{W}\right]$$

$$R_{tot} = \Sigma R = R_i + R_g + R_a + R_g + R_o$$

$$R_{tot} = 0.05448 + 0.001226 + 0.2389 + 0.001226 + 0.02057$$

$$R_{tot} = 0.3164 \left[\frac{K}{W}\right]$$

$$q = \frac{(T_i - T_o)}{R_{tot}} = \frac{(+25 - (-10))}{0.3164} = 110.6 \ [W]$$

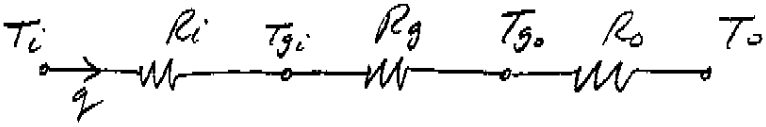
$$T_{gi} = T_i - q R_i = 25 - (110.6)(0.05448)$$

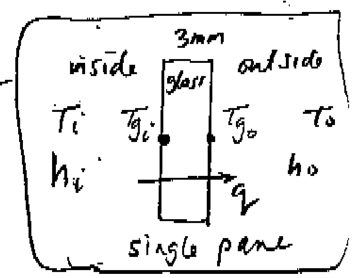
$$T_{gi} = 19.0 \ [^\circ C]$$

5-2/2

5 (b) repeat (a) for single pane

New thermal resistance network





$$R_{tot} = R_i + R_g + R_o = 0.05448 + 0.001226 + 0.02057$$

$$R_{tot} = 0.07628 \left[\frac{K}{W}\right]$$

$$q = \frac{(25 - (-10))}{0.07628} = 458.8 \ [W]$$

$$T_{gi} = T_i - q R_i = 25 - 458.8 (0.05448)$$

$$T_{gi} = 0.0 \ [°C]$$

(c) Dewpoint temperature is given as 13.0 [°C]

Double glazed: $T_{gi} = 19.0$ [°C]; $T_{gi} > T_{dp}$ ⇒ no condensation

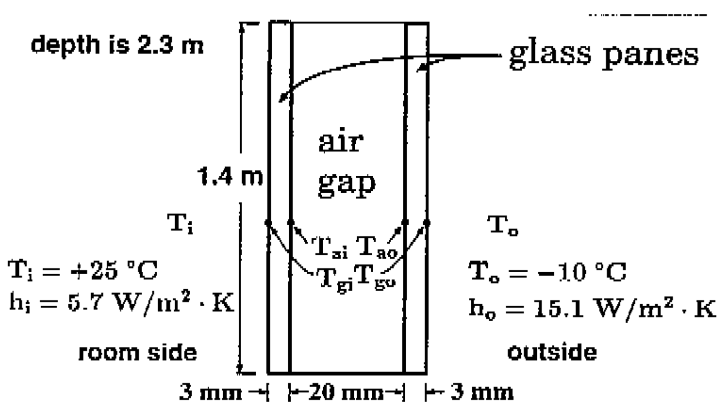
Single pane: $T_{gi} = 0.0$ [°C]; $T_{gi} < T_{dp}$ ⇒ condensation will occur

$\Delta x_g = 0.003$ m

$\Delta x_a = 0.20$ m

$k_g = 0.76 \ \frac{W}{mK}$

$k_a = 0.026 \ \frac{W}{mK}$



double-glazed window schematic

← Figure for Part (a)