9:00 a.m. 23 April 2009 FINAL EXAMINATION

PAPER NO.: 650 PAGE NO.: 1 of 4

DEPARTMENT & COURSE NO.: ENG 1460 TIME: 3 HOURS

EXAMINATION: Introduction to Thermal Sciences EXAMINERS: Profs. B.C. Wang, D. Kuhn, J. Bartley

Instructions:

(a) You are permitted to use the course textbook and a non-programmable calculator.
(b) Clear, systematic solutions are required. **Show all the steps in presenting your work.** In general, write the applicable equation to be used, substitute for the quantities appearing in the equation, and calculate a result. Marks will not be assigned for solutions that require unreasonable (in the opinion of the instructor) effort to decipher.
(c) Ask for clarification if any problem statement is not clear to you.
(d) Use linear interpolation between table entries as necessary.
(e) Retain all the significant figures in the property values taken from the tables and indicate the units. Use 4 to 5 significant figures in your calculations. Final answers must have 4 to 5 significant figures with units.
(f) Unless the phase is given in the question, provide the reasoning (justification) in deciding the phase of a substance (*i.e.*, compressed liquid, superheated vapour, saturated mixture, etc.).

value 15 **1.**

Provide short answers to the following questions. Show any necessary equations and calculations to support your answers.

4 (a) For the substance R-410a at P = 8000 [kPa] and T = 0 [°C], describe the state, providing sufficient reasoning (justification). Show the expression for calculating the enthalpy, h, for this state and evaluate the enthalpy.

3 (b) What can we conclude from applying the first law of thermodynamics to a throttle valve?

4 (c) Lisa has two big refrigerators in her apartment. On a hot summer evening, she left the doors of both refrigerators wide open (while they are plugged in), hoping that this would make her apartment cooler. How would the temperature change in Lisa's apartment later that night? Explain.

4 (d) Bart has a dream to sail the Atlantic Ocean after he grows up. From one of his science classes, he learned that the general thermal efficiency for a heat engine is: $\eta = 1 - Q_L / Q_H$. Bart wishes to design a powerful and efficient engine for his dream ship, with a target ratio $Q_L / Q_H = 0.15$. Bart plans to use a special steel to build the ship engine, and the melting point of this steel is 1500 [^{o}C]. When he designs his engine, he assumes that the low-temperature reservoir is the surrounding environment with an average temperature T_L = 27 [^{o}C]. Is Bart's proposal feasible? Explain.

value 10 **2.**

The indoor temperature of a computer lab is maintained at 20 ^{o}C. During the summer season, the average outdoor temperature is 36 ^{o}C. Computer users dissipate heat to the indoor environment at a constant rate $\dot{Q}_{users} = 0.5$ kW. The computers generate heat at a constant rate $\dot{Q}_{compter} = 5$ kW. During a sunny day, the roof temperature is higher than the indoor air temperature because of the sun's radiation, and this provides a heat rate of $\dot{Q}_{roof} = 2.5$ kW to the lab. In addition, there is heat leaking into the lab through the walls, doors and windows at a constant rate $\dot{Q}_{leak} = 2$ kW. The nominal coefficient of performance (COP, denoted as β) for the lab air conditioner is 4. Using the operating parameters of a sunny day given above,

3 (a) Determine the power required for operating the air conditioner (i.e., $\dot{W}_C$).

2 (b) Determine the rate of heat dissipation to the outdoor environment by the air conditioner (i.e., $\dot{Q}_H$).

2 (c) What is the maximum possible COP value (β) for an air conditioner for the operating conditions described above.

3 (d) A sales representative claims that his new air conditioner product consumes only $\dot{W} = 0.5$ kW in order to maintain the required lab temperature. Should the lab manager purchase this new product? Explain.

value 15 **3.**

A turbojet aircraft engine is shown in the figure below. The temperature and mean speed of the air flow at the inlet of the engine are $T_a = -40\,^{o}$C and $\overline{V}_a = 260$ m/s, respectively. Air enters the diffuser at a mass flow rate of $\dot{m}_{air} = 50$ kg/s. The mean speed of the air flow is negligible inside the engine (i.e., $\overline{V}_1 = \overline{V}_2 = \overline{V}_3 = \overline{V}_4 = 0$ m/s), except at the inlet and at the outlet of the engine (i.e., $\overline{V}_a \neq 0$ m/s and $\overline{V}_5 \neq 0$ m/s). The temperature of the air at the entrance and exit of the turbine is $T_3 = 1300\,^{o}$C and $T_4 = 700\,^{o}$C, respectively. 90% of the power produced by the turbine is used for driving the compressor (i.e., $|\dot{W}_{comp}| = 0.9 \cdot |\dot{W}_{turb}|$). The temperature at the exit of the nozzle is $T_5 = 350\,^{o}$C. The heating value of the aviation fuel is 43000 kJ/kg. The contribution of the fuel to the total mass flow rate of the working fluid can be neglected. The working fluid can be treated as air, which can be assumed to be an ideal gas.

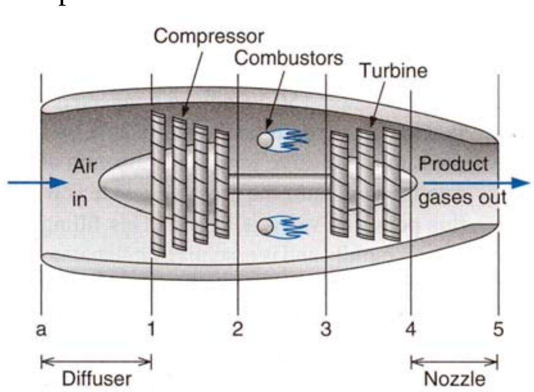
3 (a) Determine the temperature at the exit of the diffuser (i.e., T_1).

3 (b) Determine the total power generated by the turbine (i.e., $\dot{W}_{turb}$).

3 (c) Determine the temperature at the exit of the compressor (i.e., T_2).

3 (d) Determine the rate of the fuel comsumption (i.e., $\dot{m}_{fuel}$).

3 (e) Determine the mean speed of the air flow at the exit of the nozzle (i.e., $\overline{V}_5$).



[Figure source: Borgnakke and Sonntag, 7th ed., Wiley, 2009]

value 35 **4.**

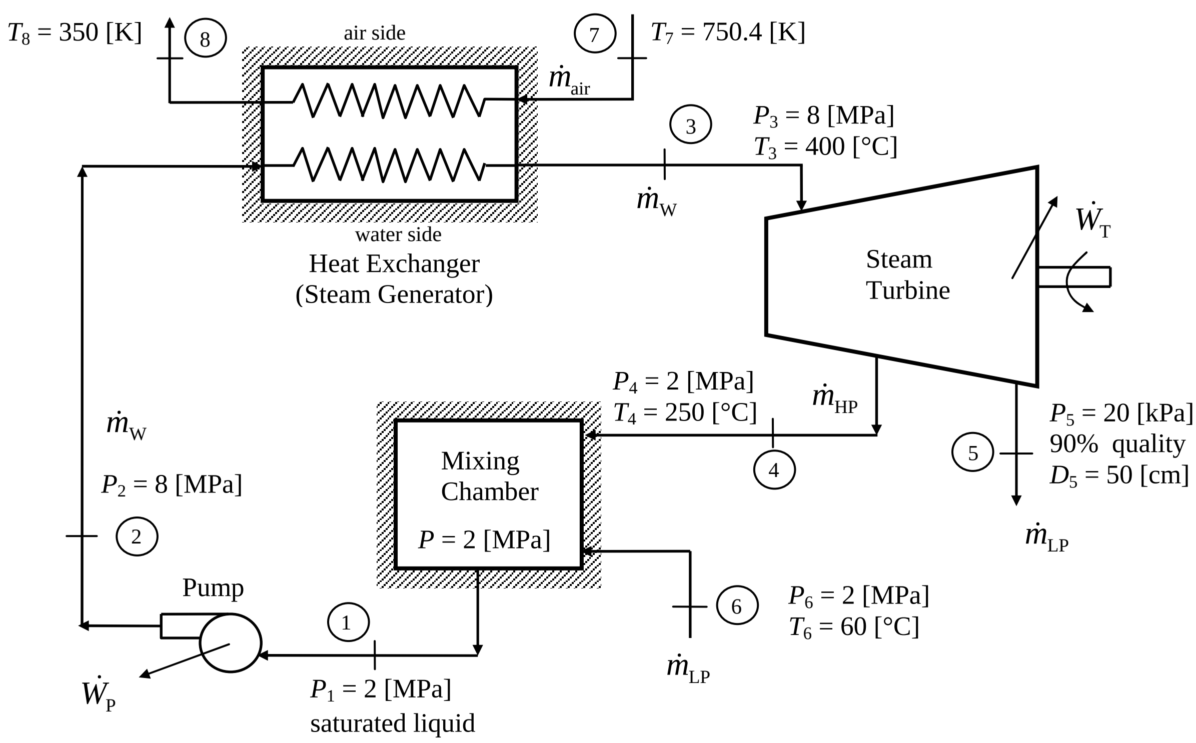
The figure below shows a schematic diagram of a steam power cycle, excluding the condensing stage and one pumping stage. Steam for the power cycle is produced in an air-to-water heat exchanger. Air with mass flow rate $\dot{m}_{\mathrm{air}} = 50$ [kg/s] enters the heat exchanger at temperature T_7 = 750.4 [K] and leaves the heat exchanger with temperature T_8 = 350 [K]. The mass flow of water, $\dot{m}_{\mathrm{W}}$, passes through the heat exchanger, receiving heat from the flow of air, and the steam then enters the turbine with a pressure of 8 [MPa] and a temperature of 400 [°C] (State3). A portion of the steam, with mass flow rate $\dot{m}_{\mathrm{HP}}$, is extracted from the turbine at State 4 where it has a pressure of 2 [MPa] and a temperature of 250 [°C]. The remainder of the steam continues to expand through the turbine and exit through a 50 [cm] diameter pipe with a pressure of 20 [kPa] and a quality of 90% (State 5). The mass flow rate of the steam at State 5 is $\dot{m}_{\mathrm{LP}}$ and this mass flow is returned to the power cycle at State 6 where it has a pressure of 2 [MPa] and a temperature of 60 [°C]. The two mass flow streams, $\dot{m}_{\mathrm{HP}}$ and $\dot{m}_{\mathrm{LP}}$, are mixed at constant pressure in a mixing chamber to produce saturated liquid at State 1, which is also at a pressure of 2 [MPa]. The combined flow is then pumped to a pressure of 8 [MPa] (State 2) before entering the heat exchanger again. Further details of the cycle and its configuration are shown in the figure below. For purposes of analysis, assume that all of the components in the cycle operate adiabatically. Assume that the air flowing through the heat exchanger behaves as an ideal gas.

13 (a) Determine the rate of heat transfer to the water in the heat exchanger (steam generator), $\dot{Q}_{\mathrm{SG}}$, and determine the power required by the pump, $\dot{W}_{\mathrm{P}}$.

14.5 (b) Determine the individual mass flow rates of steam in the power cycle, $\dot{m}_{\mathrm{HP}}$ and $\dot{m}_{\mathrm{LP}}$; and determine the power produced by the turbine, $\dot{W}_{\mathrm{T}}$.

1.5 (c) Calculate the thermal efficiency, η_{th}, of the power cycle.

6 (d) On a T–v (temperature–specific volume) diagram, show and label all known state points pertaining to the water side of the power cycle. It is not necessary to show process lines; however, show and label constant-pressure lines that pass through the state points and their associated saturation temperatures. Label the diagram showing all relevant T and v values.



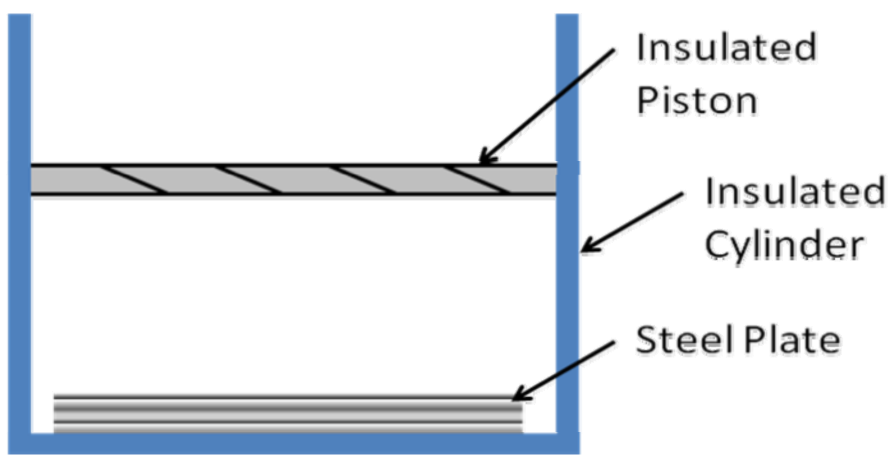
value 25 **5.**

An insulated piston-cylinder system encloses air and a steel plate fixed to the bottom of the cylinder as shown in the figure below. The cylinder contains 0.01 kg air. At State 1, the initial pressure of the air is $P_{a,1}$ =300 kPa and the initial volume is $V_{a,1}$ = 0.01 m^3; the initial temperature of the steel plate is $T_{S,1}$ = 160^{O}C. The system is then allowed to reach thermal equilibrium (State 2). The piston is allowed to float freely between State 1 and State 2. At State 2, the volume of the air is $V_{a,2}$ = 0.005 m^3. In the next process from State 2 to State 3, a force is applied to the top of the piston such that the air is compressed polytropically to a final temperature of $T_{a,3}$ = 280 ^{O}C. At State 3 the entire system is in thermal equilibrium. Assume air behaves as an ideal gas. The steel has a heat capacitance (specific heat) of $C_{p,S}$ = 0.46 kJ /kg K.

3 (a) Determine the initial temperature of the air, $T_{a,1}$. Assume at State 1 the temperature of the air is unaffected by the temperature of the steel plate.

9 (b) Determine the work done between State 1 and State 2, ${}_1W_2$, and the mass of the steel plate, m_S .

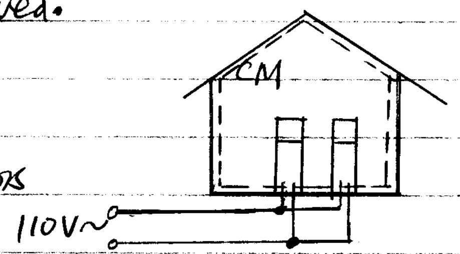
13 (c) Determine the work done between State 2 and State 3, ${}_2W_3$, the polytropic exponent, n, the final volume, $V_{a,3}$, and the final pressure, $P_{a,3}$.



Short Problems

#1 part (c) (The 1st law of thermodynamics)

(a) Lisa's goal could NOT be achieved.



(b) CM: Lisa's apartment

— Does not matter whether the doors of the refrigerator are open or closed, there is a NET electrical power input ($-W>0$) to the apartment.

(c) $Q - W = \Delta U$

$\therefore \Delta U \propto -W > 0$

For the indoor air, $\Delta U = mC\Delta T > 0 \Rightarrow \Delta T > 0$

$\therefore$ The temperature would increase later that night.

Bonus: keeping the doors of the refrigerators open, can only make the refrigerators (or, its motors) run faster. Therefore, there is more net energy input to the apartment.

#1 part (d) (The 2nd Law of Thermodynamics)

(Method 1)

(a) Yes, there is an upper Limit, which is the Carnot efficiency.

(b) Not feasible

The upper Limit: $\eta_{carnot} = 1 - \frac{T_L}{T_H}$

Assume: $T_L = 27 + 273.15 = 300.15 (K)$

$T_H = 1500 + 273.15 = 1773.15 (K)$

Then: $\eta_{carnot} = 1 - \frac{300.15}{1773.15} = 83.07\%$

(c) Because $\eta_{Bart} = 1 - 0.15 = 0.85 > \eta_{carnot}$

$\therefore$ Not feasible

(Method 2)

(a) Yes, there is an upper limit, which is the Carnot efficiency.

(b) The upper limit: $\eta_{Carnot} = 1 - \frac{T_L}{T_H}$

$0.85 = 1 - \frac{300.15}{T_H}$

$\therefore T_H = 2001 (K)$ or, $1727.85 (°C)$

(c) Because $T_H > 1500°C$, the steel used for building the engine will melt.

$\therefore$ Not feasible.

Problem #2 (2^{nd} Law)

(a) $\dot{Q}_L = \dot{Q}_{users} + \dot{Q}_{comp} + \dot{Q}_{roof} + \dot{Q}_{leak}$

$= 0.5 + 5 + 2.5 + 2$

$= 10 \text{ (kW)}$

$$\dot{W}_c = \frac{\dot{Q}_L}{COP} = \frac{10}{4} = 2.5 \text{ (kW)}$$

(b) $\dot{Q}_H = \dot{Q}_L + \dot{W}_c$

$= 10 + 2.5$

$= 12.5 \text{ (kW)}$

(c) $COP_{carnot} = \dfrac{T_L}{T_H - T_L} = \dfrac{20 + 273.15}{36 - 20} = 18.32$

(d) $COP_{sales} = \dfrac{\dot{Q}_L}{\dot{W}_c} = \dfrac{10}{0.5} = 20$

$COP_{sales} > COP_{carnot}$

$\therefore$ Imposible. The Lab manager should NOT buy it.

Problem #3

For air, $C_{po} = 1.004\ \mathrm{KJ/Kg \cdot K}$

(a) Diffuser

$$\cancel{\dot{Q}_{a1}} - \cancel{\dot{W}_{a1}} = \dot{m}[(h_1 - h_a) + \tfrac{1}{2}(\cancel{\bar{V}_1^2} - \bar{V}_a^2)]$$

$$\therefore\ \tfrac{1}{2}\bar{V}_a^2 = C_{po}(T_1 - T_a)$$

$$\tfrac{1}{2}\times 260^2 = 1.004\ (T_1 + 40)\times 1000$$

$$\therefore\ T_1 = -6.33\ (^\circ C)$$

(b) turbine

$$\cancel{\dot{Q}_{34}} - \dot{W}_{34} = \dot{m}_{air}(h_4 - h_3)$$

$$\therefore\ \dot{W}_{34} = \dot{m}_{air} C_{po}(T_3 - T_4)$$

$$\therefore\ \dot{W}_{turb} = \dot{W}_{34} = 50\times 1.004\times(1300-700) = 30120\ (KW)$$

(c) Compressor

$$\cancel{\dot{Q}_{12}} - \dot{W}_{12} = \dot{m}_{air}(h_2 - h_1) = \dot{m}_{air} C_{po}(T_2 - T_1)$$

$$-\dot{W}_{12} = 0.9\ \dot{W}_{turb} = 0.9\times 30120 = 27108\ (KW)$$

$$\therefore\ 27108 = 50\times 1.004\times(T_2 + 6.33)$$

$$\therefore\ T_2 = 533.67\ (^\circ C)$$

(d) combustor

$$\dot{Q}_{23} - \cancel{\dot{W}_{12}} = \dot{m}_{air}(h_3 - h_2) = \dot{m}_{air} C_{po}(T_3 - T_2)$$

$$\therefore\ \dot{Q}_{23} = 50\times 1.004\times(1300 - 533.67)$$

$$= 38469.77\ (KW)$$

$$\dot{m}_{gas} = \dot{Q}_{23}/43000 = 0.895\ (kg/s)$$

(e) Nozzle

$$\cancel{\dot{Q}_{45}} - \cancel{\dot{W}_{45}} = \dot{m}_{air}[(h_5 - h_4) + \tfrac{1}{2}(\bar{V}_5^2 - \cancel{\bar{V}_4^2})]$$

$$\therefore\ \tfrac{1}{2}\bar{V}_5^2 = h_4 - h_5 = C_{po}(T_4 - T_5)$$

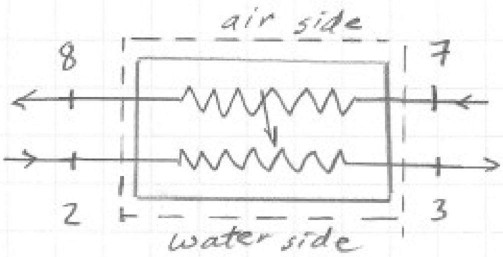
$$\therefore\ \tfrac{1}{2}\bar{V}_5^2 = 1.004\times(700 - 350)\times 1000$$

$$\therefore\ \bar{V}_5 = 838.33\ (m/s)$$

Question #4

assumptions: air behaves as an ideal gas; constant specific heats can be used.
- All components are adiabatic – no heat exchange with the surroundings.
- All devices operate as steady-state, steady flow

(a) heat exchanger: heat from the air side is transferred to the water side, producing steam.



conservation of mass: $\dot{m}_2 + \dot{m}_7 = \dot{m}_3 + \dot{m}_8$

conservation of energy: (First law)

$$\cancel{\dot{Q}} - \cancel{\dot{W}} = \left(\dot{m}_{air} h_8 + \dot{m}_w h_3\right) - \left(\dot{m}_{air} h_7 + \dot{m}_w h_2\right)$$

adiabatic

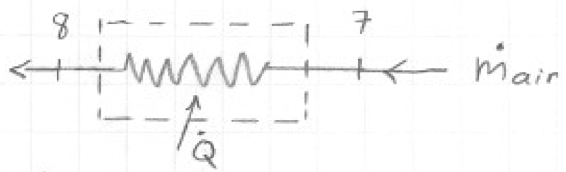
neglecting Δke, Δpe

$$\therefore \dot{m}_{air}\left(h_8 - h_7\right) = \dot{m}_w\left(h_2 - h_3\right)$$

$$\dot{m}_w = \frac{\dot{m}_{air} C_{P_0}\left(T_8 - T_7\right)}{h_2 - h_3} \qquad Eq.(1)$$

Rate of heat transfer between the air and water in the heat exchanger:

e.g., air side:



$$\dot{Q}_{air} - \cancel{\dot{W}}^{\,0} = \dot{m}_{air}\left(h_8 - h_7\right)$$

$$= \dot{m}_{air} C_{p_0}\left(T_8 - T_7\right)$$

$$\dot{Q}_{air} = 50 \times 1.004 \times (350 - 750.4)$$

$$\dot{Q}_{air} = -20\,100 \text{ kW}$$

where $C_{p_0} = 1.004$ kJ/kg·K

Table A.5

$\therefore$ The rate of heat transfer to the water, $\dot{Q}_{SG}$, is $\dot{Q}_{SG} = -\dot{Q}_{air} = 20\,100$ kW

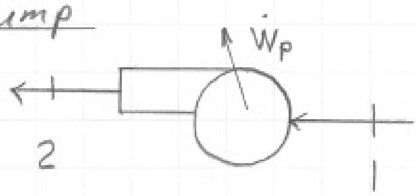
To determine the power required by the pump we need $\dot{m}_w$. From Eq.(1) we need h_2 and h_3.

<u>state 3</u>: $T_3 = 400°C$, $P_3 = 8$ MPa At 8 MPa, $T_{sat.} = 295.06°C$

$T_3 > T_{sat.}$ ∴ superheated vapour.

Table B.1.3, $h_3 = 3138.28$ kJ/kg
$v_3 = 0.03432$ m³/kg

<u>Pump</u>



energy: $\cancel{\dot{Q}_P}^{\text{adiabatic}} - \dot{W}_P = \dot{m}_W (h_2 - h_1)$

neglecting Δke, Δpe

<u>state 1</u>: $P_1 = 2$ MPa, saturated liquid

Table B.1.2, $v_f = 0.001177$ m³/kg
$h_f = 908.77$ kJ/kg
$T_{sat.} = 212.42$ °C

Across the pump, $h_2 - h_1 \simeq v_1 (P_2 - P_1)$

$$\therefore h_2 \simeq 0.001177(8000-2000) + 908.77$$
$$= 915.83 \text{ kJ/kg}$$

{ Alternatively, realizing state 2 is a compressed liquid,

$$h_2 = h_{f_{at\,T}} + v_{f_{at\,T}} \left(P_2 - P_{sat_{at\,T}}\right)$$

where $T = T_1 = 212.42°C$ ($T_{sat.}$ for 2000 kPa)

as above, $h_2 = 908.77 + 0.001177(8000-2000) = 915.83$ kJ/kg }

Using Eq.(1), $\dot{m}_W = \dfrac{50 \times 1.004(350-750.4)}{915.83 - 3138.28}$

$$\dot{m}_W = 9.0441 \text{ kg/s}$$

{ Alternatively, $\dot{Q}_{SG} = \dot{m}_W (h_3 - h_2)$ considering the water side

Back to the pump, $-\dot{W}_P = \dot{m}_w (h_2 - h_1)$

$$\dot{W}_P = \dot{m}_w v_1 (P_1 - P_2)$$
$$= 9.044 \times 0.001177 \times (2000 - 8000)$$
$$\dot{W}_P = -63.86 \text{ kW}$$

↳ indicates power <u>required</u> (input)

(b) <u>Steam Turbine</u>

<u>State 4</u> $P_4 = 2\text{ MPa}$, $T_4 = 250\,°C$

$T_{sat.}$ for 2 MPa is 212.42 °C

$T_4 > T_{sat.}$ ∴ superheated vapour

Table B.1.3 $h_4 = 2902.46 \text{ kJ/kg}$

$v_4 = 0.11144 \text{ m}^3/\text{kg}$

<u>State 5</u> saturated mixture with $x_5 = 0.90$

$P_5 = 20 \text{ kPa}$

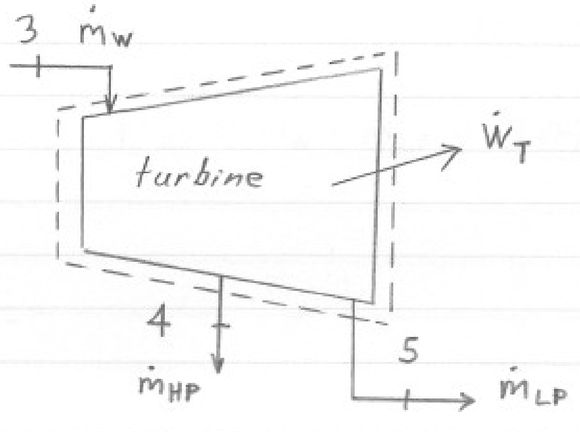
$T_{sat.} = 60.06\,°C$ Table B.1.2

$v_f = 0.001017 \text{ m}^3/\text{kg}$ $h_f = 251.38 \text{ kJ/kg}$

$v_g = 7.64937 \text{ m}^3/\text{kg}$ $h_g = 2609.70 \text{ kJ/kg}$

$$v_5 = (1-x) v_f + x \cdot v_g = (1-0.9)0.001017 + 0.9 \times 7.64937$$
$$v_5 = 6.8845 \text{ m}^3/\text{kg}$$

$$h_5 = (1-x) h_f + x \cdot h_g = (1-0.9) \times 251.38 + 0.9 \times 2609.70$$
$$h_5 = 2373.86 \text{ kJ/kg}$$



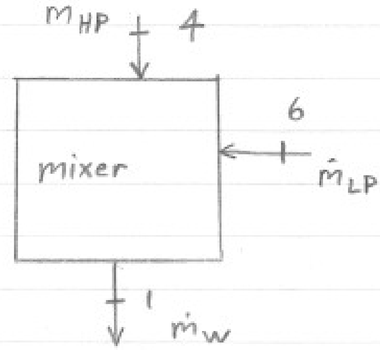
mass: $\dot{m}_w = \dot{m}_{HP} + \dot{m}_{LP}$

energy: $\cancel{\dot{Q}_T} - \dot{W}_T = \dot{m}_{LP}(h_5 + \frac{1}{2}\bar{V}_5^2) + \dot{m}_{HP}(h_4 + \frac{1}{2}\cancel{\bar{V}_4^2}) - \dot{m}_w(h_3 + \frac{1}{2}\cancel{\bar{V}_3^2})$ Eq.(2)

For the turbine we can neglect $\bar{V}_3$ and $\bar{V}_4$ because we do not know the size of pipe. Also, Δpe neglected.

Three unknowns: $\dot{m}_{HP}$, $\dot{m}_{LP}$ and $\dot{W}_T$

$\therefore$ Consider the <u>mixing Chamber</u>:



<u>state 6</u> $P_6 = 2\,MPa$, $T_6 = 60°C$

$T_6 < T_{sat.}$ $\therefore$ compressed liquid
(212.4°C)

$$v_6 \simeq v_{f\ at\ 60°C} = 0.001017\ m^3/kg$$

$$h_6 \cong h_{f\ at\ 60°C} + v_{f\ at\ 60°C}\left(P_6 - P_{sat.\ at\ 60°C}\right)$$

$$= 251.11 + 0.001017 \times \left(2000 - 19.941\right) \qquad \text{Table B.1.1}$$

$$\therefore h_6 = 253.12\ kJ/kg$$

mass: $\dot{m}_W = \dot{m}_{HP} + \dot{m}_{LP}$

energy: $\cancel{\dot{Q}} - \cancel{\dot{W}} = \dot{m}_W h_1 - \left(\dot{m}_{HP} h_4 + \dot{m}_{LP} h_6\right)$
adiabatic

substitute: $\dot{m}_W h_1 = \left(\dot{m}_W - \dot{m}_{LP}\right) h_4 + \dot{m}_{LP} h_6$

$$\dot{m}_{LP} = \frac{\dot{m}_W \left(h_1 - h_4\right)}{h_6 - h_4}$$

$$\therefore \dot{m}_{LP} = \frac{9.0441\left(908.77 - 2902.46\right)}{253.12 - 2902.46} = 6.8058\ kg/s$$

$$\therefore \dot{m}_{HP} = \dot{m}_W - \dot{m}_{LP} = 9.0441 - 6.8058 = 2.2383\ kg/s$$

Back to turbine, Eq.(2), $\dot{m}_5 = \dfrac{\bar{V}_5 A}{v_5}$

$D_5 = 50$ cm $\quad \therefore \bar{V}_5 = \dfrac{\dot{m}_{LP} \cdot v_5}{\pi/4 (D)^2} = \dfrac{6.8058 \times 6.8845}{\pi/4\,(0.5)^2}$

$$\bar{V}_5 = 238.62 \text{ m/s}$$

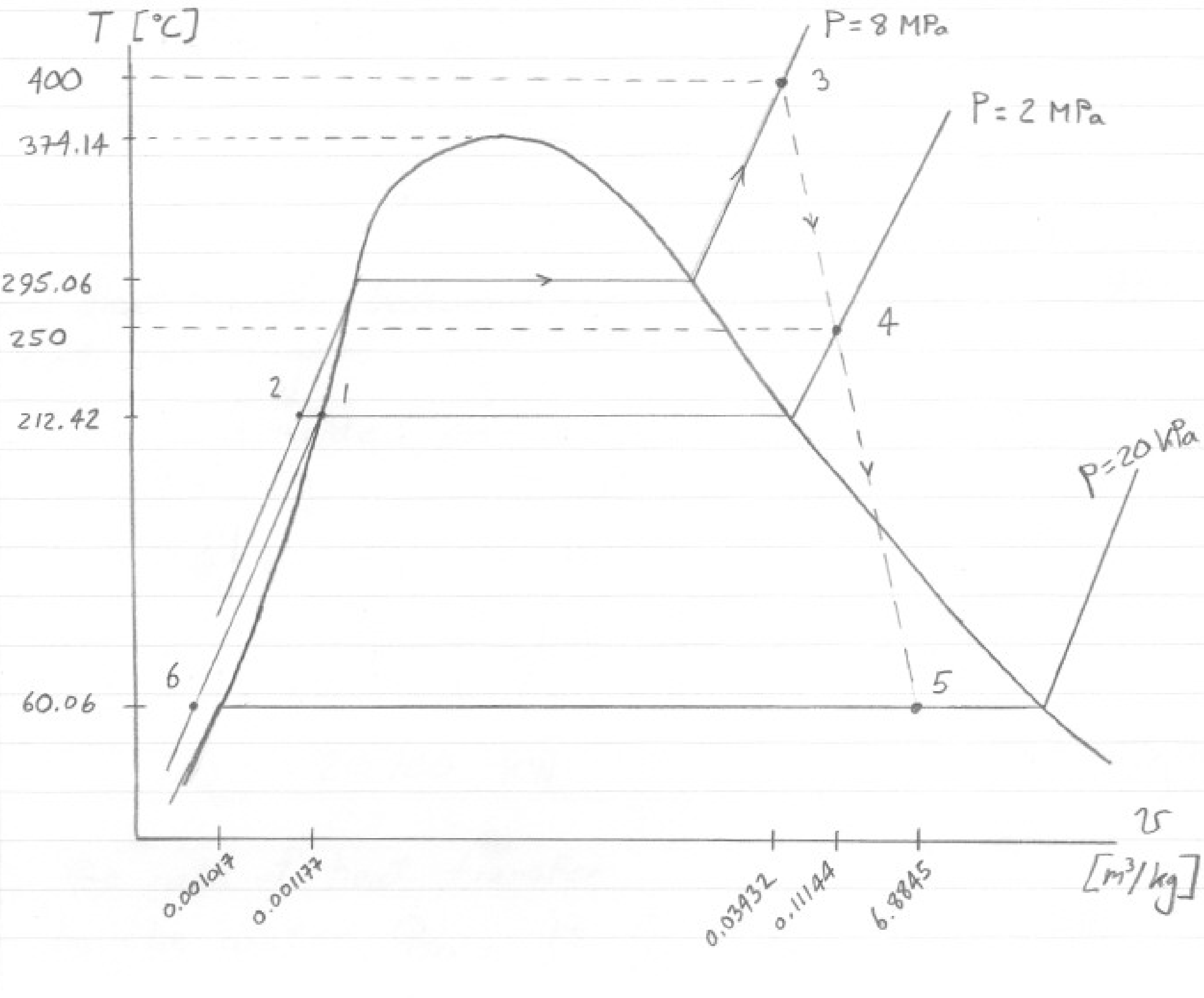
turbine energy eqn.,

$$-\dot{W}_T = 6.8058\left(2373.86 + \tfrac{1}{2}(238.62)^2 \tfrac{1}{1000}\right) + 2.2383 \times 2902.46 - 9.0441 \times 3138.28 = -5536.5 \text{ kW}$$

$\therefore \quad \dot{W}_T = 5536.5$ kW

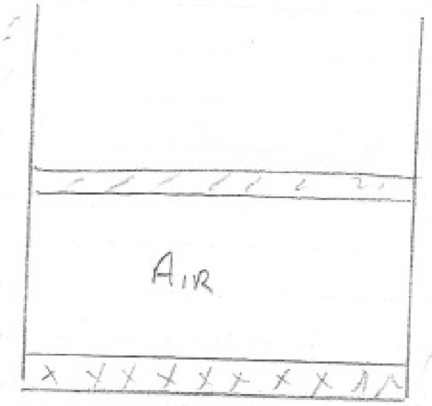
(c) $\eta_{th} = \dfrac{\dot{W}_{net}}{\dot{Q}_{SG}} = \dfrac{\dot{W}_T - |\dot{W}_P|}{\dot{Q}_{SG}} = \dfrac{5536.5 - 63.86}{20100} = 0.2722$

(d)



PISTON – CYLINDER + STEEL PLATE

Solution to Problem #5



GIVEN: AIR – IDEAL GAS ; $C_{P,S} = 0.46 \frac{kJ}{kg \cdot K}$

STATE 1: $m_a = 0.01$ kg

$P_{a,1} = 300$ kPa

$V_{a,1} = 0.01$ m^3

$T_{s,1} = 160$ °C

STATE 2: $V_{a,2} = 0.005$ m^3

STATE 3: $T_{a,3} = 230$ °C

- STATE 2 IS A THERMAL EQUILIBRIUM.
- PISTON IS ALLOWED TO FLOAT FREELY FROM STATE 1 TO 2
- POLYTROPIC COMPRESSION FROM STATE 2 TO 3

a) FIND: $T_{a,1}$

SOL'N: $P_{a,1} V_{a,1} = m_a R T_{a,1}$

$$T_{a,1} = \frac{P_{a,1} V_{a,1}}{m_a R}$$

$$= \frac{300 \times 0.01}{0.01 \times 0.287} \quad ; \text{ R FROM TABLE A.5}$$

$$= 1045.30 \text{ K}$$

b) FIND: ${}_1W_2$, m_s

SOL'N: $P_{a,2} = P_{a,1}$ $\because$ piston is allowed to float freely from state 1 to state 2

$= 300$ kPa

$${}_1W_2 = P_{a,1}(V_{a,2} - V_{a,1})$$

$$= 300(0.005 - 0.01)$$

$$= -1.5 \text{ kJ} \quad \text{(i.e. COMPRESSION)}$$

Use 1st LAW TO SOLVE FOR m_s. + $T_{a,2} = T_{s,2}$ // THERMAL EQUILIBRIUM

$${}_1Q_2 - {}_1W_2 = m_a(u_{a,2} - u_{a,1}) + m_s(u_{s,2} - u_{s,1}) + \Delta PE + \Delta KE$$

(${}_1Q_2 = 0$, INSULATED; $\Delta PE = 0$; $\Delta KE = 0$)

$$-{}_1W_2 = m_a C_{v_0,a}(T_{a,2} - T_{a,1}) + m_s C_{p,s}(T_{a,2} - T_{s,1})$$

$$T_{a,2} = \frac{P_{a,2}\ V_{a,2}}{m_a\ R}$$

$$= \frac{300 \times 0.005}{0.01 \times 0.287} \qquad \text{TABLE A.5}$$

$$= 522.648\ K$$

$$T_{s,2} = 522.649\ K$$

$$m_s = \frac{-{}_1W_2 - m_a C_{v0,a} (T_{a,2} - T_{a,1})}{C_{p,s} (T_{a,2} - T_{s,1})} \qquad \text{TABLE A.5}$$

$$= \frac{1.5 - 0.01 \times 0.717 \times (522.648 - 1045.30)}{0.46 \times (522.648 - 433.15)}$$

$$= \frac{1.5 + 3.7474}{41.16908}$$

$$= 0.127459\ kg$$

c) FIND ${}_2W_3$, n, $V_{a,3}$

$$\cancel{{}_2Q_3}^{0} - {}_2W_3 = m_a C_{v0,a} (T_{a,3} - T_{a,2}) + m_s C_{p,s} (\underbrace{T_{s,3}}_{= T_{a,3}\ \text{Thermal Equil.}} - T_{a,2}) + \Delta \cancel{KE}^{0} + \Delta \cancel{PE}^{0}$$

$$_2W_3 = -m_a C_{v0,a} (T_{a,3} - T_{a,2}) - m_s C_{p,s} (T_{a,3} - T_{a,2})$$

$$= -0.01 \times 0.717 \times (553.15 - 522.65) - 0.127459 \times 0.46 \times (553.15 - 522.65)$$

$$= -0.218685 - 1.78825$$

$$= -2.0069\ kJ$$

$$_2W_3 = \frac{m_a R (T_{a,3} - T_{a,2})}{1 - n}$$

$$-2.0069 = \frac{0.01 \times 0.287 (553.15 - 522.65)}{1 - n}$$

$$n = 1.043617$$

$$P_{a,3} V_{a,3}^{n} = P_{a,2} V_{a,2}^{n}$$ Polytropic Process

$$= (300)(0.005)^{1.043617}$$
$$= 1.19049 \quad kPa \cdot m^3$$

$$P_{a,3} V_{a,3} = m_a R (T_3 - T_2) + P_2 V_2$$ IDEAL GAS

$$= 0.01 \times 0.287 \times (553.15 - 522.6481) + (300)(0.005)$$
$$= 1.58754 \quad kPa \cdot m^3$$

$$\frac{P_{a,3} V_{a,3}^{n}}{P_{a,3} V_{a,3}} = \frac{1.19049}{1.58754}$$

$$V_{a,3}^{n-1} = 0.74990$$

$$\underline{V_{a,3} = 0.001362 \quad m^3}$$

$$P_{a,3} V_{a,3} = 1.58754 \quad kPa \cdot m^3$$ [above]

$$P_{a,3} = 1165.6 \quad kPa$$