Kafrelsheikh University
Faculty of Engineering
Dept. Mech. Engineering
Year: First year
Subject: Thermodynamics I

Semester: 2nd Semester
Final Examination
Date: June 16th, 2014
Time allowed: 3 hours
Full Mark: 60

(a) No. of questions: 10 -No. of questions: ٥
(b) This is a close book exam. Only thermodynamics tables and calculator are permitted
(c) Clear, systematic answers and solutions are required. In general, marks will not be assigned for answers and solutions that require unreasonable (in the opinion of the instructor) effort to decipher.
(d) Retain all the significant figures of properties taken from tables. Final results should have at least 3 to 5 significant digits.
(e) Ask for clarification if any question statement is not clear to you.
(f) Solve all questions.
(g) The exam will be marked out of 60. There are 20 marks bonus.

Question #1 (13 Marks)

Choose the correct answer. Justify your answer with calculations or explanations or both whenever possible. If answer requires justification, marks will not be given to the correct answer without justification.

1. Engineering thermodynamics does not include energy **(0.5 Marks)**

(A) transfer
(B) utilization
(C) storage
(D) transformation

2. Which of the following is not an extensive property? **(0.5 Marks)**

(A) Momentum
(B) Internal energy
(C) Temperature
(D) Volume

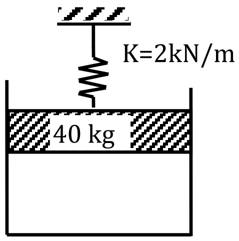
3. Calculate the pressure in the 240-mm-diameter cylinder shown. The spring is compressed 60 cm. Neglect friction. **(2 Marks)**

(A) 198 kPa
(B) 135 kPa
(C) 100 kPa
(D) 35 kPa

$$p = p_{atm} + (mg + kx)/A_p$$

$$p = 100 + \left(40 \times 9.81 \times 10^{-3} + 2 \times 0.60\right) / \left(\frac{\pi}{4} \times (0.240)^2\right)$$

$$p = 135.20 \quad \text{kPa}$$



4. The volume occupied by 4 kg of 200°C steam at a quality of 80 percent is nearest **(1 Marks)**

(A) 0.004 m³
(B) 0.104 m³
(C) 0.4 m³
(D) 4.1 m³

From saturated steam tables at 70 °C

$v_g = 0.001157$ m³/kg

$v_g = 0.12721$ m³/kg

$v = v_f + x(v_g - v_g) = 0.001157 + 0.8 \times (0.12721 - 0.001157) = 0.102$ m³/kg

$V = mv = 4 \times 0.102 = 0.4080$ m³

5. Saturated steam is heated in a rigid tank from 70 to 800°C. P_2 is nearest **(2 Marks)**

(A) 100 kPa
(B) 200 kPa
(C) 300 kPa
(D) 400 kPa

From saturated steam tables at 70 °C

$v_g = 5.0396 \text{ m}^3/\text{kg}$

$v_2 = v_1 = v_g = 5.0396 \text{ m}^3/\text{kg}$

From superheated steam tables at 800 °C and 5.0396 m³/kg

$p_2 = 0.099 \text{ MPa} \approx 0.1 \text{ MPa}$

7. A vertical circular cylinder holds a height of 1 cm of liquid water and 100 cm of vapor. If P = 200 kPa, the quality is nearest **(1.5 Marks)**

(A) 0.01
(B) 0.1
(C) 0.4
(D) 0.8

From saturated steam tables at 200 kPa

$v_f = 0.0.001061 \text{ m}^3/\text{kg}$

$v_g = 0.88578 \text{ m}^3/\text{kg}$

$$x = \frac{m_g}{m_g + m_f} = \frac{V_g / v_g}{V_g / v_g + V_f / v_f} = \frac{h_g A / v_g}{h_g A / v_g + h_f A / v_f} = \frac{h_g / v_g}{h_g / v_g + h_f / v_f}$$

$$x = \frac{1.00 / 0.88578}{1.00 / 0.88578 + 0.01 / 0.001061} = 0.107$$

8. The point that connects the saturated-liquid line to the saturated-vapor line is called the **(0.5 Marks)**

(A) triple point
(B) critical point
(C) superheated point
(D) compressed liquid point

9. Air (R=0.287 kJ/kg.K) undergoes a three-process cycle. Find the net work done for 2 kg of air if the processes are

$1 \rightarrow 2$: constant-pressure expansion
$2 \rightarrow 3$: constant volume
$3 \rightarrow 1$: constant-temperature compression

The necessary information is T_1 = 100°C, T_2 = 600°C, and P_1 = 200 kPa. **(3 Marks)**

(A) 105 kJ
(B) 96 kJ
(C) 66 kJ
(D) 11.5 kJ

$$W_{1-2} = mp(v_2 - v_1) = mR(T_2 - T_1) = 2 \times 0.287 \times (600 - 100) = 287 \text{ kJ}$$

$$W_{2-3} = 0$$

$$W_{3-1} = mRT_1 \ln\left(\frac{v_1}{v_3}\right) = mRT_1 \ln\left(\frac{v_1}{v_2}\right) = mRT_1 \ln\left(\frac{RT_1 / p_1}{RT_2 / p_2}\right) = mRT_1 \ln\left(\frac{T_1}{T_2}\right)$$

$$W_{3-1} = 2 \times 0.287 \times 373 \times \ln\left(\frac{373}{873}\right) = -182.06 \text{ kJ}$$

$$W_{net} = W_{1-2} + W_{2-3} + W_{3-1} = 287 + 0 - 182.06 = 104.94 \approx 105 \text{ kJ}$$

10. Select a correct statement of the first law if kinetic and potential energy changes are neglected. **(1 Marks)**

(A) Heat transfer equals the work done for a process.
(B) Net heat transfer equals the net work for a cycle.
(C) Net heat transfer minus net work equals internal energy change for a cycle.
(D) Heat transfer minus work equals internal energy for a process.

Question #2 (14 Marks)

A closed system, containing 1.5 kg of helium (He), is 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=500 kPa and T_2=150°C. The second process (state 2 to state 3) is an adiabatic expansion until the pressure and temperature are P_3=200 kPa and T_3=-10 °C

a. Calculate the value of the polytropic exponent, n, for the first process (state 1 to state 2). **(4 Marks)**
b. Calculate the work done by the system in the first process, W_{12} in kJ. **(2 Marks)**
c. Calculate the heat transfer by the system in the first process, Q_{12} in kJ. **(2 Marks)**
d. Calculate the work done by the system in the second process, W_{23} in kJ. **(2 Marks)**
e. Show the two processes on a P-V (pressure-volume) diagram. Clearly identify the states and show the processes paths with respect to constant temperature lies. **(4 Marks)**

(N.B. use the following constants for helium, R = 2.0785 kJ/kg.K, C_{vo}=3.1156 kJ/kg.K)

Solution

a. For a closed system, polytropic process

$$P_1V_1^n = P_2V_2^n \rightarrow \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n \rightarrow n = \frac{\ln(P_2/P_1)}{\ln(V_1/V_2)}$$

$$V_1 = mRT_1/P_1 = 1.5\times 2.0785\times(60+273)/120 = 8.652\,\text{m}^3$$

$$V_2 = mRT_2/P_2 = 1.5\times 2.0785\times(150+273)/500 = 2.638\,\text{m}^3$$

$$n = \frac{\ln(P_2/P_1)}{\ln(V_1/V_2)} = \frac{\ln(500/120)}{\ln(8.652/2.638)} = 1.2$$

b. Work done by the system in the first process (process 1→2 is a polytropic process)is expressed as

$$W_{12} = \frac{P_2V_2 - P_1V_1}{1-n} = \frac{500\times 2.638 - 120\times 8.652}{1-1.2} = 1403.8\ \text{kJ}$$

c. Heat transfer by the system in the first process, Q_{12} is

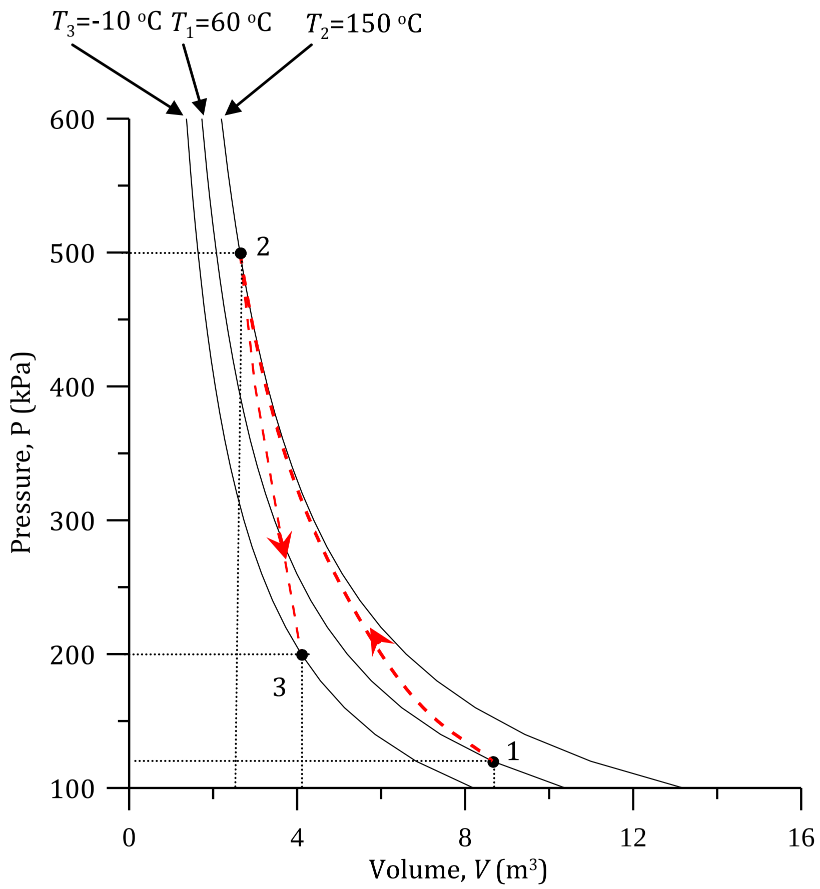
$$Q_{12} = mC_v(T_2 - T_1) = 1.5\times 3.1156\times(150-60) = 420.606\ \text{kJ}$$

d. Work done by the system in the second process, W_{23}

$$Q_{32} - W_{32} = mC_v(T_3 - T_2)$$

$$W_{32} = mC_{v0}(T_2 - T_3) = 1.5\times 3.1156\times(150+10) = 747.744\ \text{kJ}$$

e.



Question #3 (6 Marks)

A rigid and well-insulated chamber is divided by a partition that is initially pinned in place at the position shown in Figure 1. The partition separates two gases, air and CO_2 gas, and the partition is free to move without friction once the pin is pulled. The partition allows for the transfer of heat between both sides of the chamber. There is 1.5 kg of air which is at an initial pressure and temperature of 500 kPa and 350 K, respectively. On the other side of the partition is 4 kg of CO_2 gas at an initial pressure and temperature of 200 kPa and 478 K, respectively. Assume the air and CO_2 are ideal gases with constant specific heats. A process occurs whereby the pin is pulled out and the gases in the chamber are allowed to reach a new state of equilibrium in a quasi-equilibrium manner (assume the partition moves very slowly as the states change).

(a) Determine the final temperature, T_2, corresponding to the final state of the gases. **(4 Marks)**

(b) Determine the final pressure, P_2 . Assue R =0.216 kJ/kg.K for a mixture of air and CO_2. **(2 Marks)**

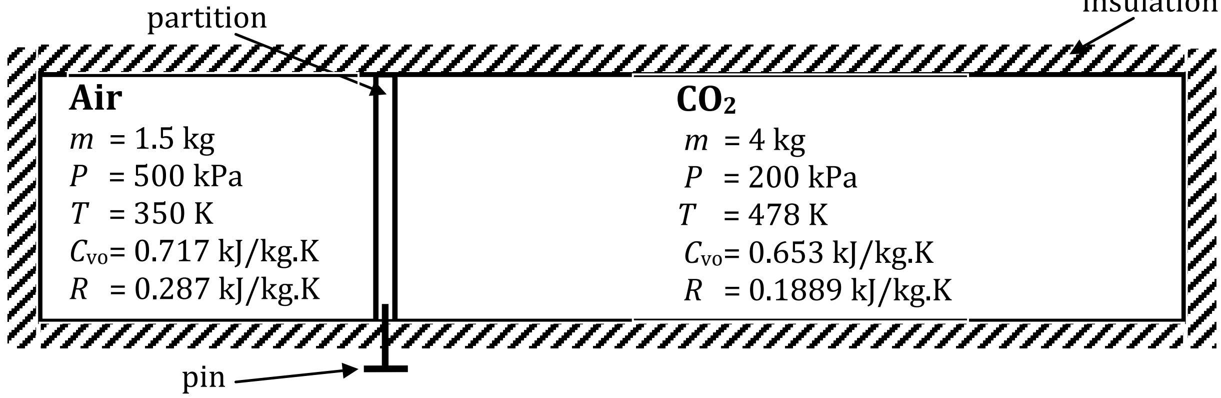


Figure 1 Sketch of problem in question #3

Solution

a. From first law of thermodynamic for a control mass system including the entire chamber

$$ {}_1Q_2 - {}_1W_2 = (U_2 - U_1) \qquad\qquad ({}_1Q_2 = {}_1W_2 = 0) $$

$$ U_2 - U_1 = 0 $$

$$ U_2 = U_1 $$

$$ m_{air}u_{air,2} + m_{CO_2}u_{CO_2,2} = m_{air}u_{air,1} + m_{CO_2}u_{CO_2,1} $$

$$ m_{air}C_{v,air}T_2 + m_{CO_2}C_{v,CO_2}T_2 = m_{air}C_{v,air}T_{1,air} + m_{CO_2}C_{v,CO_2}T_{1,CO_2} $$

$$ T_2 = \frac{m_{air}C_{v,air}T_{1,air} + m_{CO_2}C_{v,CO_2}T_{1,CO_2}}{m_{air}C_{v,air} + m_{CO_2}C_{v,CO_2}} = \frac{1.5\times 0.717\times 350 + 4\times 0.653\times 478}{1.5\times 0.717 + 4\times 0.653} = 440.66\ \text{K} $$

b. The final pressure P2 can be calculated as follows:

$$ V_{air,1} = \frac{m_{air}R_{air}T_{air,1}}{P_{air,1}} = \frac{1.5\times 0.287\times 350}{500} = 0.301\ \text{m}^3 $$

$$ V_{CO_2,1} = \frac{m_{CO_2}R_{CO_2}T_{CO_2,1}}{P_{CO_2,1}} = \frac{4\times 0.1889\times 478}{200} = 1.806\ \text{m}^3 $$

$$ V_2 = V_{air,1} + V_{CO_2,1} = 0.301 + 1.806 = 2.107\ \text{m}^3 $$

$$ P_2 = \frac{m_2RT_2}{V_2} = \frac{(1.5+4)\times 0.216\times 440.66}{2.107} = 248.459\ \text{kPa} $$

Question #4 (20 Marks)

An industrial steam turbine (*shown in Figure. 2 in the next page*) receives 2 kg/s of superheated steam at 10 MPa and 500 ^{0}C. At a point in the turbine where the pressure is 1 MPa and temperature is 200 ^{0}C, steam is extracted for an industrial process at a rate of 0.5 kg/s. The rest of steam continues expansion in the turbine. The steam exits from turbine at 10 kPa and quality of 90% is cooled in a condenser to a saturated liquid. Calculate the following

a) The mass flow rate at the exit from turbine, $\dot{m}_3$. **(2 Marks)**

b) The power produced by the turbine, $\dot{W}_T$ with neglecting effect of kinetic energy in energy equation. **(6 Marks)**

c) If the diameter at the extraction pipe from the turbine (state 2) is 40 cm, calculate the exit velocity from this pipe. **(3 Marks)**

d) Rate of heat transfer removed from the steam in the condenser. **(3 Marks)**

e) Draw a *T-v* diagram showing the state points and process path(s). Label the values of T and v for each state point and clarify label the constant temperature lines that passess through the state points. **(6 Marks)**

Solution

a. From mass conservation equation for control volume enclosing turbine

$$ \sum \dot{m}_{in} = \sum \dot{m}_{out} $$

$$ \dot{m}_1 = \dot{m}_2 + \dot{m}_3 $$

$$ 20 = 5 + \dot{m}_3 $$

$$ \dot{m}_3 = 15\ \text{kg/s} $$

b. From superheated vapor water table (Table B.1.3) at P_1=10000 kPa and T_1=500 ^{o}C

$$ h_1 = 3373.63\ \ \text{kJ/kg} $$

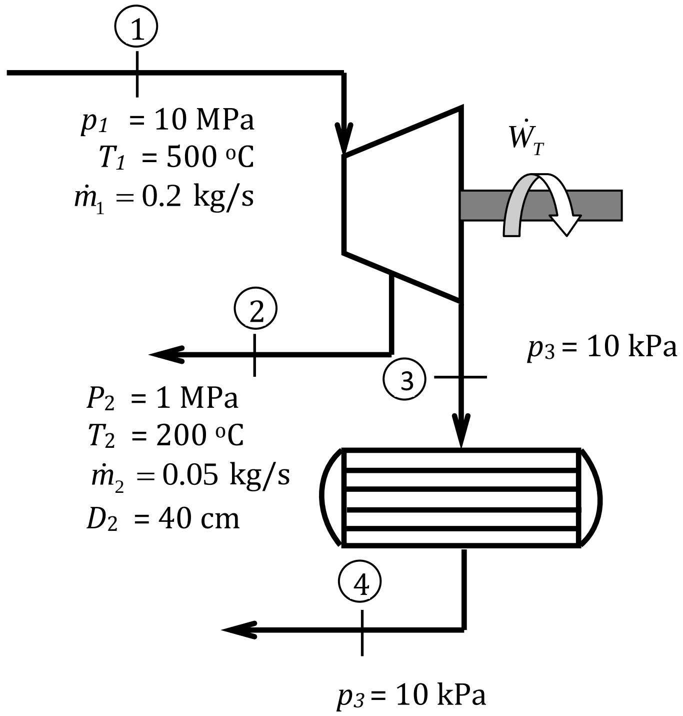


Figure 2 Sketch of problem in question #4

From saturated water table (Table. B.1.2) at P_2=1000kPa

$$T_s = 179.91\ ^oC$$

Since $T_2 > T_s\ @1000\ \text{kPa}$, state 2 is superheated. From superheated vapour water table (Table B.1.3) at P_1=1000 kPa and T_1=200 °C

$$h_2 = 2827.86\ \text{kJ/kg}$$

From saturated water table (Table. B.1.2) at P_2=10kPa

$$h_{f3} = 191.81 \qquad \text{kJ/kg}$$

$$h_{fg3} = 2392.82 \qquad \text{kJ/kg}$$

$$\begin{aligned} h_3 &= h_{f3_1} + x_3 h_{fg3} \\ &= 191.81 + 0.9 \times 2392.82 \\ &= 2345.35 \qquad \text{kJ/kg} \end{aligned}$$

From fist law of thermodynamics of a control volume enclosing the turbine

$$\dot{Q}_T - \dot{W}_T = \left(\sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in}\right) + \frac{1}{2}\left(\sum \dot{m}_{out} V_{out}^2 - \sum \dot{m}_{in} V_{in}^2\right) + +$$

$$g\left(\sum \dot{m}_{out} z_{out} - \sum \dot{m}_{int} z_{in}\right)$$

$$0 - \dot{W}_T = \left(\sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in}\right) + 0 + 0$$

$$\begin{aligned} \dot{W}_T &= \left(\sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out}\right) \\ &= \dot{m}_1 h_1 - \left(\dot{m}_2 h_2 + \dot{m}_3 h_3\right) \\ &= 20 \times 3373.63 - \left(5 \times 28247.86 + 15 \times 2345.35\right) \\ &= 1815.05 \qquad \text{kW} \\ &= 1.815 \qquad \text{MW} \end{aligned}$$

c. From superheated vapor water table (Table B.1.3) at P_1=1000 kPa and T_1=200 °C

$$v_2 = 0.20596 \qquad \text{m}^3\text{/kg}$$

The cross sectional area of extraction pipe is

$$A_2 = \pi D_2^2 / 4$$
$$= \pi \times (0.4)^2 / 4$$
$$= 0.12566$$

From equation of mass flow rate at state 2

$$\dot{m}_2 = A_2 \cancel{V}_2 / v_2$$
$$\cancel{V}_2 = \dot{m}_2 v_2 / A_2$$
$$= 5 \times 0.20596 / 0.12566$$
$$= 8.195 \quad \text{m/s}$$

d. Since state 4 is saturated liquid

$$h_4 = h_f \, @10 \text{ kPa} = 191.81 \quad \text{kJ/kg}$$

From fist law of thermodynamics for a control volume enclosing the condenser

$$\dot{Q}_C - \dot{W}_C = \dot{m}\left[(h_4 - h_3) + \frac{1}{2}(\cancel{V}_2^2 - \cancel{V}_2^2) + g(z_2 - z_1)\right]$$
$$\dot{Q}_C - 0 = \dot{m}[(h_4 - h_3) + 0 + 0]$$
$$\dot{Q}_C = \dot{m}(h_4 - h_3)$$
$$= 15(191.81 - 2345.35)$$
$$= -32303.1 \text{ kW}$$
$$= -32.303 \text{ MW}$$

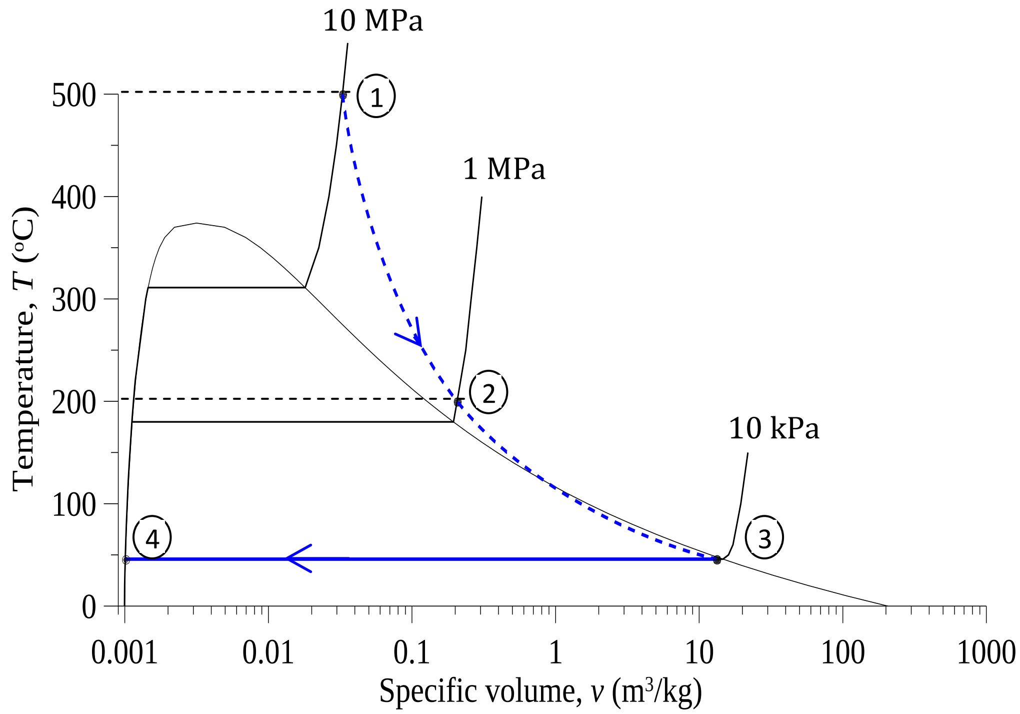
e. From superheated vapour water table (Table B.1.3)

$$v_1 = 0.03279 \quad \text{m}^3/\text{kg}$$
$$v_2 = 0.20596 \quad \text{m}^3/\text{kg}$$

From saturated water table (Table. B.1.2) at P_2=10kPa

$$v_{f3} = 0.00101 \text{ m}^3/\text{kg}$$
$$v_{fg3} = 14.67254 \quad \text{m}^3/\text{kg}$$

$$v_3 = v_{f3_1} + x_3 v_{fg3}$$
$$= 0.00101 + 0.9 \times 14.67254$$
$$= 13.206296 \quad \text{m}^3/\text{kg}$$



Question #5 (27 Marks)

Two springs with the same spring constant are installed in a piton/cylinder arrangement with outside air at 100 kPa. The cylinder (shown in Figure 3) contains 1 kg of water initially at 110 °C and a quality of 15% (state 1). Heat is added to the cylinder until the pressure and temperature inside the cylinder are 1 MPa and 1300 C (state 4), respectively. If the piston comes in contact with the first spring when the volume of the cylinder equals =0.25 m³ (state 2) and with the second spring when the volume of the cylinder is doubled (state 3). Calculate

a. Mass of piston if its cross sectional area is 500 cm². **(3 Marks)**
b. Springs constant. **(11 Marks)**
c. Pressure at which piston comes in contact with the second spring, P_3. **(1 Marks)**
d. Work done by water in each process and net work. **(4 Marks)**
e. Heat transfer to the cylinder. **(3 Marks)**
f. Draw a *P-V* diagram showing the state points and process path(s). label the values of P and V for each state point and clarify label the constant temperature lines that passes through the state points. **(5 Marks)**

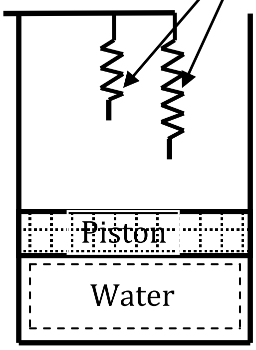
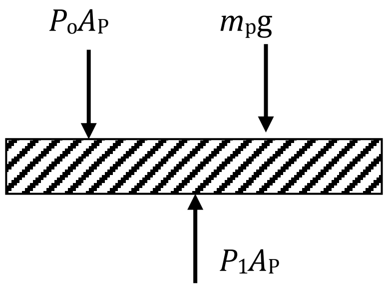


Figure 3 Sketch of problem in question #5

Solution

Summary of states

State 1 (T_1=110 °C, x_1=0.15, m_1=1 kg)
State 2 (P_2=P_1, V_2=0.25 m³, m_2=1 kg)
State 3 (V_3=0.5 m³, m_3=1 kg)
State 4 (P_3 = 1MPa,T_3=1300 °C, m_4=1 kg)



a. From saturated steam tables (Table A.4) at T_1=110 °C

$$P_1 = 143.38\,\text{kPa}$$

From foce balance of the piston

$$P_1 = P_o + \frac{m_p g}{A_p} \rightarrow 143.38 = 100 + 0.15 \times \frac{m_p \times 9.81}{0.05 \times 10^3}$$

$$m_p = \frac{(P_1 - P_o)A_p}{g} = \frac{(143.38 - 100) \times 10^3 \times 0.0500}{9.81} = 221.101 \text{ kg}$$

b. Calculating the spring constant

From saturated steam tables (Table A.4) at T_1=110 °C

$$v_{f1} = 0.001052 \text{ m}^3/\text{kg}$$

$$v_{g1} = 1.2094 \text{ m}^3/\text{kg}$$

$$v_2 = \frac{V_2}{m_2} = \frac{0.25}{1} = 0.25 \text{ m}^3/\text{kg}$$

Since P_2=P_1, $v_{g2} = v_{g1} = 1.2094$, and $v_2 < v_{g2}$, state 2 is saturated mixture and P_2=P_1=143.38 kPa

From superheated team tables (Table A-6) at 1 MPa and 1300 °C

$$v_4 = 0.72610 \text{ m}^3/\text{kg}$$

$$V_4 = m_4 v_4 = 1 \times 0.72610 = 0.72610 \text{ m}^3$$

From spring equation

$$P_3 = P_2 + \frac{K}{A_p^2}\left(V_3 - V_2\right) \qquad (1)$$

$$P_4 = P_3 + \frac{2K}{A_p^2}\left(V_4 - V_3\right) \qquad (2)$$

Using Eq. (1) in Eq. (2)

$$P_4 = P_2 + \frac{K}{A_p^2}\left(V_3 - V_2\right) + \frac{2K}{A_p^2}\left(V_4 - V_3\right) = P_2 + \frac{K}{A_p^2}\left(2V_4 - V_2 - V_3\right)$$

$$K = \frac{A_p^2\left(P_4 - P_2\right)}{\left(2V_4 - V_2 - V_3\right)} = \frac{(0.0500)^2 \times (1000 - 143.38)}{(2 \times 0.7261 - 0.25 - 0.50)} = 3.050 \text{ kN/m}$$

c. Calculating the Pressure P_3

Substitute value of K in Eq. (1)

$$P_3 = P_2 + \frac{K}{A_p^2}\left(V_3 - V_2\right) = 143.38 + \frac{3.050}{(0.0500)^2} \times (0.50 - 0.25) = 448.38 \text{ kPa}$$

d. Calculating the work done by water for each process

Process 1→2 is an isobaric expansion process

Process 2→3 is a spring expansion process with spring constant K

Process 3→4 is a spring expansion process with spring constant 2K

$$v_1 = v_{f1} + x_1\left(v_{g1} - v_{f1}\right) = 0.001052 + 0.15 \times (1.2095 - 0.001052) = 0.1823 \text{ m}^3/\text{kg}$$

$$V_1 = m_1 v_1 = 1 \times 0.1823 = 0.1823 \text{ m}^3$$

$$W_{12} = P_1\left(V_2 - V_1\right) = 143.38 \times (0.25 - 0.1823) = 9.707 \text{ kJ}$$

$$W_{23} = \frac{\left(P_2 + P_3\right)}{2}\left(V_3 - V_2\right) = \frac{(143.38 + 448.38)}{2} \times (0.50 - 0.25) = 73.970 \text{ kJ}$$

$$W_{34} = \frac{\left(P_3 + P_4\right)}{2}\left(V_4 - V_3\right) = \frac{(448.38 + 1000)}{2} \times (0.72610 - 0.50) = 163.739 \text{ kJ}$$

$$W_{net} = \sum W = W_{12} + W_{23} + W_{34} = 9.707 + 73.970 + 163.739 = 247.416 \text{ kJ}$$

e. Calculating the heat transfer to the cylinder

From saturated steam tables (Table A.4) at T_1=110 °C

$$u_{f1} = 461.27 \text{ kJ/kg}$$

$$u_{fg1} = 2056.4 \text{ kJ/kg}$$

$$u_1 = u_{f1} + x_1 u_{fg1} = 461.27 + 0.15 \times 2056.4 = 769.73 \text{ kJ/kg}$$

From superheated team tables (Table A-6) at 1 MPa and 1300 °C

$$u_4 = 4685.8 \text{ kJ/kg}$$

$$Q - W = m\left(u_4 - u_1\right)$$

$$Q - 247.416 = 1 \times (4685.8 - 769.73)$$
$$Q = 4163.486 \text{ kJ}$$

f. Drawing the P-V diagram showing the state points and process path