BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI (RAJ)
Second Semester (2017-2018)
Course No: BITS F111 Thermodynamics; Mid semester test (Open book)

Max Marks 90 **Tuesday, 6th March 2018** **Duration 90 min**

- The Question paper has two parts**: Part A (25 marks) and Part B (65 Marks)**
- Answer **Part A** in the **question paper** itself, in the space provided**.**
- Answer **Part B** in the answer book
- **Please highlight the answers**

Name: Id: Section No:

PART A

Q 1. A) True or false **[15M]**

A		**During an isothermal expansion of an ideal gas**	
	I	The internal energy of the gas increases	F
	II	The work done by the gas is positive	T
	III	Heat must be added to the gas	T
B		**When heat is added to an ideal gas during isochoric process**	
	I	The work done by the gas is negative	F
	II	The pressure of the gas increases	T
	III	The internal energy of the gas remains constant	F
C		**When the ideal gas is compressed in the constant pressure process**	
	I	The work done by the gas is positive	F
	II	Heat must be removed from the gas	T
	III	The internal energy of the gas must decrease	T
D		**According to the First Law of thermodynamics**	
	I	If heat is added to the system, the internal energy of the system ***must*** increase	F
	II	If heat is added to the system, system ***must*** do work on the surrounding	F
	III	If no heat is added to the system, system can do no work on the surrounding	F
E		**In a cyclic process involving an ideal gas**	
	I	Net heat transfer to the system must be zero	F
	II	Net work done is always positive	F
	III	The net change in internal energy of the gas is always zero	T

C) Bromine (Br_2) is at a pressure of 1 MPa and 1500 K (state 1). It is throttled to a pressure of 100 kPa. Estimate the final temperature of bromine. Justify any assumptions used.
[5M]

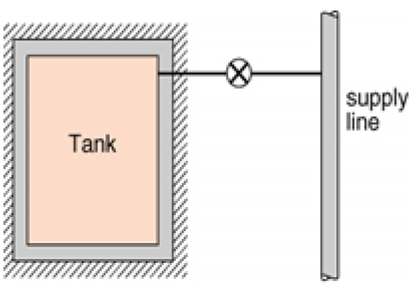
$$T_r = \frac{T}{T_c} = \frac{1500}{588} = 2.55\ and P_r = \frac{P}{P_c} = \frac{1000}{10300} = 0.09708$$

Therefore, from chart no. D.1
$Z \cong 1$
Hence, Bromine will behave as an ideal gas **[2M]**
In throttling,
h1-h2 as enthalpy is a function of temperature for an ideal gas T1=T2
Therefore, Temperature of bromine after throttling is 1500 K **[3M]**

D) An initially evacuated tank is connected by a valve to a helium supply line flowing helium at 127°C, 1000 kPa. The valve is opened, and helium flows into the tank until the pressure reaches 500 kPa.

Determine the final temperature of helium, assuming the process is adiabatic. **[3M]**

Explain the reason for change in temperature in one line. **[2M]**



$m_i h_i = m_2 u_2$; $m_i = m_2$

$h_i = u_2$; $C_p T_i = C_v T_2$;

T2=Cp/Cv Ti; T2=1.667*400.15=667.05 K [3M]

$h_i = u_2$; $u_i + P_i v_i = u_2$; $P_i v_i = u_2 - u_i$;

therefore change in temperature is due to the flow work [2M]

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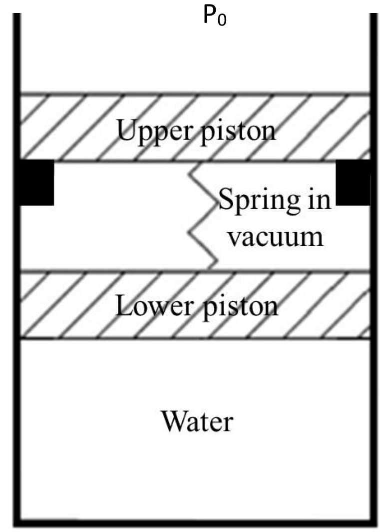
PART B

Q 2. A vertical cylinder/piston contains 1 kg of water as shown in the figure. The lower piston (area = 0.1 m^2) and linear spring (spring constant = 3.69 kN/m) are both massless. The upper piston (area = 0.1 m^2) is initially resting on stops and has a mass such that a pressure of 500 kPa (includes atmospheric pressure) will float it. The system initially consists of saturated liquid water at 55 °C (State 1). The system is now heated until water reaches a temperature of 150 °C (State 2). If the lower piston touches the stops, the volume of water will be 0.5 m^3. Answer the following questions:



(a) Is the lower piston touching the stops in the final state (State 2)? Justify.
(b) Will the upper piston float in the final state (State 2)? Justify.
(c) Find the pressure exerted by the spring in the final state (State 2)?
(d) Find the work done during the process (${}_1W_2$ in kJ).
(e) Calculate the heat transferred during the process (${}_1Q_2$ in kJ).
(f) Represent the process on a P-v (pressure vs. specific volume) diagram. **[20 M]**

Solution

State 1 — Section 3M

$T_1 = 55$ °C
$v_1 = v_f = 0.001015$ m^3/kg (at saturated liquid line)
$V_1 = 0.001015$ m^3 **1M**
$P_1 = 15.758$ kPa **1M**
$u_1 = 230.19$ kJ /kg **1M**

(a) Is the lower piston touching the stops in the final state (State 2)? Justify. — Section 4 M
Assume that the lower piston touches the stops:
$V_2 = 0.5$ m^3
$v_2 = 0.5$ m^3/kg
$T_2 = 150$ °C (superheated)
$P_2 = 382$ kPa (by interpolation) **1M**
$u_2 = 2565.6086$ kJ/kg (by interpolation) **1M**

Computing the max pressure that can be exerted by the spring
$P_{2,\text{ spring-max}} - P_1 = k/A^2 * \Delta V$

$P_{2,\ spring\text{-}max} = k(V_2\text{-}V_1)/A^2 + P_1$
$P_{2,\ spring\text{-}max} = 3690*(0.5 – 0.001015)/0.1^2 + 15758 = 199.88$ kPa
Since $P_{2,\ spring\text{-}max} < P_2 \Rightarrow$ the lower piston is touching the upper stops.

Also note that if $P_2 < P_{2,\ spring\text{-}max} \Rightarrow v_2$ will be $> 0.5\ m^3 \Rightarrow$ the lower piston has to be touching the upper stops. **2M for showing it touches stops with correct calculations, no marks for guess work**

(b) Is the upper piston touching the stops in the final state (State 2)? Justify. 2 M

Since the lower piston is touching the stops in the final state and P_2 (382 kPa) < P_{float} (500 kPa), this means that the upper piston is also touching the stops and not floating. **Must give correct property value justifying upper piston on stops, no marks for guess work**

(c) Find the pressure exerted by the spring in the final state? 2 M

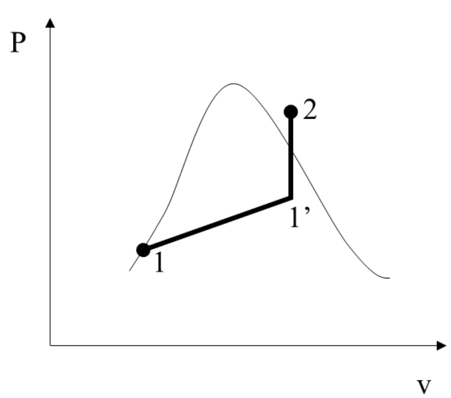
$P_{2,\ spring} = k/A^2*\Delta V + P_1 = 3690*(0.5 – 0.001015)/0.1^2 + 15758 = 199.88$ kPa
2M for correct final value, no marks for only equation

(d) Find the work done during the process (${}_1W_2$ in kJ). 3 M

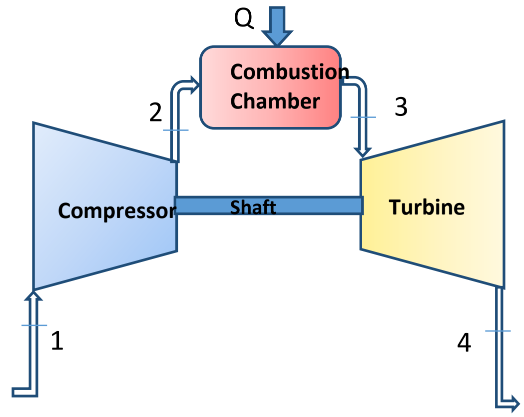
$W_{total} = W_{1\text{-}1'} + W_{1'\text{-}2} = (P_1 + P_{1'})/2*(V_{1'} – V_1) + 0$
$\Rightarrow W_{total} = (15.758 + 199.88)/2*(0.5 – 0.001015) = 53.8009$ kJ
3M for correct final value, no marks for only equation

(e) Calculate the heat transferred during the process (${}_1Q_2$ in kJ). 3 M
$Q = \Delta U + W$
$Q = m(u_2 – u_1) + W = 1*(2565.6086 - 230.19) + 53.8009 = 2389.2195$ kJ
3M for correct final value, no marks for only equation

(f) Represent the process on a P-v (pressure vs. specific volume) diagram. 3 M
Saturation dome + process 1 to 1’ + process 1’ to 2 correctly for full 3M



Q 3. Air enters the compressor at the ambient condition of 100 kPa and 25 ^{0}C (state 1). At the exit (state 2) of the compressor the pressure is 10 times of inlet pressure. The compression process is polytropic with n=1.40645. Constant pressure heat addition takes place in the combustion chamber. The temperature at the exit of the combustion chamber is 726.85 ^{0}C (state 3). The pressure at the exit of the turbine is 110 kPa (state 4) and the expansion process in the turbine is polytropic with n=1.592. Assume air as an ideal gas with mass flow rate of 15 kg/sec and use steady state energy equation to determine



a) the amount of power required for the compression process. [7M]
b) Heat added in the combustion chamber [4M]
c) Power generated by the turbine [7M]
d) Net power output from the plant. [2M] [20M]

Solution:

State 1: P1=100 kPa and T1=298.15 K

State 2: P2=1000 kPa

T2/T1=(P2/P1)$^{(n-1/n)}$

T2= 298.15*(10)$^{(0.40645/1.40645)}$ = 579.99 K=580K [3M]

$$\dot{m}(h_1) = \dot{W} + \dot{m}(h_2)$$ [2M]

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

$$15(298.62 - 586.35) = \dot{W}$$

$$\dot{W} = -4315.95\ kW$$ [2M]

"-" sign shows that the work is done on the air.

State 3:

$$\dot{m}(h_2) + \dot{Q} = \dot{m}(h_3)$$ [2M]

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

$$\dot{Q} = 15(1046.22 - 586.35) = 6898.05\ kW$$ [2M]

Heat added in the combustion chamber =6898.05 kW

State 4:

T_4/T_3=(P4/P3)(0.592/1.592)=0.440081 [3M]

T4=0.440081*1000=440.081 K

$$\dot{m}(h_3) = \dot{W} + \dot{m}(h_4)$$ [2M]

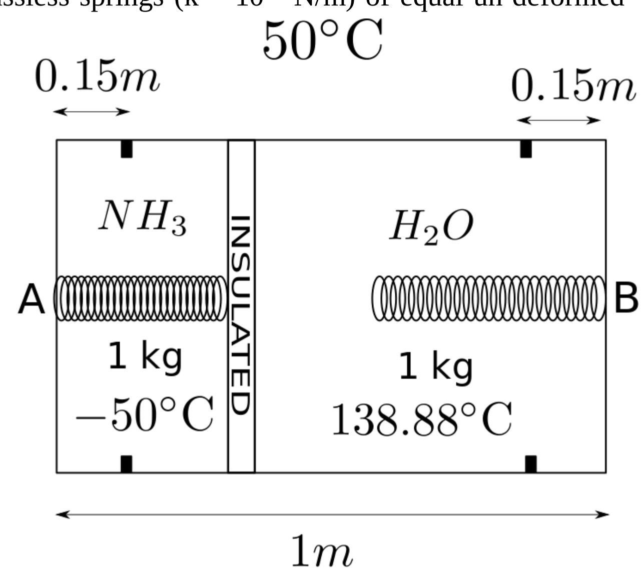
$$\dot{m}(h_3 - h_4) = \dot{W}$$

$$15(1046.22 - 441.93) = \dot{W}$$
$$\dot{W} = 9064.35\ kW$$ [2M]

Power generated by the turbine=9064.35 kW

Net power generated=4748.4 kW [2M]

Q 4. Figure below shows a cylindrical container with an insulated, frictionless piston of negligible thickness and cross-sectional area of 0.1 m^2. There are two linear, massless springs (k = 10^5 N/m) of equal un-deformed length (0.5 m) fixed with the container at point A and point B. The piston can touch either of these springs while it moves but it is not attached to these. There are two stops at a distance of 0.15 m from either cylinder end. Initially 1 kg of saturated Ammonia (0 < x < 1) at -50 ^{0}C is there in the left chamber and 1 kg of saturated water (0 < x < 1)at 138.88 ^{0}C is there in the right chamber with the piston in equilibrium under the pressure and the spring forces. Now the container is exposed to the surroundings and it finally comes in equilibrium with the surroundings at 50 ^{0}C.



Do the following:

1) Write the equation which gives the net heat heat transfer of the system with the surroundings. [3M]
2) Calculate the change in internal energy of the springs during the process [6M]
3) Calculate the change in internal energy of Ammonia during the process. [6M]
4) Calculate the change in internal energy of water during the process. [6M]
5) Calculate the net heat transfer that occurs during the process. [4M]

We have from first law:

$$\Delta U^{NH_3}_{fluid} + \Delta U^{NH_3}_{spring} = \delta Q^{NH_3} - \delta W^{NH_3}$$
$$\Delta U^{H_2O}_{fluid} + \Delta U^{H_2O}_{spring} = \delta Q^{H_2O} - \delta W^{H_2O}.$$

Now we have: $\delta W^{NH_3} = -\delta W^{H_2O}$.

Adding the above two we get: $\delta Q^{NH_3} + \delta Q^{H_2O} = \Delta U^{NH_3}_{fluid} + \Delta U^{NH_3}_{spring} + \Delta U^{H_2O}_{fluid} + \Delta U^{H_2O}_{spring}$.

Let $1 \equiv$ Initial state and $2 \equiv$ Final state

We have the net heat transfer:

$Q_{net} = [U^{NH_3}_{fluid,2} - U^{NH_3}_{fluid,1} + U^{NH_3}_{spring,2} - U^{NH_3}_{spring,1}] + [U^{H_2O}_{fluid,2} - U^{H_2O}_{fluid,1} + U^{H_2O}_{spring,2} - U^{H_2O}_{spring,1}]$

Now: $U^{NH_3}_{spring,2} = 0$ and $U^{H_2O}_{spring,1} = 0$ because of no deflection.

$\Rightarrow Q_{net} = [U^{NH_3}_{fluid,2} - U^{NH_3}_{fluid,1} - U^{NH_3}_{spring,1}] + [U^{H_2O}_{fluid,2} - U^{H_2O}_{fluid,1} + U^{H_2O}_{spring,2}]$ **3 marks**

We have to find the initial and final enthalpies of the fluids and the energy stored in the springs.

step 1: Initial position of the piston

From the initial balance of spring and pressure forces we have: $(P^{H_2O}_{\text{initial}} - P^{NH_3}_{\text{initial}})A_p = k * \Delta x$

$\Rightarrow (350 - 40.9) \times 10^3 * 0.1 = 10^5 \Delta x$. So the initial NH_3 spring deflection is $\Delta x_1 = 0.3091$ m.

$\Rightarrow U^{NH_3}_{spring,1} = \frac{1}{2} * 10^5 * 0.3091^2 = 4.777$ kJ. **3 marks**

step 2: Initial physical properties of the fluids:

Initial volume of the NH_3 chamber = $A_p * (0.5 - 0.3091) = 0.01909$ m^3. Sp. volume of NH_3 is given by $v_f^{NH_3} + x * v_{fg}^{NH_3} = 0.001424 + x * 2.62557$. Since mass of NH_3 is 1 kg, we get quality $x = 6.728 \times 10^{-3}$ as the initial quality of Ammonia initially.

$\Rightarrow U_{fluid,1}^{NH_3} = (-43.82 + 6.728 \times 10^{-3} * 1309.1) * 1\text{kg} = -35.01$ kJ. **3 marks**

Similarly for water we have: Volume = $(0.5 + 0.3091)A_p = 0.08091$ m^3. To find the quality of water we have: sp. vol = $0.001079 + x * 0.52317$. Since mass of water is also equal to 1 kg, we get the initial quality $x = 0.1526$.

$\Rightarrow U_{fluid,1}^{H_2O} = (583.93 + 0.1526 * 1964.98) * 1\text{kg} = 883.768$ kJ. **3 marks**

step 3: Final physical properties of the fluids:

The final volume of NH_3 assuming that the piston touches right stops is: 0.85* A_p = 0.085 m^3. We have Ammonia at superheated state at 50°C and sp. volume of 0.085 m^3/kg $\Rightarrow$ $P_{\text{superheated}}^{NH_3} = 1600$ kPa.

A sp. volume of 0.015 m^3/kg and 50°C shows that water will be in saturated state $\Rightarrow$ $P_{sat}^{H_2O} = 12.35$ kPa.

A pressure balance shows that indeed the piston is touching the right stops in final state: $(1600 \times 10^3)A_p > (k * \underbrace{\Delta x}_{0.35m} + 12.35 \times 10^3 * A_p)$.

$\Rightarrow U_{fluid,2}^{NH_3}$ @ 50°C and 1600 kPa = 1364.9 kJ. **3 marks**

For water we have the final sp. volume equal to 0.015 m^3 at 50°C. The quality can be calculated by $0.001012 + x * 12.0308 = 0.015 \Rightarrow x = 1.162 \times 10^{-3}$.

$$\Rightarrow U^{H_2O}_{fluid,2} = 209.3 + 1.162 \times 10^{-3} * 2234.17 = 211.89 \text{ kJ.} \qquad \textbf{3 marks}$$

Spring potential energy in final state is because of a deflection of 0.35 m.

$$\Rightarrow U^{H_2O}_{spring,2} = \frac{1}{2} * 10^5 * 0.35^2 = 6.125 \text{ kJ.} \qquad \textbf{3 marks}$$

step 4: Heat transfer calculation

Putting things for 1 kg of both Ammonia and water into

$$Q_{net} = [U^{NH_3}_{fluid,2} - U^{NH_3}_{fluid,1} - U^{NH_3}_{spring,1}] + [U^{H_2O}_{fluid,2} - U^{H_2O}_{fluid,1} + U^{H_2O}_{spring,2}]$$

we get:

$$Q_{net} = 1364.9 - (-35.01) - 4.777 + 211.89 - 883.768 + 6.125$$

$$Q = 729.38 \text{ kJ} \qquad \textbf{4 marks}$$