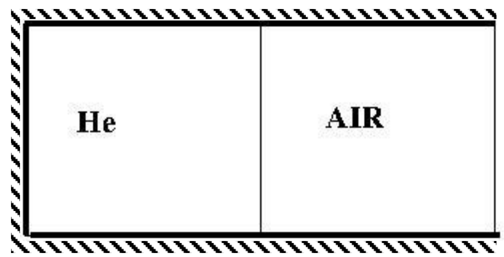
BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI (RAJ)
Second Semester (2017-2018)
BITS F111 Thermodynamics
Comprehensive Examination (close book)

Max Mark 20+100=120 | **Thursday, 3rd May 2018** | **Duration 180 min**

- The Question paper has two parts**: Part A (2x15M +1 X 20M= 50 marks) + Part B (2x25M = 50 Marks).**
- Solve Part A and Part B on separate answer sheets. Mark answer sheets as **Part-A** and **Part-B**.
- Use of Thermodynamics table is permitted.
- **Underline the answers and write in proper units.**

Part-A

Q 1. A horizontal cylinder is separated into two compartments by an adiabatic, frictionless piston. The piston is free to move horizontally in the cylinder. One side of the cylinder contains 0.5 m^3 of air and the other side contains 0.25 kg of helium, both initially at 25 ^{0}C and 90 kPa. The sides of the cylinder and the helium end are insulated. Now heat is added to the air side from a reservoir at 400 ^{0}C until the pressure of the helium rises to 125 kPa. Determine



a. the final temperature of the helium,
b. the final volume of the air,
c. the heat transferred to the air, and
d. the entropy generation during this process.
e. Exergy destruction (Assuming ambient Temperature as T_0=25 ^{0}C)

b) Sol: Assuming negligible changes in KE & PE and treating helium and air as ideal gases.

(a) Isentropic process for the transition in Helium, thus using the relation,

$$T_{2,He} = T_1 \left[\frac{P_2}{P_1}\right]^{(k-1)/k} = 340.03K$$ **[2]**

(b) The **initial and final volumes of helium** will be (by taking, ***R*** (He) = 2.0771 kJ/(kg-K)

$$V_{1,He} = \frac{mRT_1}{P_1} = 1.7202m^3 \ldots\ldots\ldots V_{2,He} = \frac{mRT_2}{P_2} = 1.41255m^3$$ **[2]**

Thus, the **final volume of air** will be,

$$V_{2,air} = V_{1,air} + V_{1,He} - V_{2,He} = 1.7202 + 0.5 - 1.41255 = 0.80765m^3$$ **[2]**

(c) The **final temperature** and **the mass of air** will be,

$$m_{air} = \frac{P_1 V_1}{RT_1} = 0.52589kg \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots T_{2,air} = P_2 \frac{V_2}{mR} = 668.893K$$ **[3]**

The heat transferred to the air can be determined from I law as,

$$Q_0 = \Delta U_{air} + \Delta U_{He} = [mc_v(T_2 - T_1)]_{air} + [mc_v(T_2 - T_1)]_{He}$$

$$= 0.52589 * 0.717 * (668.893 - 298.15) + 0.25 * 3.116 * 340.03 - 298.15)$$

$$= 172.4185\ kJ$$ **[2**]

(d) **Entropy generation** for the process from II law as,

$$S_{gen} = \Delta S_{air} + \Delta S_{surr} = m_{air}\left[c_p ln\frac{T_2}{T_1} - R ln\frac{P_2}{P_1}\right] - \frac{Q_0}{T_0}$$

$$S_{gen} = 0.52589 * \left[1.04 * ln\left(\frac{668.893}{298.15}\right) - 0.287 * ln\left(\frac{125}{90}\right)\right] - \frac{172.4185}{673.15} = 0.1362\, kJ/K$$ **[3]**

Since, Helium is undergoing an isentropic process!

(d) **Exergy destruction** will be $T_0 S_{gen}$ = *298.15*0.1362 = 40.61* **kJ** **[1]**

Q 2. Refrigerant-134a enters an adiabatic compressor at -30^{0}C as a saturated vapor at a rate of 0.50 m^3/min and leaves at 1000 kPa and 60^{0}C. Determine

a. the power input to the compressor, kJ/sec
b. the isentropic efficiency of the compressor, and
c. the rate of exergy destruction kJ/sec
d. the second-law efficiency of the compressor. Take T_0 = 27^{0}C. [15M]

Solution:

Given Data

State 1.

T1= -30^{0}C; x=1, Volume flow rate= 0.50 m^3/min;

Therefore, P1=85.1 kPa; v1= v_g = 0.22402 m^3/kg, h1= h_g = 379.80; s1=sg=1.7493 kJ/kg K [2M]

State 2

P2=1000 kPa; T2=60^{0}C

Therefore, from table: h2= 441.89 kJ/kg; s2=1.7818 kJ/kg K [2M]

Mass flow rate = 2.232 kg/min =0.0372 kg/sec

W= m(h2-h1) =0.0372 (441.89-379.80) = **2.30975 kW** [2M]

For isentropic work;

P_2= 1000 kPa; s_2=s_1=1.7493 kJ/kgK

h_{2s}= 431.24 kJ/kg [2M]

Ws = m (h2s-h1)=0.0372 (431.24-379.80)=1.9136 kW

η isentropic = m (h2s-h1)/ m (h2-h1) = 1.9136/2.31=0.8283 [2M]

= **82.83%**

Wrev= m(ψ_2- ψ_1) = m[(h2-h1)-T0(s2-s1)]= 0.0372[(441.89-379.80)- 300.15(1.7818-1.7493)]

= 1.9468 kW [2M]

I = W-Wrev = 2.30975-1.9468=**0.363 kW**

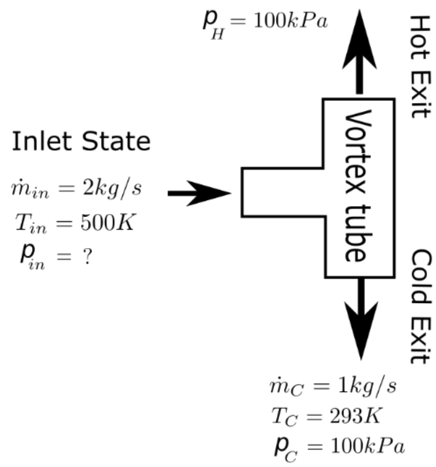
= T_0 m(s2-s1) =300.15x 0.0372(1.7818-1.7493)= **0.363 kW** [2M]

η II law efficiency = Wrev/ Wac = 1.9432/2.31=0.8412

= **84.28 %** **[1M]**

Q 3. A Vortex tube is a device which accepts hot air at high pressure and separates them into two separate streams one at a higher temperature and the other at lower temperature involving no mechanical parts (see the illustration). It can be shown, using the laws of thermodynamics that such a process is possible only if the ratio of the inlet pressure to that of outlet of the Vortex tube is greater than a certain value which is a function of the temperatures of the inlet and outlet streams.

If you have a steady supply of air ($\dot{m}_1$ = 2 kg/s , T_1 = 500 K, P_1 = 100 kPa) from some source, it may be required to increase the pressure p_{in} at the inlet (T_{in} = 500 K) of the Vortex tube so that cold air (T_C = 293 K, P_C = 100 kPa, $\dot{m}_C$ = 1kg/s) will exit from the cold side and also given that the hot side exit pressure is maintained at P_H =100 kPa. Determine



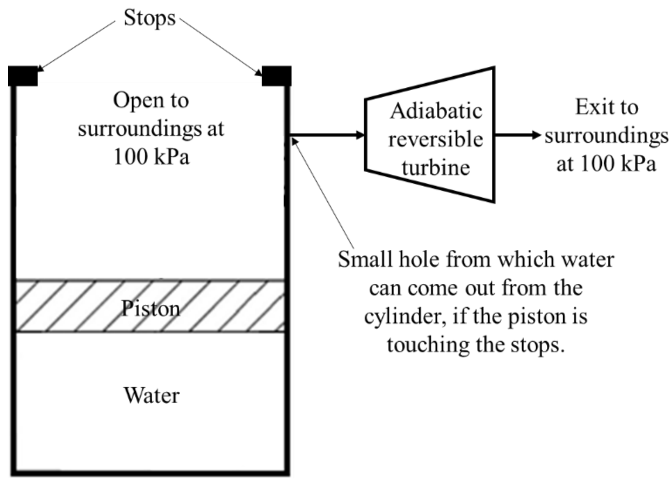
a. the minimum pressure P_{in} at the inlet side of the Vortex tube, required to achieve the desired cooling.
b. exergy available at the inlet and the two exits of the vortex tube
c. exergy destruction during the process
d. reversible work for the given inlet and the exit condition.

Assume constant specific heat, ideal gas behavior and neglect any changes in the kinetic and potential energies and heat transfer from the surroundings. The ambient temperature in the location is given as 25 ^{0}C. [20M]

Solution: Part (a)	Marks
1. $\dot{m}_H(h_H - h_i) + \dot{m}_C(h_C - h_i) = 0$ 2. $(h_H - h_i) + (h_C - h_i) = 0$ 3. $(T_H - T_i) + (T_C - T_i) = 0$ $T_H = 2T_i - T_C$ = 707 K 4. $(s_H - s_i) + (s_C - s_i) = \dot{s}_{gen} \geq 0$ 5. $c_p ln\left[\frac{T_H T_C}{T_1^2}\right] - R ln\left[\frac{p_H p_C}{p_1^2}\right] \geq 0$ 6. $p_1 \geq \sqrt{\left(\frac{T_1^2}{T_H T_C}\right)^{c_p/R} p_H p_C}$ = 138.98 kPa	T_H (2 Marks) Formulae (4 Marks) Final Answer (2 Marks)
Part (b) Exergy at inlet and exits $$\psi_{in} = h_{in} - T_0 s_{in} - h_0 + T_0 s_0$$ ψ_{in}=Cp*(T1-T0)-T0*(Cp*log(T1/T0)-R*log(p1/p0)) = 76.110 kJ/kg ψ_H=Cp*(TH-T0)-T0*(Cp*log(TH/T0)-R*log(pH/p0)) =152.17 kJ/kg ψ_C=Cp*(TC-T0)-T0*(Cp*log(TC/T0)-R*log(pC/p0)) =0.045 kJ/kg	8 Marks 2 Mark for formula 2 Marks for each answer
Part (c) Exergy destruction in the process = 0	2 Marks
Part (d) Reversible work done in the process = 0	2 Marks

Part-B

Q 4. A cylinder piston arrangement as shown in the figure contains 1000 kg of water. The water is initially in thermal equilibrium with surroundings at a temperature of 25 °C and a pressure of 200 kPa (float pressure of the piston). The volume of the cylinder is known to be 2.006 m^3 when the piston is touching the stops. The cylinder and piston are well-insulated, except the bottom part of the cylinder. There is a small hole near the top of the cylinder from which the water can escape and pass through a turbine (adiabatic and reversible) as shown in the figure. Note that water can escape from the cylinder only when the piston is touching the stops. The system is now heated slowly by bringing the cylinder's bottom into contact with a heat source at a temperature of 120.23 °C (saturation temperature at 200 kPa) until all the water in the cylinder gets converted into saturated vapor. Now the heat source is removed and water in the cylinder is slowly cooled by rejecting heat to the surroundings until thermal equilibrium is reached. Compute the following:



a. The heat transferred from the source at 120.23 °C during the heating process in MJ?
b. The heat transferred to the surroundings during the cooling process in MJ?
c. The shaft work done by water during this process in MJ?
d. The boundary work done by water during this process in kJ?
e. The entropy generation during the heating process in kJ/K?
f. The entropy generation during the cooling process in kJ/K?
g. The total exergy destruction. [30M]

State 1	State 2 (Heating stopped and cooling started)	State 3 (Final equilibrium state)
Subcooled liquid m_1 = 1000 kg P_1 = 200 kPa T_1 = 25 C $v_1 = v_f$ @ 25 C v_1 = 0.001003 m3/kg V_1 = 1.003 m^3 u_1 = 104.86 kJ/kg-K s_1 = 0.3673 kJ/kg-K	Saturated vapor P_2 = 200 kPa $v_2 = v_g$ v_2 = 0.88573 m3/kg V_2 = 2.006 m^3 $m_2 = V_2/v_2$ = 2.006/0.88573 m_2 = 2.26 kg u_2 = 2529.49 kJ/kg s_2 = 7.1271 kJ/kg-K	Subcooled liquid m_3 = 2.26 kg P_3 = 200 kPa T_3 = 25 C v_3 = 0.001003 m3/kg $V_3 = m_4 * v_4$ V_3 = 0.00226678 m^3 u_3 = 104.86 kJ/kg-K s_3 = 0.3673 kJ/kg-K

State i (inlet to turbine)	State e (exit to turbine)
Saturated vapor Pi = 200 kPa T_i = 120.23 C s_i = 7.1271 kJ/kg-K h_i = 2706.63 Kj/KG	P_e = 100 kPa s_e = 7.1271 kJ/kg-K $s_f < s_e < s_g$ => Saturated mixture $s_e = s_f + xs_{fg}$=> $x = (s_e - s_f)/s_{fg}$ x_e = (7.1271 - 1.3025)/6.0568 = 0.9617 x_e = 0.9617 $h_e = h_f + xh_{fg}$ = 417.44 + 0.9617*2258.02 h_e = 2588.98 kJ/kg

Calculation of the mass left in the cylinder and the mass that has escaped:

$m_2 = V_2/v_2 = 2.006/0.88573$

$m_2 = 2.26$ kg

$\Delta m = 997.74$ kg [2 marks]

1^{st} law for transient heating process (1→2):

$Q_{cv\text{-}heating} = m_e h_e + (m_2 u_2 - m_1 u_1) + W_{1\to2}$ [2 Marks]

$Q_{cv\text{-}heating} = (1000 - 2.26)*2706.63 + (2.26*2529.49 - 1000*104.86) + 200.6$

$Q_{cv\text{-}heating} = 2601.57$ MJ [4 Marks]

2^{nd} law for transient heating process (1→2):

$m_2 s_2 - m_1 s_1 = -m_e s_e + Q_{cv\text{-}heating}/T_b + S_{gen1\to2}$ [2 Marks]

$S_{gen1\to2} = 2.26*7.1271 - 1000*0.3673 + (1000 - 2.26)*7.1271 - 2601570/393.38$

$S_{gen1\to2} = 146.42$ kJ/K [4 Marks]

Boundary work done during the process (1→2→3)

Approach #1

$W_{1\to3} = 200*(0.00226678 - 1.003)$

$W_{boundary} = -200.15$ kJ [4 Marks]

Approach #2

Work done during the heating process (1→ 2)

$W_{1\to2} = P_{float}*(V_2 - V_1)$

$W_{1\to2} = 200*(2.006 - 1.003)$

$W_{1\to2} = 200.6$ kJ (Boundary work) [2 Marks]

Work done during the cooling process (2→3)

$W_{2\to3} = P_{float}*(V_3 - V_2)$

$W_{2\to3} = 200*(0.00226678 - 2.006)$

$W_{2\to3} = -400.75$ kJ (Boundary work) [2 Marks]

$W_{boundary} = -200.15$ kJ

Shaft (Turbine) work done

$w_{Ts} = h_i - h_e = 2706.63 - 2588.98$

$w_{Ts} = 117.65$ kJ/kg

$W_{Ts} = (m_2 - m_3) w_{Ts}$

$W_{Ts} = (1000 - 2.26)*117.65$

$W_{Ts} = 117.38$ MJ (Shaft work) [2 Marks]

1st law for cooling process (2→3):

$Q_{cv\text{-}cooling} = m_3(u_3 - u_2) + W_{cv2\rightarrow3}$

$Q_{cv\text{-}cooling} = 2.26*(104.86 - 2529.49) + (-400.75)$

$Q_{cv\text{-}cooling} = -5.88$ MJ [4 Marks]

2nd law for cooling process (2→3):

$m_3(s_3 - s_2) = Q_{cv\text{-}cooling}/T_b + S_{gen2\rightarrow3}$

$S_{gen2\rightarrow3} = 2.26*(0.3673 - 7.1271) - (-5880)/298.15$

$S_{gen2\rightarrow3} = 4.44$ kJ/K [4 Marks]

Exergy destruction

$T_0S_{gen} = (146.42 + 4.44)*298.15$

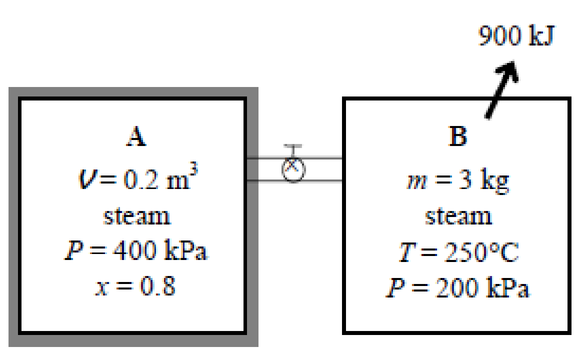
$T_0S_{gen} = 44.98$ MJ [2 Marks]

IMPORTANT REMARKS:

- Marks have been strictly awarded as per the abovementioned marking scheme.
- No marks have been awarded for state properties.
- For calculating a) $Q_{CV\text{-}heating}$, a few students have used the following equation:

$$Q_{CV\text{-}heating} = m*(h_{g@200\,kPa} - h_1)$$

Q 5. Two rigid tanks are connected by a valve. Tank A is insulated and contains 0.2 m^3 of steam at 400 kPa and 80 percent quality. Tank B is uninsulated and contains 3 kg of steam at 200 kPa and 250^{0}C. The valve is now opened, and steam flows from tank A to tank B until the pressure in tank A drops to 300 kPa. During this process 900 kJ of heat is transferred from tank B to the surroundings at 0^{0}C.



Assuming the steam remaining inside tank A to have undergone a reversible adiabatic process. Assuming Final pressure in tank B is 143.3 kPa (refer table B.1.1).
Determine (a) the final temperature in each tank (b) entropy generated (c) the work potential wasted during this process (d) reversible work.

[20M]

Solution:

Tank A state 1	
$V=0.2\ m^3$	
P=400 kPa	
x=0.8	
$v_{1A}=0.001084+0.8*0.46138=0.370188\ m^3/kg$	1M
$s_{1A}=1.7766+0.8*5.1193=5.87204$ kJ/kgK	1M
$m_{1A}=V/v_{1A}=0.540$ kg	1M

Tank A state 2	
$V= 0.2\ m^3$	
P=300 kPa	
$s_{2A}=s_{1A}=5.87204$ kJ/kgK	
$x =s_{1A}-sf/sfg=0.7895$	1M
$v_{2A}=vf+xvfg=0.001073+0.7895*0.60475=0.4785$	1M
$m_{2A}=V/v_{2A}=0.4179$ kg	1M

Tank B state 1	
$m_{1B}=3$ kg	
P=200 kPa	
$T=250\ ^0C$	
$v_{1B}=1.19880\ m^3/kg$	1M
$s_{1B}=7.7085$ kJ/kgK	
$V=v_{1B}*3=1.19880*3=3.5964\ m^3$	1M

Tank B state 2	
$m_{2B}=3\ kg+(m_{1A}-m_{2A})= 3+0.122=3.122$ kg	1M
P=143.3 kPa	
$v_{2B}= 3.5964/3.122=1.1519\ m^3/kg$	1M
$x=(v_{2B}-v_f)/v_{fg}=0.9518$	1M
$s_{2B}=s_f+xs_{fg}= 1.4184+0.9518*5.8202=6.9580$	1M

(a) the final temperature in each tank

For Tank A=133.55 ^0C saturation temperature at 300 kPa [1M]

For Tank B =110 ^0C saturation temperature at 143.3 kPa [1M]

(b) entropy generated

$S_{gen} = (m_2s_2-m_1s_1)_A+(m_2s_2-m_1s_1)_B-Q/T_{surr}$ [1M]

=(0.4179*5.87204-0.540*5.87204)+(3.122*6.9580-3*7.7085)+900/273.15

=-0.7169-1.40+3.295=1.1779 kJ/K [2M]

(c) the work potential wasted during this process = T_0S_{gen} =321.768 kJ [1M]

(d) reversible work.= the work potential wasted during this process=321.768 kJ [2M]