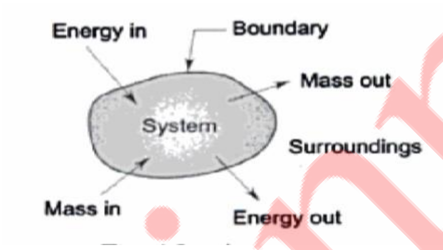
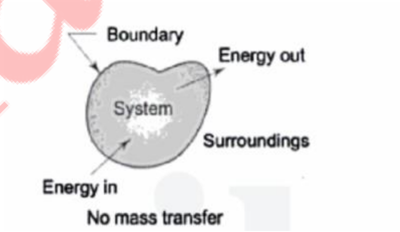
MECHANICAL ENGINEERING

THERMODYNAMICS

(CBCGS- MAY-2019)

1.(a)What is the difference between a closed and open system? (5)

OPEN SYSTEM	CLOSED SYSTEM
It is a thermodynamic system which can exchange mass and energy with the surrounding.	It is a thermodynamic system which can exchange energy but not matter with the surrounding.
Boundaries are open.	Boundaries are closed.
Mass of the system will vary.	Mass of the system is constant.
For example, the earth can be recognized as an open system. In this case, the earth is the system, and space is the surrounding. Sunlight can reach the earth surface and we can send rockets to space. Sunlight and rocket can be explained as energy and matter, respectively.	For example, if a warm cup of water is covered by placing a lid on the top of the cup, then steam cannot escape the system because of the lid. The gas molecules in the air also cannot enter the cup because of the lid. So, there is no exchange of matter.
	

1.(b) Define mechanical efficiency in case of reciprocating air compressor and state the methods used to improve isothermal efficiency? (5)

Mechanical efficiency is defined as the ratio of indicated power (I.P) to brake power (B.P) of the compressor.

The power required to drive the compressor is called brake power or shaft power of the compressor.

$$\eta_m = \frac{I.P}{B.P}$$

Isothermal efficiency is defined as ratio of isothermal work output to the actual work done.

$$\eta_{iso} = \frac{isolathermal\ work}{actual\ work}$$

Methods used to improve isothermal efficiency are:

- Improve the quality of the air intake.
- Match the air compressor controls.
- Improve system design.
- Consider compressed air needs.
- Minimize pressure drop.
- Maintain your compressor at regular interval of time.

1.(c) Define available energy, dead state and irreversibility. (5)

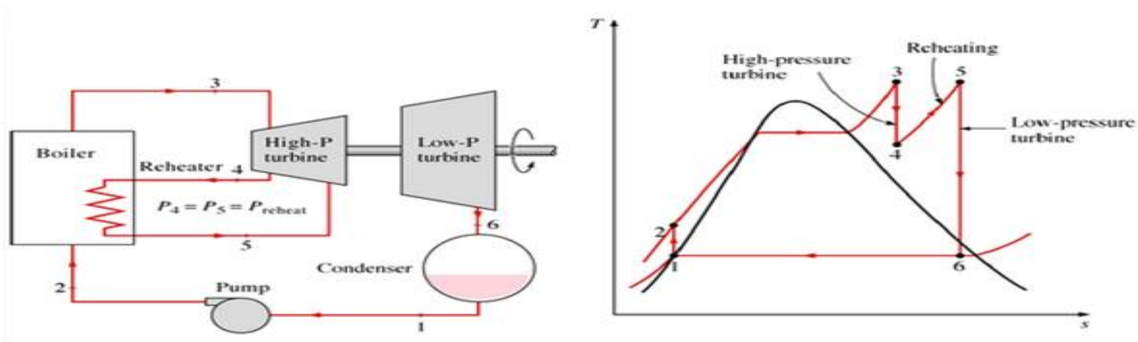
In thermodynamics, **available energy** is the greatest amount of mechanical work that can be obtained from a system or body, with a given quantity of substance.

When the system is in equilibrium with the surroundings, it should be in pressure and temperature equilibrium with the surroundings i.e. p_0 and t_0. Also, it should be in chemical equilibrium with the surroundings. The system should have zero velocity and minimum potential energy. This is called **dead state**.

The actual work done by the system is always less than the idealised reversible work and the difference between the two is called **irreversibility.**

$$I = W_{max} - W$$

1.(d) Draw a simple schematic diagram of a thermal power plant with one reheater. Also represent this on T-S diagram. (5)



1.(e) Write four Maxwell relation. **(5)**

$$+\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V$$
$$+\left(\frac{\partial T}{\partial P}\right)_S = +\left(\frac{\partial V}{\partial S}\right)_P$$
$$+\left(\frac{\partial S}{\partial V}\right)_T = +\left(\frac{\partial P}{\partial T}\right)_V$$
$$-\left(\frac{\partial S}{\partial P}\right)_T = +\left(\frac{\partial V}{\partial T}\right)_P$$

2.(a) A fluid system contained in a piston cylinder machine, passes through a complete cycle of four processes. The sum of all heat transfer during the cycle is -170 kJ. The system completes 100 cycles/min. Complete the following table showing the method for each process and compute the net rate of work output in KW. **(10)**

Process	Q(KJ/min)	W(KJ/min)	∆E(KJ/min)
1-2	0	2170	-----
2-3	21000	0	-----
3-4	-2100	-----	-36600
4-1	-----	-----	------

Let the processes **1-2, 2-3, 3-4, 4-1** be **a-b, b-c, c-d, d-a** respectively.

Process 1-2:

Q = ΔE + W

$\therefore 0 = \Delta E + 2170$ = -2170 KJ/min

Process 2-3:

Q = ΔE + W

$\therefore$ 21000= ΔE + 0

$\therefore \Delta E$ = 21000KJ/min

Process 3-4:

Q = ΔE + W

$\therefore$ -2100 = -36600 +W

$\therefore$ W = 34500KJ/min

Process 4-1:

ΣQ = -170 kJ

The system completes 100 cycles/min.

$Q_{12} + Q_{23} + Q_{34} + Q_{41}$ = -17000 kJ/min

0 + 21000 – 2100 + Q_{41} = -17000

$\therefore Q_{41}$ = -35900kJ/min.

Now $\oint dE = 0$, since cyclic integral of any property is zero.

$\Delta E_{12} + \Delta E_{23} + \Delta E_{34} + \Delta E_{41} = 0$

-2170+21000-36600+ΔE_{41} =0

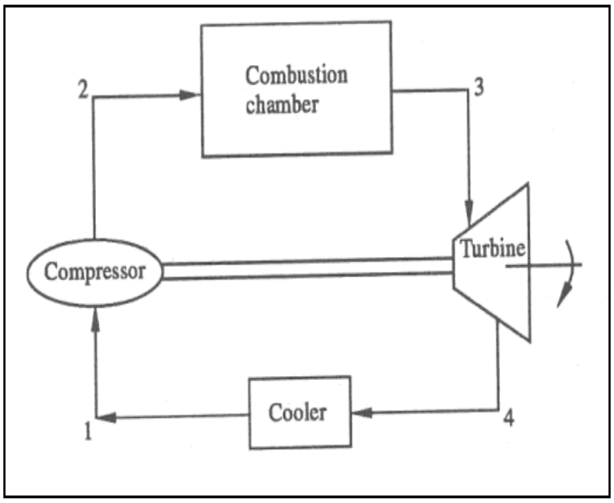
$\therefore \Delta E_{41}$ = 17770 kJ/min

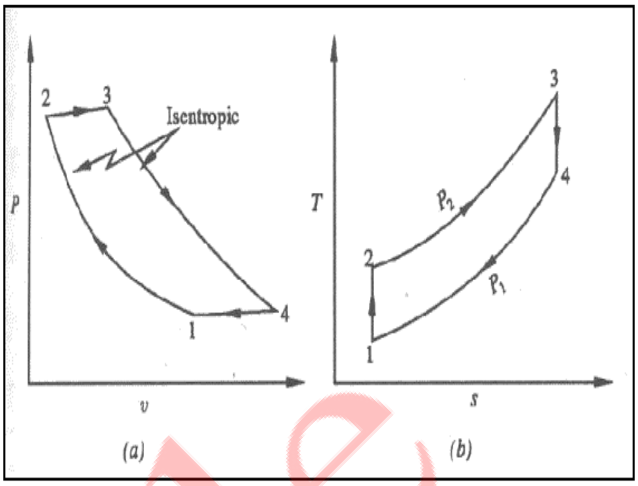
$W_{41} = Q_{41} - \Delta E_{41}$

= -35900-17770 = -53670 kJ/min

Process	Q(KJ/min)	W(KJ/min)	ΔE(KJ/min)
1-2	0	2170	-2170
2-3	21000	0	21000
3-4	-2100	34500	-36600
4-1	-35900	-53670	17770

2.(b) Derive and show that the efficiency of Brayton cycle depends on the pressure ratio. (10)





Processes: -

1-2: isentropic compression

2-3: constant pressure energy addition
3-4: isentropic expansion

4-1: constant pressure energy rejection

Energy added, $Q_1 = mC_p\,(T_3 - T_2)$

Energy rejected, $Q_2 = mC_p\,(T_4 - T_1)$

Thermal efficiency,

$$\eta = \frac{Q1 - Q2}{Q1} = 1 - \frac{T4 - T1}{T3 - T2}$$

$$\eta = 1 - \frac{T1\left(\left(\frac{T4}{T1} - 1\right)\right)}{T2\left(\left(\frac{T3}{T2} - 1\right)\right)}$$

The pressure ratio of the Brayton cycle, r_p is defined as,

$$r_p = \frac{P_1}{P_2}$$

Then,

$$\frac{P_3}{P_4} = \frac{P_2}{P_1}$$

The processes 1-2 and 3-4 are isentropic. Hence,

$$\frac{T_2}{T_1} = \frac{P_2}{P_1}^{(\gamma-1)/\gamma}$$

$\frac{T_3}{T_4} = \frac{P_3}{P_4}^{(\gamma-1)/\gamma}$

We get,

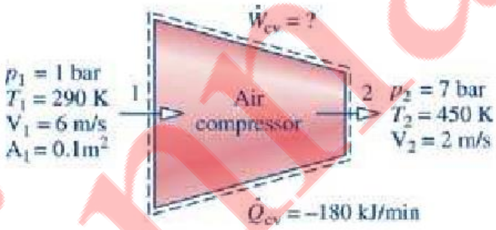
$\frac{T_2}{T_1} = \frac{T_3}{T_4}$

$\frac{T_4}{T_1} = \frac{T_3}{T_2}$

$\eta = 1- \frac{T_1}{T_2} = 1- (\frac{P_1}{P_2})^{(\gamma-1)/\gamma}$

$= 1- (\frac{1}{r_p})^{(\gamma-1)/\gamma}$

3.(a) Air enters a compressor operating at steady state at a pressure of 1 bar, a temperature of 290 K and a velocity of 6m/s through an inlet with an area of 0.1 m2. At exit the pressure is 7 bar, the temperature is 450 K and the velocity is 2 m/s. Heat transfer from the compressor to the surroundings occur at the rate of 180 KJ/min. Employing the ideal gas model, calculate the power input to the compressor. (10)



Apply the steady state energy balance between (1) and (2) gives

$h_2 - h_1 + g\,(z_2 - z_1) + \frac{1}{2}(V_2^2 - V_1^2) = \frac{Q}{m} - \frac{W}{m}$

The mass flow rate is given by:

$m^{\circ} = \frac{A1.V1}{v1}$

The specific velocity can be found by:

$v_1 = \frac{\left(\frac{R}{M}\right)T1}{p1} = \frac{(\frac{8314}{28.97})290}{10^5} \qquad = 0.8324\ kg/m^3$

The mass flow rate is then:

$m^{\circ} = \frac{A1.V1}{v1} = \frac{0.1(6)}{0.8324} = 0.7209\ kg/s$

The change in air enthalpy can be obtained by:

$h_1 - h_2$ = 290.6kJ/kg – 452.3 kJ/kg = -161.7 kJ/kg

The change in kinetic energy is evaluated:

$\frac{1}{2}(V_1^2 - V_2^2) = 0.5(6^2 - 2^2) = 0.02$ kJ/kg

The power input to the compressor is then

$W_s = Q + m((h_1 - h_2) + \frac{V_1^2 - V_2^2}{2})$

$\therefore W_s = -119.6$ kW

3.(b) Calculate the decrease in energy when 25 kg of water at 95°C mix with 35 kg of water at 35°C, the pressure being taken as constant and the temperature of surroundings being 15°C. (10)

m1= 25 kg , m2= 35 kg, T_1 = 95+273= 368 K, T_2 = 35+273= 308K,

T_0 = 15+ 273= 288K

$E_1 = mC_p \int_{T_0}^{T}\left(1 - \frac{T_0}{T}\right) dT$

$= 25 \times 4.2 \int_{288}^{368}\left(1 - \frac{388}{T}\right) dT$ = 987.49KJ

$E_2 = mC_p \int_{T_0}^{T}\left(1 - \frac{T_0}{T}\right) dT$

$= 25 \times 4.2 \int_{288}^{308}\left(1 - \frac{308}{T}\right) dT$ = 97.59KJ

$E = E_1 + E_2 =$ 1085.08 KJ

After mixing, final temperature is: 25 x 4.2(368-T) = 35 x 4.2 (T – 308)

$\therefore T = 333K$

Final available energy is

$E = (25+35) \times 4.2((333-288) - 288 \ln(\frac{333}{288})$

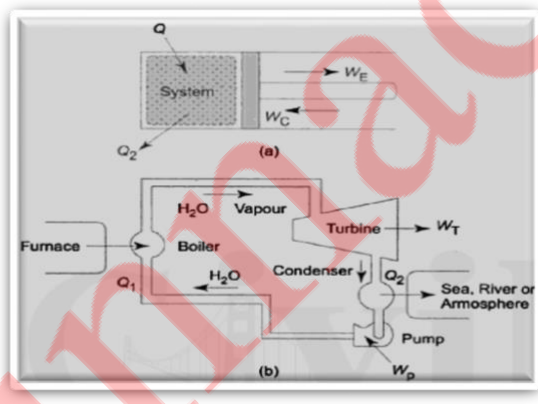
$= 803.27KJ$

$\therefore$ decrease in energy = 281.80KJ

4.(a) Explain the Carnot heat engine cycle executed by a) a stationary system and b) a steady flow system. (10)

A heat engine cycle is a thermodynamic cycle in which there is a net heat transfer to the system and a net work transfer from the system. The heat engine may be in the form of a mass of gas confined in a cylinder and piston machine or a mass moving in a steady flow through a steam power plant.

In the cyclic heat engine, fig(a), heat Q_1 is transferred to the system, work W_E is done by the system, work W_C is done upon the system and then heat Q_2 is rejected from the system. The system is brought back to the initial state through all these four successive processes which constitute a heat engine cycle.In fig(b), heat Q_1 is transferred from the furnace to the water in the boiler to form steam which then works on the turbine rotor to produce work W_T, then the steam is condensed in which an amount Q_2 is rejected from the system, and finally work W_P is done on the system to pump it to the boiler. The system repeats the cycle.



The net heat transfer in a cycle to either of the heat engines

$Q_{net} = Q_1 - Q_2$

And the net work transfer in a cycle is,

$W_{net} = W_T - W_P$

By the first law of thermodynamics, we have

$\Sigma Q = \Sigma W$

$\therefore Q_{net} = W_{net}$

$\therefore Q_1 - Q_2 = W_T - W_P$

The following figure shows a cyclic heat engine in the form of block diagram consisting of Boiler(B), Turbine(T), Condenser(C) and Pump(P), all four together constitute a heat engine.

The efficiency of Carnot heat engine cycle is given by

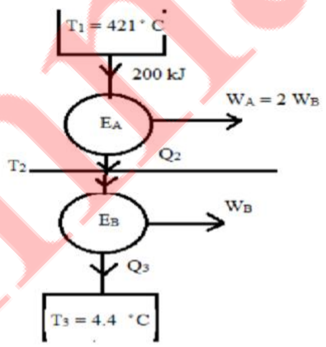
$$\eta = \frac{Wnet}{Q1}$$

$$\therefore \eta = \frac{Wt - Wp}{Q1}$$

$$\therefore \eta = \frac{Q1 - Q2}{Q1}$$

$$\therefore \eta = 1 - \frac{Q2}{Q1}$$

4.(b) Two reversible heat engines A and B are arranged in series, A rejecting heat directly to B. Engine A receives 200 kJ at a temperature of 421°C from a hot source, while engine B is in communication with a cold sink at a temperature of 4.4°C. if the work output of A is twice that of B, find a) intermediate temperature between A and B b) efficiency of each engine and c) the heat rejected to the cold sink. (10)



Solution:
From Thermodynamic temperature scale we know that,

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \quad ; \quad \frac{Q_2}{Q_3} = \frac{T_2}{T_3}$$

But $\frac{Q_1}{Q_3} = \frac{Q_1}{Q_2} x \frac{Q_2}{Q_3} = \frac{T_1}{T_3}$

➔ **$Q_3 = 79.94$ kJ**

Since, $W_A = 2\, W_B$

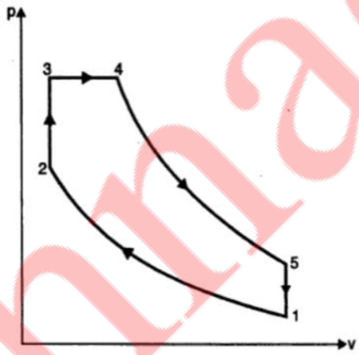
$Q_1 - Q_2 = 2(Q_2 - Q_3)$ ➔ **$Q_2 = 119.96$ kJ**

$$\frac{Q_1}{Q_2} = \frac{T_1}{T_2} \quad \Rightarrow T_2 = 143.26\ ^\circ C\ ;$$

$$\eta_A = \frac{W_A}{Q_1} = 40\% \quad \text{where } W_A = Q_1 - Q_2$$

$$\eta_B = \frac{W_B}{Q_2} = 33.36\% \quad \text{where } W_B = Q_2 - Q_3$$

5.(a) In an IC engine operating on dual cycle, the temperature of the working fluid(air) at the beginning of the compression is 27°C. The ratio of the maximum and minimum pressures of the cycle is 70 and compression ratio is 15. The amounts of heat added at constant volume and constant pressure are equal. Compute the air standard thermal efficiency of the cycle. (10)



T1 = 27+273= 300K

$$\frac{P3}{P1} = 70$$

$$\frac{V1}{V2} = \frac{V1}{V3} = 15$$

Consider adiabatic process 1-2:

$$\frac{T2}{T1} = \frac{V1}{V2}^{\gamma-1} = 15^{1.4-1} = 2.954$$

$\therefore T_2 = 300 \times 2.954 = 886.2$ K

$$\frac{P2}{P1} = \frac{V1}{V2}^{\gamma} = 15^{1.4}$$

$\therefore P_2 = 44.3\ P_1$

Constant pressure process 2-3:

$$\frac{P2}{T2} = \frac{P3}{T3}$$

$\therefore T_3 = \frac{P3}{P2} \times T2 \quad \therefore T_3 = 886.2 \times \frac{70P1}{44.3\,P1} \quad \therefore T_3 = 1400K$

Also, Heat added at constant volume = Heat added at constant pressure

$C_v(T_3 - T_2) = c_p(T_4 - T_3)$

$\therefore T_3 - T_2 = \gamma\,(T_4 - T_3)$

$\therefore T_4 = T_3 + \frac{T_3 - T_2}{\gamma} = 1400 + \frac{1400-886.2}{1.4} = 1767$ K

Constant volume process 3-4:

$$\frac{V3}{T3} = \frac{V4}{T4} \Rightarrow \frac{V4}{V3} = \frac{T4}{T3} = \frac{1767}{1400} = 1.26$$

Also, $\frac{V4}{V3} = \frac{V4}{(\frac{V1}{15})} = 1.26$ or $V_4 = 0.084\,V_1$

Also, $V_5 = V_1$

Adiabatic expansion process 4-5:

$$\frac{T4}{T5} = \frac{V5}{V4}^{\gamma-1} = \frac{V1}{0.084V1}^{1.4-1} = 2.69$$

$\therefore T_5 = \frac{T4}{2.69} = \frac{1767}{2.69} = 656.9K$

$\eta_{\text{air-standard}} = \frac{Work\ done}{Heat\ Supplied} = \frac{Heat\ supplied - Heat\ rejected}{Heat\ supplied}$

$= 1 - \frac{Heat\ rejected}{Heat\ supplied}$

$= 1 - \frac{Cp(T_5 - T_1)}{Cv(T_3 - T_2) + Cp(T_4 - T_3)}$

$= 1 - \frac{(T_5 - T_1)}{(T_3 - T_2) + \gamma(T_4 - T_3)}$

$= 1 - \frac{(656.9-300)}{(1400-886.2)+1.4(1767-1400)}$

$\therefore \eta = 0.653$ or 65.3 %

5.(b) Air initially occupying 1 m^3 at 1.5 bar, 20°C undergoes an internally reversible compression for which PV^n = constant to a final state where the

pressure is 6 bar and temperature is 120°C. Determine i) the value of n ii) the work and heat transfer iii) change in entropy. **(10)**

$V_1 = 1\ m^3$, $P_1 = 1.5$ bar= 1.5×10^5 Pa $V_2 = ?$, $P_2 = 6 \times 10^5$ Pa

$T_1 = 293$ K $T_2 = 393$ K

$$\frac{P1.V1}{T1} = \frac{P2.V2}{T2}$$

$\therefore V_2 = 0.335\ m^3$

$P_1 V_1^n = P_2 V_2^n$

$\therefore$ n= 1.267

$W = \frac{P2\,V2 - P1\,V1}{1-n} = 1.9 \times 10^5$ J= 190 KJ

$\Delta U = mCv\,\Delta T$

PV= mRT

$\therefore$ m= 1.78 kg

$\Delta U = 1.78 \times 0.718\ (120-20) = 128$ KJ

From first law,

$Q = \Delta U + W$

$\therefore Q = 318$ KJ

6.(a) In a rankine cycle the stream at the inlet to the turbine is at 100 bar and 500 C. If the exhaust pressure is 0.5 bar, determine the pump work, turbine work, condenser heat flow and Rankine efficiency. **(10)**

$P_1 = 100$ bar, $P_2 = 0.5$ bar

Since, $T_{sup} = 500\,^{\circ}C$ it is a condition of supersaturated steam.

$\therefore$ At 100 bar, $T_{sat} = 310.9C$

$h_1 = h_g + C_{pv}(T_{sup} - T_{sat}) = 2727 + 2.1(500 - 31.09) = 3124.6$KJ/kg

$S_1 = S_g + C_{pv} \log(\frac{Tsup}{Tsat}) = 5.62 + 2.1 \log\frac{773}{583.9} = 6.20$KJ/kg K

To find dryness fraction,

$S1 = S2 = S_f + xS_{fg} = 6.20$

$\therefore x_2 = 0.78$

H_2 = 2138.7 KJ/kg

$h_3 = h_f$ = 340.5KJ/kg

Pump Work $W_p = \frac{100-0.5}{10}$ = 10 KJ/kg

∴ $h_4 = h_3 + W_p$ = 340.5 + 10= 350.5 KJ/kg

Turbine Work, $W_t = h_1 - h_2$ =985.9 KJ/kg

Turbine shaft work = $W_t - W_p$ = 975.9 KJ/kg

Condensor heat flow, qr= h_2-h_3 = 1798.2KJ/kg

$\eta = \frac{Ws}{q1} = \frac{975.1}{2774.1}$ = 35.1 %

6.(b) What is meant by complete and perfect intercooling in case of multistage air compressor? What is the effect of multi staging over the volumetric efficiency of reciprocating air compressor? (10)

For a given condensation temperature, the lower the evaporator temperature, the higher the compressor pressure ratio. For a reciprocating compressor, a high pressure ratio across a single stage means low volumetric efficiency. Also, with dry compression the high pressure ratio results in high compressor discharge temperature which may damage the refrigerant. To reduce the work of compression and improve the COP, multistage compression with intercooling may be adopted. Since the intercooler temperature may be below the temperature of available cooling water used for the condenser, the refrigerant itself may be used as the intercooling medium.

For minimum work, the intercooler pressure p_i is the geometric mean of the evaporator and condenser pressures, p_1 and p_2 or

$p_i = \sqrt{(p_1 . p_2)}$

By making an energy balance of the direct contact heat exchanger,

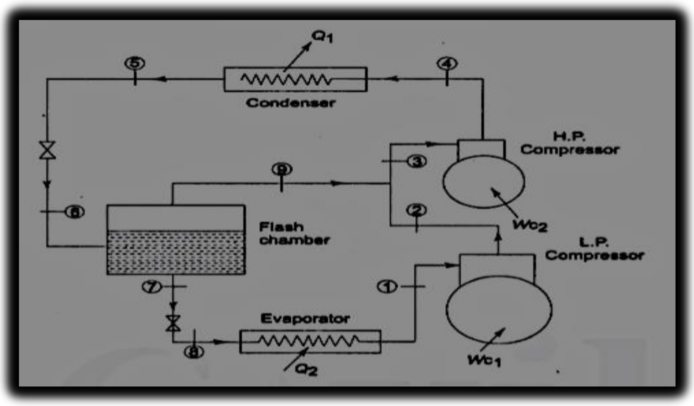
$m_2h_2 + m_1h_6 = m_2h_7 + m_1h_3$

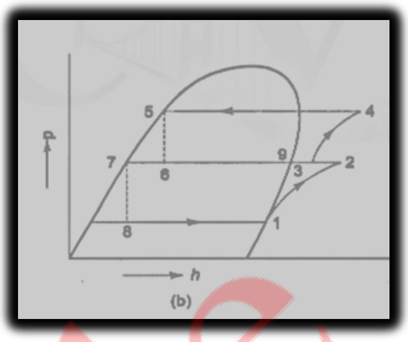
∴ $\frac{m1}{m2} = \frac{h2-h7}{h3-h6}$

The desored refrigerating effect determines the flow rate in the low pressure loop, m_2, as given below

$m_2(h_1 - h_g) = \frac{14000}{3600}$ x P where P is the capacity, in tonnes of refrigeration.

$$\therefore m_2 = \frac{3.89P}{h_1 - h_g} \text{ kg/s}$$





Multi-stage compression **increases** the volumetric efficiency and reduces the power consumption, the power input being a minimum if the total work is divided equally between the stages.
