

UNIT - I

Introduction to

Refrigeration and Air refrigeration

Def of Refrigeration:— The science of providing and maintaining the temp of substance (or) space below that of the surrounding temperature.

Unit of Refrigeration:— the unit of refrigeration is "Ton of Refrigeration". It is denoted by letters "TR".

One ton of Refrigeration is defined as the amount of heat removed to produce one ton of ice at 0°C from water at 0°C in 24 hours.

One ton of Refrigeration is defined as the heat removed from the ice at the rate of 210 kJ/min .

C.O. coefficient of performance:— The effectiveness of refrigerating machine is expressed by energy ratio in the form of coefficient of performance. It is abbreviated as COP.

C.O.P. of performance of a refrigerating machine is defined as the ratio of refrigeration effect produced to the work supplied.

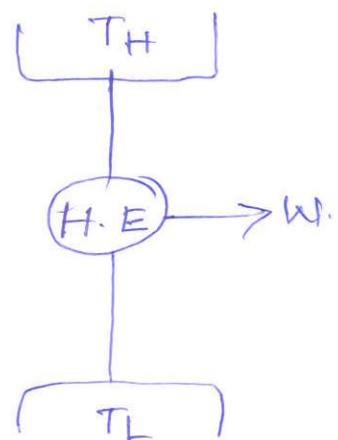
$$\boxed{\text{C.O.P} = \frac{\text{Refrigeration effect}}{\text{Work supplied}} = \frac{N}{W}}$$

Sensible heat:— the amount of heat removed (or) extracted from a substance without changing its state is called sensible heat.

Latent heat:— The amount of heat removed (or) extracted from a substance during phase change is called latent heat.

Comparison between Heat Engine, Refrigerator and Heat pump:-

Heat engine converts heat energy into mechanical work. In heat engine heat flows from engine which is at higher temp to surrounding temperature.



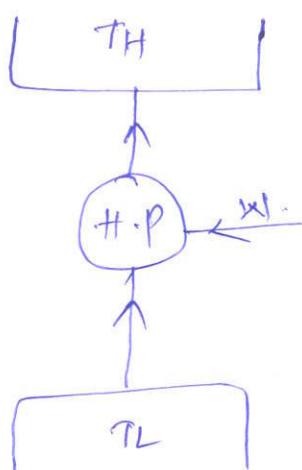
$$W = T_H - T_L$$

$$O/P = T_H - T_L$$

$$I/P = T_H$$

$$C.O.P = \frac{T_H - T_L}{T_H}$$

Heat pump converts mechanical work into heat energy. In a heat pump, heat flows from pump which is at lower temperature.

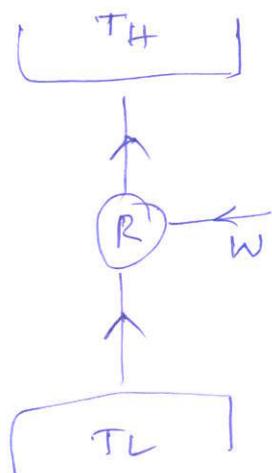


$$W = T_H \cdot$$

$$I/P = T_H - T_L$$

$$C.O.P = \frac{T_H}{T_H - T_L}$$

Refrigerator:-



$$W = T_H - T_L$$

$$I/P = T_L$$

$$C.O.P = \frac{T_L}{T_H - T_L}$$

problems! -

- (1) Find the C.O.P of refrigerating system if the work input is $200 \frac{\text{KJ}}{\text{min}}$ and refrigerating effect produced is 400KJ/min .

Work input $N = 200 \text{ KJ/min}$,

$$N = 400 \text{ KJ/min}$$

$$\text{C.O.P} = \frac{\text{Ref. effect}}{\text{Work supplied}} = \frac{N}{W} = \frac{400}{200} = 2$$

- (2) The capacity of refrigerating machine is rated as 30TR calculate the refrigerating effect produced by the refrigerating machine.

$$\text{Capacity of ref. machine} = 30 \text{TR}$$

One ton of refrigeration = cooling effect produced at the rate of

$$210 \frac{\text{KJ}}{\text{min}}$$

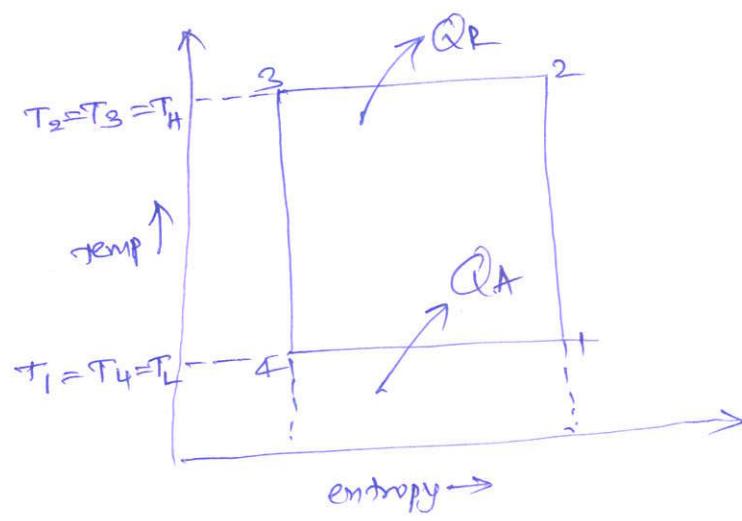
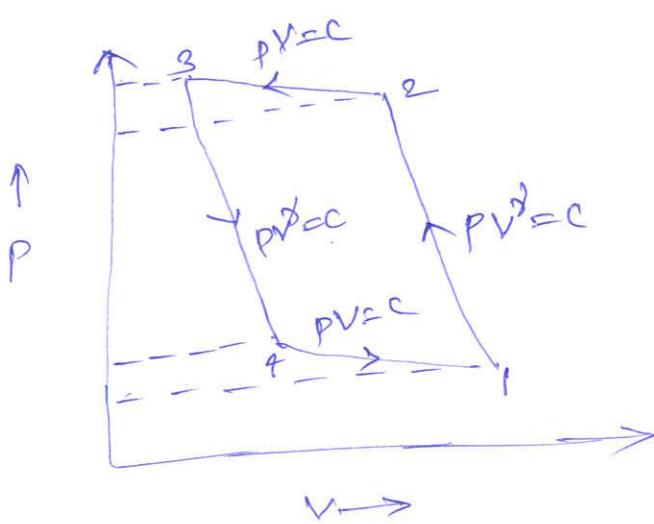
cooling effect produced by 30TR ref. machine = 30×210

$$= 6300 \frac{\text{KJ}}{\text{min}}$$

▷

Air Refrigeration: A refrigeration system which employs air as working fluid is known as air refrigeration.

Carnot cycle air refrigeration: A Carnot refrigeration cycle consists of two isentropic and two isothermal processes. All the processes are reversible thermodynamic processes and hence the cycle is known as reversible Carnot cycle.



process 1-2: Isentropic compression in the compressor.

$$PV^{\gamma} = C$$

$$\boxed{P_1 V_1^{\gamma} = P_2 V_2^{\gamma}}$$

process 2-3: Isothermal compression.

$$PV = \text{constant}$$

$$P_2 V_2 = P_3 V_3$$

$$T_2 = T_3 = T_H$$

$$\boxed{Q_R = T_H (S_2 - S_3)}$$

process 3-4: Isentropic expansion in the expander.

$$PV^{\gamma} = C$$

$$\boxed{P_3 V_3^{\gamma} = P_4 V_4^{\gamma}}$$

process 4-1: Isothermal expansion in the refrigerator.

$$PV = \text{constant}$$

$$P_4 V_4 = P_1 V_1$$

$$T_4 = T_1 = T_L$$

$$Q_A = T_L (S_1 - S_4)$$

$$Q_R = T_H (S_2 - S_3)$$

$$Q_A = N = T_L (S_1 - S_4)$$

$$W = Q_R - Q_A = T_H (S_2 - S_3) - T_L (S_1 - S_4)$$

$$W = (S_1 - S_4) (T_H - T_L)$$

$$\text{C.O.P.} = \frac{\text{Ref. effect}}{\text{Work supplied}} = \frac{N}{W} = \frac{T_L (S_1 - S_4)}{(S_1 - S_4) (T_H - T_L)} = \frac{T_L}{T_H - T_L}$$

$$\therefore \text{for a Carnot cycle air refrigeration C.O.P} = \frac{T_L}{(T_H - T_L)},$$

- ① A machine working on a Carnot cycle operates between 20°C and 260K. Determine C.O.P when it's operated as 1. refrigerating m/c
2. heat pump and 3. heat engine.

Given temperatures $T_L = 260K$, $T_H = 305K$

1) C.O.P of refrigerating m/c

$$(C.O.P)_R = \frac{T_L}{T_H - T_L} = \frac{260}{305 - 260} = 5.78$$

2) C.O.P of heat pump.

$$(C.O.P)_P = \frac{T_H}{T_H - T_L} = \frac{305}{305 - 260} = 6.78$$

3) C.O.P of heat engine

$$(C.O.P)_E = \frac{T_H - T_L}{T_H} = \frac{305 - 260}{305} = 0.14711.$$

- ② 500kg of fruits are supplied to a cold storage at 20°C. The cold storage is maintained at -5°C and the fruits get cooled to -5°C. The latent heat of freezing is $105 \frac{kJ}{kg}$ and specific heat of fruits is $1.256 \frac{kJ}{kg \cdot K}$. Find the refrigeration capacity of the plant.

$$m = 500\text{kg}, \quad T_H = 20^\circ\text{C} + 273 = 293\text{K}, \quad T_f = -5^\circ\text{C} = -5 + 273 = 268\text{K}.$$

$$h_{fg} = 105 \frac{kJ}{kg}, \quad C = 1.256 \frac{kJ}{kg \cdot K}$$

Heat removed from the fruits in 10 hours

$$\begin{aligned} Q &= mc\Delta T = mC(T_2 - T_1) \\ &= 500 \times 1.256 \times (293 - 268) \\ &= 15,700 \text{ kJ.} \end{aligned}$$

Latent heat of freezing

$$Q = mxh_{fg} = 500 \times 105 = 52,500 \text{ kJ.}$$

$$\text{Total heat removed} = 15,700 + 52,500 = 68,200 \text{ kJ.}$$

Total heat removed in one minute

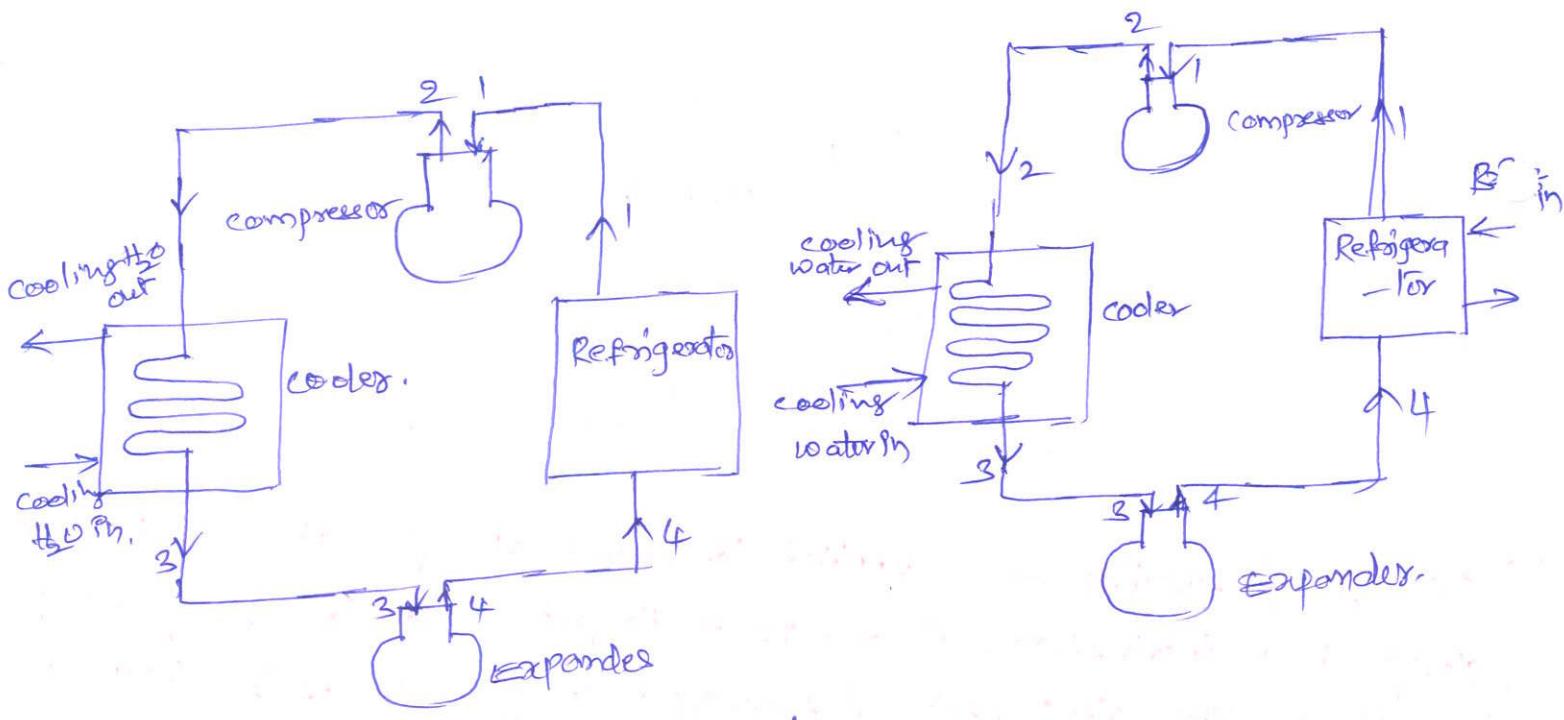
$$= \frac{68200}{10 \times 60} = 113.7 \text{ kJ/min}$$

Ref. capacity of plant $= \frac{113.7 \text{ kJ}}{210} = 0.541 \text{ TR}$

Air refrigeration working on Bell-Coleman cycle

The Bell-Coleman cycle (also called reversed Carnot or Joule cycle) is a modification of reversed Carnot cycle.

Bell Coleman cycle divided into two types: open cycle and closed cycle.



1. ISENTROPIC COMPRESSION PROCESS: — cold air from refrigerator is drawn into the compressor cylinder where it is compressed isentropically in the compressor. (1-2)

2. CONSTANT PRESSURE COOLING PROCESS: — warm air cooled by constant pressure by using condenser (2-3).

$$\dot{Q}_{2-3} = C_p (T_2 - T_3)$$

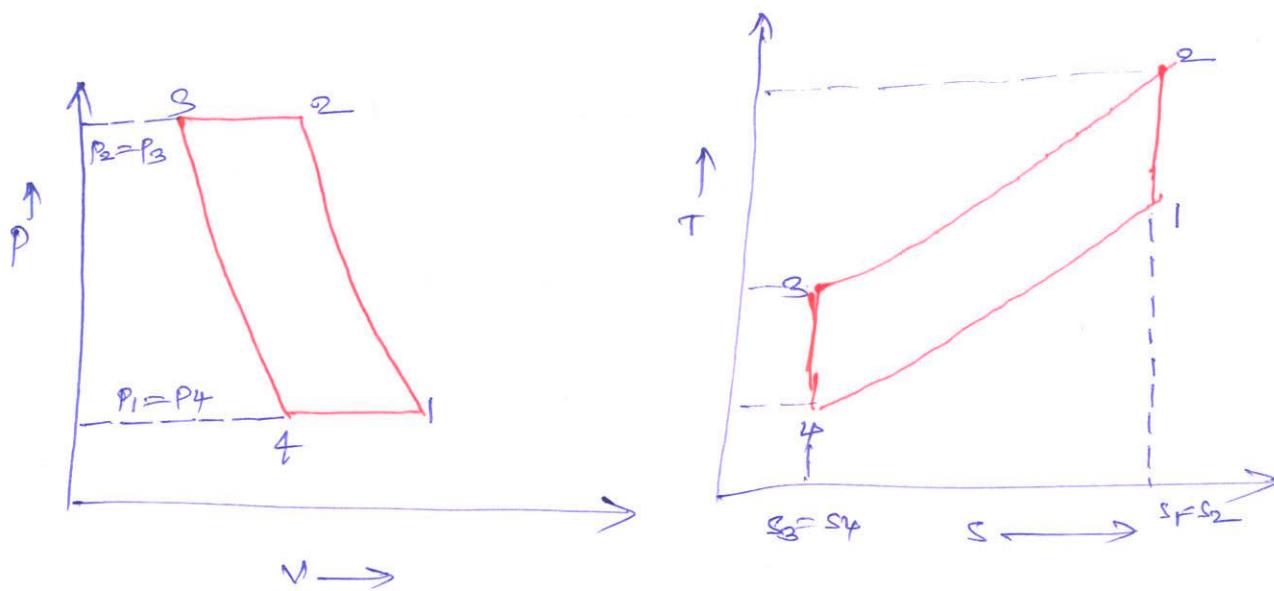
This is also called heat rejection process.

3. ISENTROPIC EXPANSION: — air from the cooler is drawn into expander and cooled down isentropically.

(4)

constant pressure expansion process:- cold air from the expander is now passed to refrigerator where it is expanded. This is also called heat absorbing process.

$$Q_A = C_p(T_1 - T_4),$$



$$\text{e.o.p} = \frac{\text{Heat absorbed}}{\text{Work done}} = \frac{Q_A}{Q_R - Q_A} = \frac{C_p(T_1 - T_4)}{C_p(T_2 - T_3) - C_p(T_1 - T_4)}$$

$$= \frac{T_1 - T_4}{(T_2 - T_3) - (T_1 - T_4)}$$

$$= \frac{T_4 \left(\frac{T_1}{T_4} - 1 \right)}{T_3 \left(\frac{T_2}{T_3} - 1 \right) - T_4 \left(\frac{T_1}{T_4} - 1 \right)}$$

We know that for isentropic compression 1-2

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{1}{\gamma}}$$

and isentropic expansion 3-4

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\frac{1}{\gamma}}$$

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad (\text{or}) \quad \frac{T_2}{T_3} = \frac{T_1}{T_4}$$

$$C.O.P = \frac{T_4}{T_3 - T_4} = \frac{1}{\frac{T_3}{T_4} - 1} = \frac{1}{\left(\frac{P_3}{P_4}\right)^{\frac{1}{n}} - 1} = \frac{1}{\left(\frac{P_3}{P_4}\right)^{\frac{1}{n}} - 1}$$

$$\gamma_p = \text{compression ratio} \leq \text{expansion ratio} = \frac{P_2}{P_1} = \frac{P_3}{P_4}$$

Sometimes compression and expansion processes take place according to law $pV^n = \text{const.}$

$$W_C = \frac{n}{n-1} (P_2 V_2 - P_1 V_1) = \frac{n}{n-1} (R(T_2 - T_1)) \\ = \frac{n}{n-1} R(T_2 - T_1)$$

3-4 process

$$W_E = \frac{n}{n-1} (P_3 V_3 - P_4 V_4) = \frac{n}{n-1} (R(T_3 - T_4)) \\ = \frac{n}{n-1} R(T_3 - T_4)$$

Heat absorbed during constant pressure $4-1$
 $= C_p (T_1 - T_4)$

$$C.O.P = \frac{C_p (T_1 - T_4)}{\frac{n}{n-1} \times R \times [(T_2 - T_1) - (T_3 - T_4)]}$$

$$R = C_p - C_v ; \quad \frac{C_p}{C_v} = \gamma$$

$$C.O.P = \frac{C_p (T_1 - T_4)}{\frac{n}{n-1} \times C_v (\gamma - 1) ((T_2 - T_1) - (T_3 - T_4))}$$

$$= \frac{\gamma (T_1 - T_4)}{\frac{n}{n-1} \times (\gamma - 1) [(T_2 - T_1) - (T_3 - T_4)]}$$

$$= \frac{T_1 - T_4}{\frac{n}{n-1} \times \frac{\gamma - 1}{\gamma} [(T_2 - T_3) - (T_1 - T_4)]} //$$

(5)

problems on Bell coleman cycle

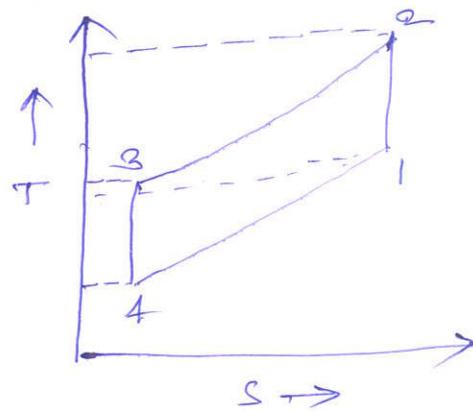
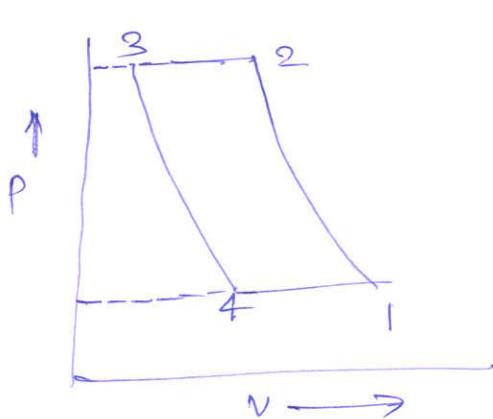
- Q) If a refrigerant plant working on Bell-coleman cycle, air is compressed to 5 bar to 1 bar. its initial temperature at 10°C after compression the air is cooled upto 28°C in a cooler before expanding back to a pressure of 1 bar. Determine the theoretical C.O.P of the plant and net refrigerating effect. Take $C_p = 1.005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$ and $C_v = 0.718 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$.

SOLⁿ

Given $P_2 = P_f = 5 \text{ bar}$; $P_1 = P_4 = 1 \text{ bar}$ $T_1 = 10^\circ\text{C} = 10 + 2T_3 = 283 \text{ K}$;

$T_3 = 28^\circ\text{C} = 20 + 2T_3 = 293 \text{ K}$; $C_p = 1.005 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$, $C_v = 0.718 \frac{\text{kJ}}{\text{kg}\cdot\text{K}}$.

$$\gamma = \frac{C_p}{C_v} = \frac{1.005}{0.718} = 1.4,$$



For isentropic compression process 1-2

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.584,$$

for isentropic expansion process 3-4

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.584.$$

$$T_4 = T_3 / 1.584 = 293 / 1.584 = 185 \text{ K}.$$

Theoretical C.O.P of plant

$$= \frac{T_4}{T_2 - T_4} = \frac{185}{293 - 185} = 1.113.$$

$$\text{Net ref. effect} = C_p(T_1 - T_4) = 1.005(283 - 185)$$

$$= 98.5 \frac{\text{kJ}}{\text{kg}}.$$

② The atmospheric air at pressure 1 bar and temperature -5°C is taken in the cylinder of the compressor of a bell-crank refrigerating machine. It is compressed isentropically to a pressure of 5 bar. In the cooler, the compressed air is cooled to 15°C , pressure remaining the same. It is then expanded to a pressure of 1 bar in an expansion cylinder, from where it is passed to the cold chamber. Find 1. The work done per kg of air and 2. C.O.P. of the plant. Assume law for expansion $\text{pv}^{1.2} = \text{c}$, law for compression $\text{pv}^{1.4} = \text{c}$, and specific heat of air at constant pressure $= 1 \frac{\text{kJ}}{\text{kg.K}}$.

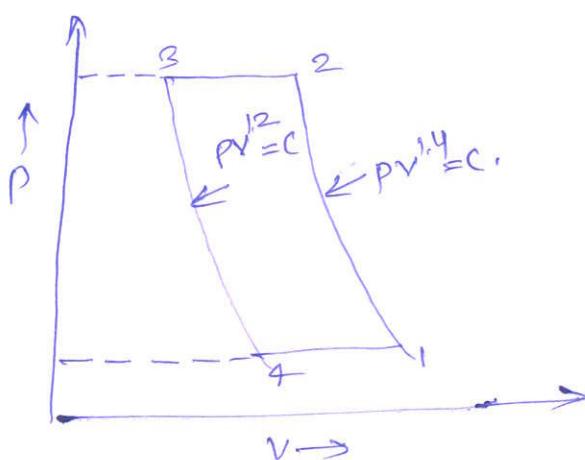
$$\text{Given } P_1 = P_4 = 1 \text{ bar}, T_1 = -5^{\circ}\text{C} + 273 = 268 \text{ K}; P_2 = P_3 = 5 \text{ bar}; T_2 = 15^{\circ}\text{C} + 273 = 288 \text{ K}$$

$$n = 1.2 \quad \gamma = 1.4 \quad c_p = 1 \frac{\text{kJ}}{\text{kg.K}}$$

Work done per kg of air

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1} \right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.585$$

$$T_2 = 1.585 \times 268 = 424.8 \text{ K}$$



The expansion process 3-4 follows the law $\text{pv}^{1.2} = \text{constant}$.

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4} \right)^{\frac{n-1}{\gamma}} = \left(\frac{5}{1} \right)^{\frac{1.2-1}{1.2}} = (5)^{0.167} = 1.31$$

$$T_4 = \frac{T_3}{1.31} = \frac{288}{1.31} = 220 \text{ K}$$

$$\begin{aligned} W_C &= W_{1-2} = \frac{\gamma}{\gamma-1} \times R (T_2 - T_1) \\ &= \frac{1.4}{1.4-1} \times 0.286 (424.8 - 268) \\ &= 150 \text{ kJ/kg} \end{aligned}$$

$$\begin{aligned} W_E &= W_{3-4} = \frac{n}{n-1} \times R \times (T_2 - T_4) \\ &= \frac{1.2}{1.2-1} \times 0.286 (288 - 220) = 118.3 \text{ kJ/kg} \end{aligned}$$

(6)

Network done per kg of air

$$\begin{aligned} W &= W_C - W_E \\ &= 159 - 118.3 \\ &= 40.7 \frac{\text{kJ}}{\text{kg}}, \end{aligned}$$

C.O.P of the plant

$$\eta_A = C_p(T_r - T_u) = 1(268 - 220)$$

$$= 48 \frac{\text{kJ}}{\text{kg}},$$

$$\text{C.O.P of the plant} = \frac{\text{Heat absorbed}}{\text{Work done}}$$

$$= \frac{48}{40.7} = 1.18 //$$

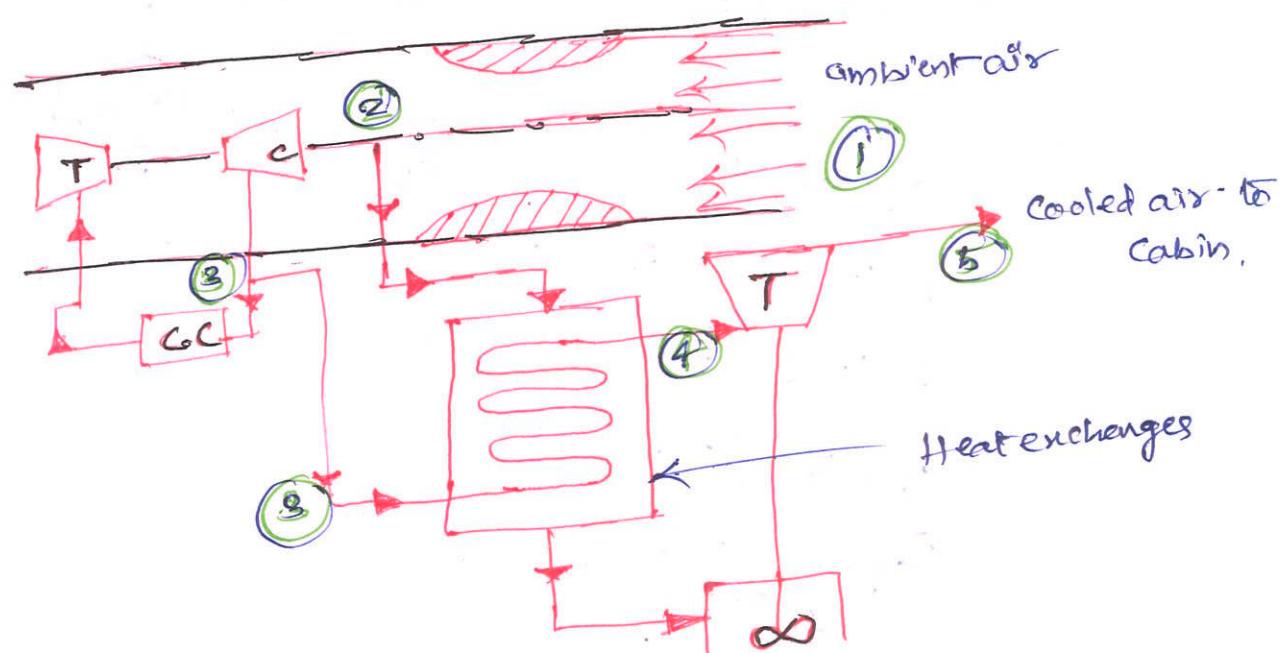


Air Refrigeration systems

METHODS:-

1. simple air cooling system.
2. simple air evaporative cooling system
3. Boot strap air cooling system.
4. Boot strap air evaporative cooling systems
5. Reduced ambient air cooling systems and
6. Regenerative air cooling system.

Simple air cooling system:- main components are gas O_2 , main compressor, combustion chamber, heat exchangers, etc.



Initially ambient air entered into ramming process at this point temperature and pressure increases slightly. Now this air divided into two parts. One part of air entered into heat exchanger and another part entered into compressor. At this point the air is heated up by using combustion chamber, and this heated air cool down by ram air, and remaining air goes to the cooling air cabin.

If 'V' is the aircraft velocity or air relative to the aircraft in meters per second.

$$\text{Running process} - \frac{1-2}{K.E = \frac{V^2}{2000} \frac{KJ}{kg}}$$

KJ per 1 kg.

$$\therefore K.E = \frac{1}{2} m v^2 : m = 1 \text{ kg} \Rightarrow F = ma \\ m = \frac{N}{(m/s)^2}$$

from the energy equation

$$h_2 - h_1 = \frac{V^2}{2000}$$

$$c_p T_2 - c_v T_1 = \frac{V^2}{2000}$$

$$T_2 - T_1 = \frac{V^2}{2000 c_p}$$

$$T_2 = \frac{V^2}{2000 c_p} + T_1$$

$$\Rightarrow T_2 = T_1 \left(\frac{V^2}{2000 c_p T_1} + 1 \right)$$

$$\frac{T_2}{T_1} = \frac{V^2}{2000 c_p T_1} + 1$$

$$\frac{T_2}{T_1} = \frac{V^2}{2000 c_p T_1} + 1$$

$$c_p - c_v = R$$

$$\frac{c_p}{c_v} = \gamma \Rightarrow \frac{c_v}{c_p} = \frac{1}{\gamma}$$

$$c_p \left(1 - \frac{1}{\gamma} \right) = R$$

$$c_p \left(1 - \frac{1}{\gamma} \right) = R$$

$$c_p \left(1 - \frac{1}{\gamma} \right) = R$$

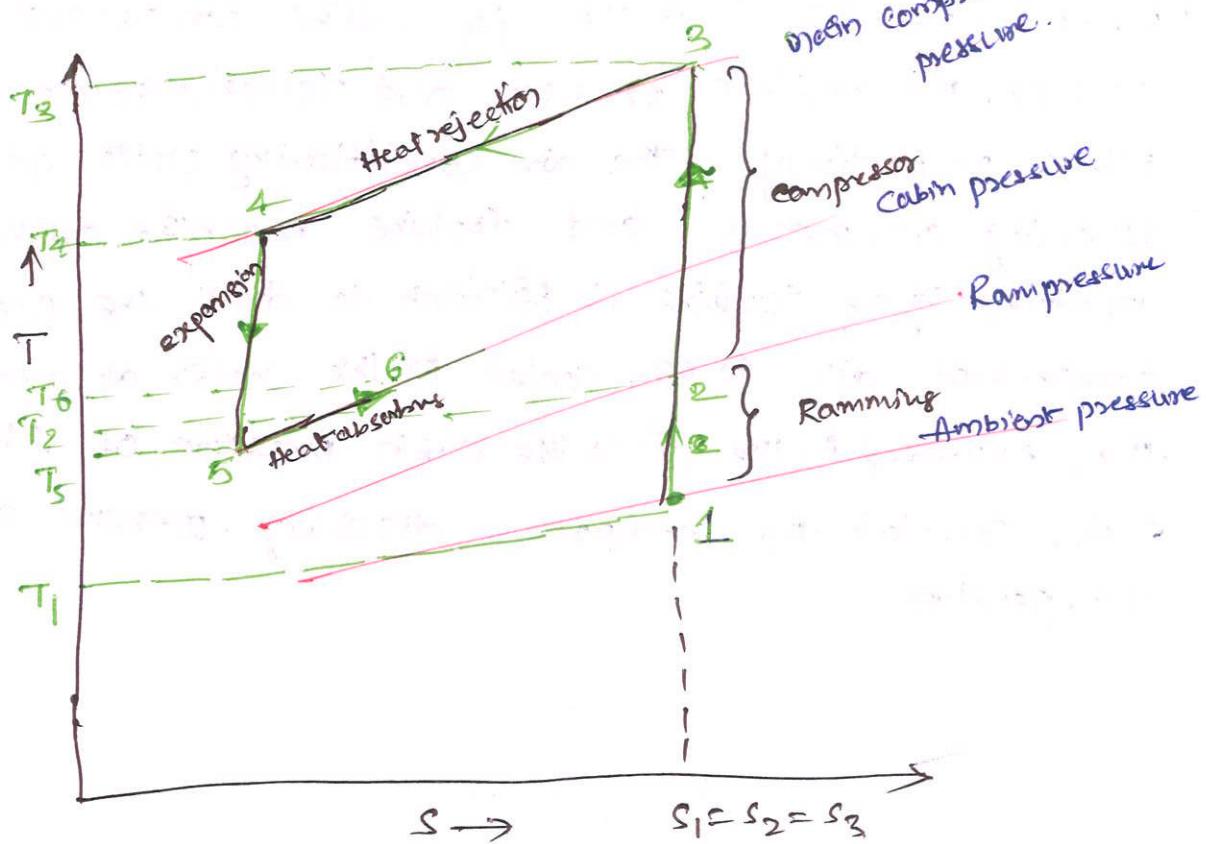
$$\boxed{c_p = \frac{\gamma R}{\gamma - 1}}$$

$$\frac{T_2}{T_1} = \frac{V^2}{2000 \left(\frac{\gamma R}{\gamma - 1} \right) T_1} + 1$$

$$\frac{T_2}{T_1} = \frac{V^2 (\gamma - 1)}{2000 \gamma R T_1} + 1$$

$$\frac{T_2}{T_1} = \frac{T_2}{T_1} = 1 + \frac{V^2 (\gamma - 1)}{2000 \gamma R T_1}$$

$$a = \text{accretion velocity} = \sqrt{\gamma R T_1}$$



finding of temperatures by using

$$\left(\frac{P_2}{P_1}\right)^{\frac{g-1}{g+1}} = \left(\frac{T_2}{T_1}\right)$$

temperature increased
from "5-6"

2-3 Isentropic compression.

$$W_C = m c_p (T_3 - T_2)$$

3-4 Isobaric heat rejection process.

$$Q_R = m c_p (T_3 - T_4)$$

4-5 Isentropic expansion

$$W_T = m c_p (T_4 - T_5)$$

5-6 Isobaric heat absorbing (Q) Refrigerating effect

$$Q_A = m c_p (T_6 - T_5)$$

$$C.O.P = \frac{m c_p (T_6 - T_5)}{m c_p (T_3 - T_2)} = \frac{T_6 - T_5}{T_3 - T_2}$$

① An air conditioning system unit of a pressurized aircraft receives its air from the jet engine compressor at a pressure of 1.25 bar. The ambient pressure and temperature are 0.2 bar and 23°FK respectively. The air conditioning unit consists of a free wheeling compressor and turbine mounted on the shaft. The work produced by the turbine sufficient to drive the compressor. The compressed air is then cooled in the cooler at a constant pressure & then expanded in the $\textcircled{1}$ to the cabin pressure of 1 bar and temp 280K. Calculate the compressor discharge pressure and cooler exit temperature.

SOLN

given

$$P_2 = 1.25 \text{ bar}$$

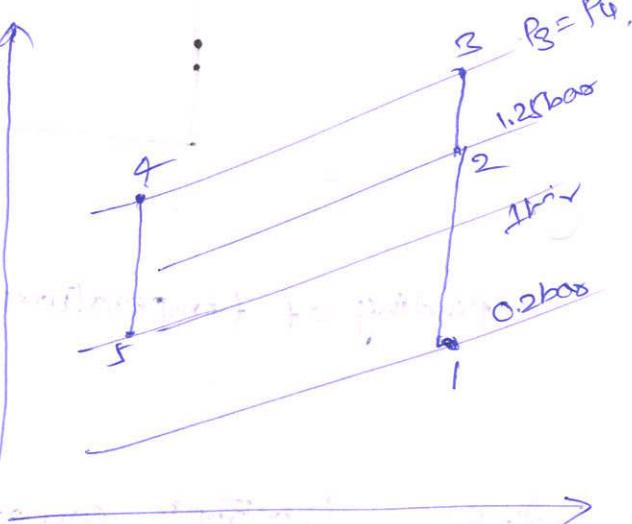
$$P_1 = 0.2 \text{ bar}$$

$$T_1 = 23^\circ\text{F} \quad \uparrow$$

$$P_5 = 1 \text{ bar}, \quad T$$

$$T_5 = 280 \text{ K}$$

P_3 = compressor discharge pressure in bar.



T_2 = Temp of air leaving the jet engine

compressor (or) entering the free wheeling compressor &

T_3 = Temp of air leaving the free wheeling compressor

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.25}{0.2} \right)^{\frac{1.4-1}{1.4}} = (6.25)^{0.286} = 1.69$$

$$T_2 = T_1 \times 1.69 = 23^\circ\text{F} \times 1.69 = 400 \text{ K}$$

Work done by the free wheeling compressor in compressing the air

$$W_C = c_p (T_3 - T_2)$$

$$W_T = c_p (T_4 - T_5)$$

\therefore The work produced by the turbine is sufficient to drive

the compressor, $\therefore W_T = W_C$

$$T_4 - T_5 = T_2 - T_1$$

$$T_5 \left(\frac{T_4}{T_5} - 1 \right) = T_2 \left(\frac{T_2}{T_1} - 1 \right)$$

$$T_5 \left[\left(\frac{P_1}{P_5} \right)^{\frac{2}{1.4}} - 1 \right] = T_2 \left[\left(\frac{P_2}{P_1} \right)^{\frac{2}{1.4}} - 1 \right]$$

$$280 \left[\left(\frac{P_2}{P_1} \right)^{\frac{0.4}{1.4}} - 1 \right] = 400 \left[\left(\frac{P_3}{1.25} \right)^{\frac{0.4}{1.4}} - 1 \right]$$

$$\left(\frac{P_2}{P_1} \right)^{\frac{0.286}{1.4}} - 1 = \frac{400}{280} \left[\left(\frac{P_3}{1.066} \right)^{\frac{0.286}{1.4}} - 1 \right]$$

$$0.34 \left(\frac{P_2}{P_1} \right)^{\frac{0.286}{1.4}} = 1.034 \left(\frac{P_3}{P_2} \right)^{\frac{0.286}{1.4}} - 1.428$$

$$P_3 = (1.26)^{\frac{1}{0.286}} = 2.2115 \text{ bar.}$$

\therefore cooler exit temperature

Let T_4 = cooler exit temperature

$$\frac{T_4}{T_5} = \left(\frac{P_4}{P_5} \right)^{\frac{2}{1.4}} = \left(\frac{2.2115}{1} \right)^{\frac{1.4-1}{1.4}} = (2.2115)^{\frac{0.286}{1.4}} = 1.26$$

$$T_4 = T_5 \times 1.26$$

$$= 280 \times 1.26$$

$$\boxed{T_4 = 352.8 \text{ K.}}$$

(2) A simple air cooled system is used for an aeroplane having a load of 10 tonnes. The atmospheric pressure and temperatures are 0.9 bar and 18°C respectively. The pressure increases to 1.013 bar due to ramming. The temperature of air is reduced by 5°C in the heat exchanger.

The pressure in the cabin is 1 bar and temperature of air leaving the cabin is 25°C . Determine 1. power required to take load of cooling in the cabin and 2. C.O.P of the system.

Assume all the expansions and compressions are isentropic. The pressure of the compressed air is 3.5 bar.

Solⁿ

$$\text{Capacity} = 10 \text{TR.}$$

$$T_1 = 18^\circ\text{C} = 10 + 273 = 283 \text{K.}$$

$$P_1 = 0.9 \text{ bar.}$$

$$P_2 = 1.013 \text{ bar.}$$

$$P_5 = P_6 = 1.01 \text{ bar.}$$

$$T_6 = 25^\circ\text{C} + 273$$

$$= 298 \text{K.}$$

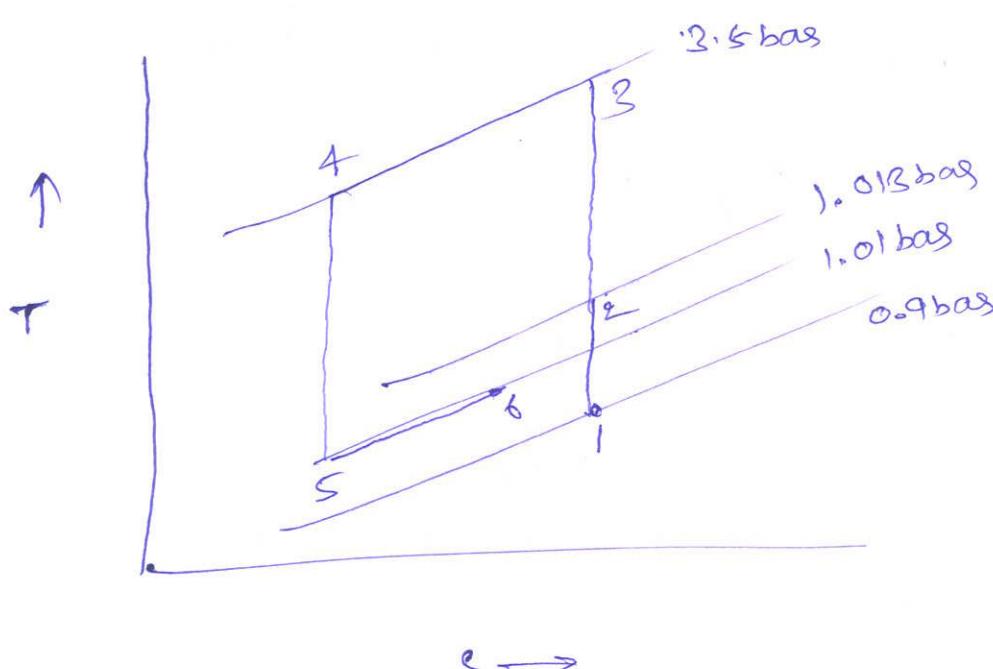
$$P_3 = 3.5 \text{ bar.}$$

T_2 = temp at the end of ramming process.

T_3 = Temp of air leaving the main compressor.

T_4 = Temp of air leaving the heat exchanger and

T_5 = Temp of air leaving the cooling turbine.



$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{1-1}{1+4}} = \left(\frac{1.013}{0.9}\right)^{\frac{1.4}{1+4}} = (1.125)^{0.286} = 1.084$$

$$T_2 = T_1 \times 1.084 = 283 \times 1.084 = 292.6 \text{ K.}$$

$$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{1-1}{1+4}} = \left(\frac{1.15}{1.013}\right)^{\frac{1.4}{1+4}} = (1.1425)^{0.286} = 1.425$$

$$T_3 = T_2 \times 1.425 = 292.6 \times 1.425 = 417 \text{ K} = 144^\circ\text{C.}$$

\therefore the temp of air required by 50°C in the heat exchanger
 \therefore temp of air leaving the next heat exchanger

$$T_4 = 144 - 50 = 94^\circ\text{C} = 367 \text{ K.}$$

$$\frac{T_5}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{1-1}{1+4}} = \left(\frac{1.01}{1.15}\right)^{\frac{1.4}{1+4}} = (0.88) = 0.7$$

$$T_5 = T_4 \times 0.7 = 367 \times 0.7 = 257 \text{ K.}$$

amount of heat added (\Rightarrow Rep. effect)

$$\begin{aligned} Q_A &= m c_p \Delta T \\ &= m c_p (T_3 - T_5) \\ &= m \cdot 1 (298 - 257) \end{aligned}$$

$$Q_A = m c_p (298 - 257) \text{ KJ/K.}$$

$$210 \times 10 = m c_p (298 - 257)$$

$$m_a = \frac{210 \times 10}{298 - 257} = 51.2 \text{ kg/min}$$

[~~kg/min~~ ~~KJ/K.~~]

$$\frac{kg}{min} = m \cdot \frac{kg}{kg \cdot min} \cdot K. \\ [M = \frac{kg}{min}].$$

Power required

$$\begin{aligned} P &= m_a c_p (T_3 - T_2) \\ &= \underline{\underline{51.2 \times 1(417 - 292.6)}} \\ &\quad 60 \end{aligned}$$

$$= 106 \text{ kW}$$

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(11)

C.O.P of the system.

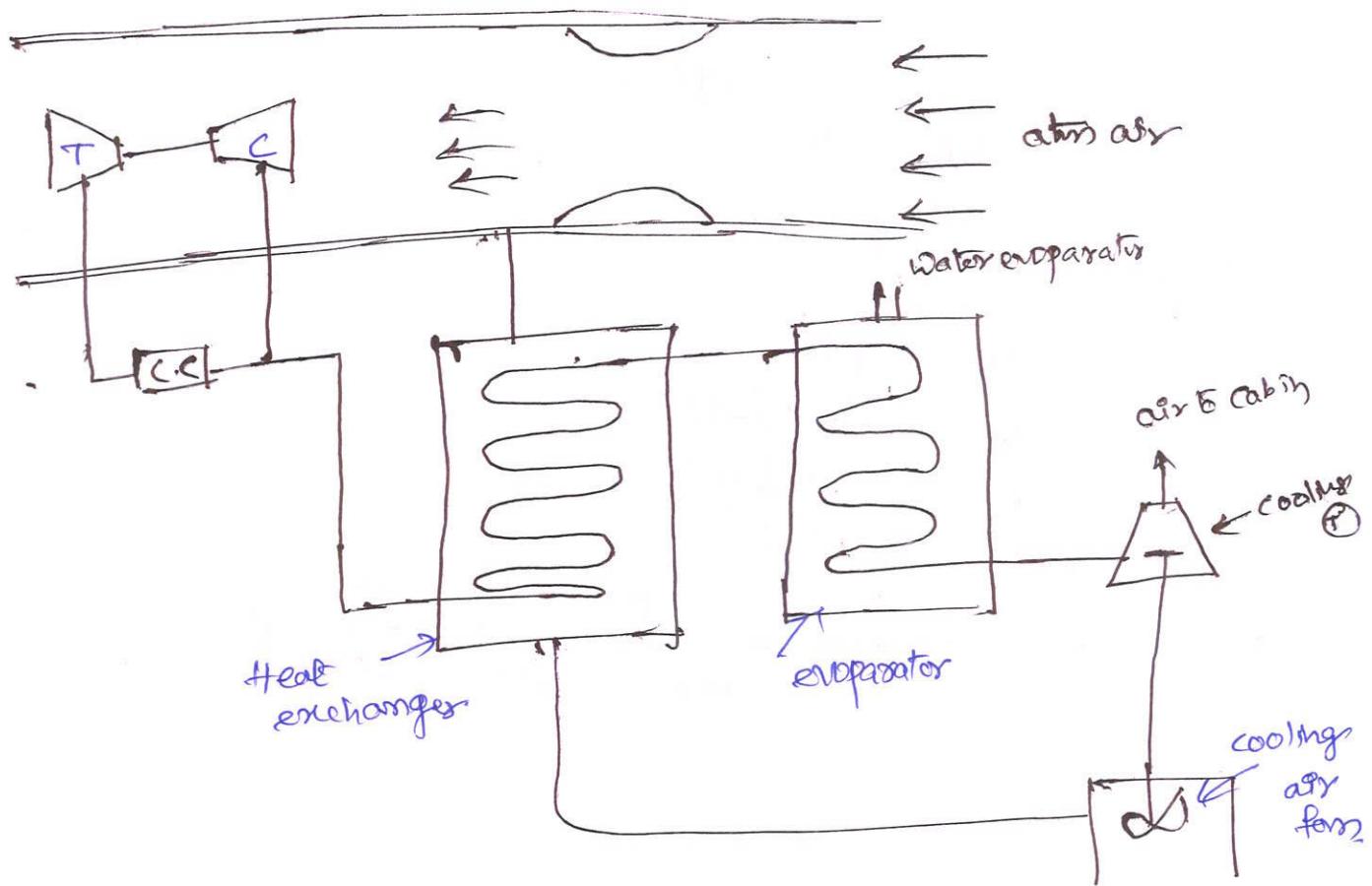
$$\text{C.O.P} = \frac{\text{Ref}}{W}$$

$$= \frac{210 \times 10}{106 \times 60}$$

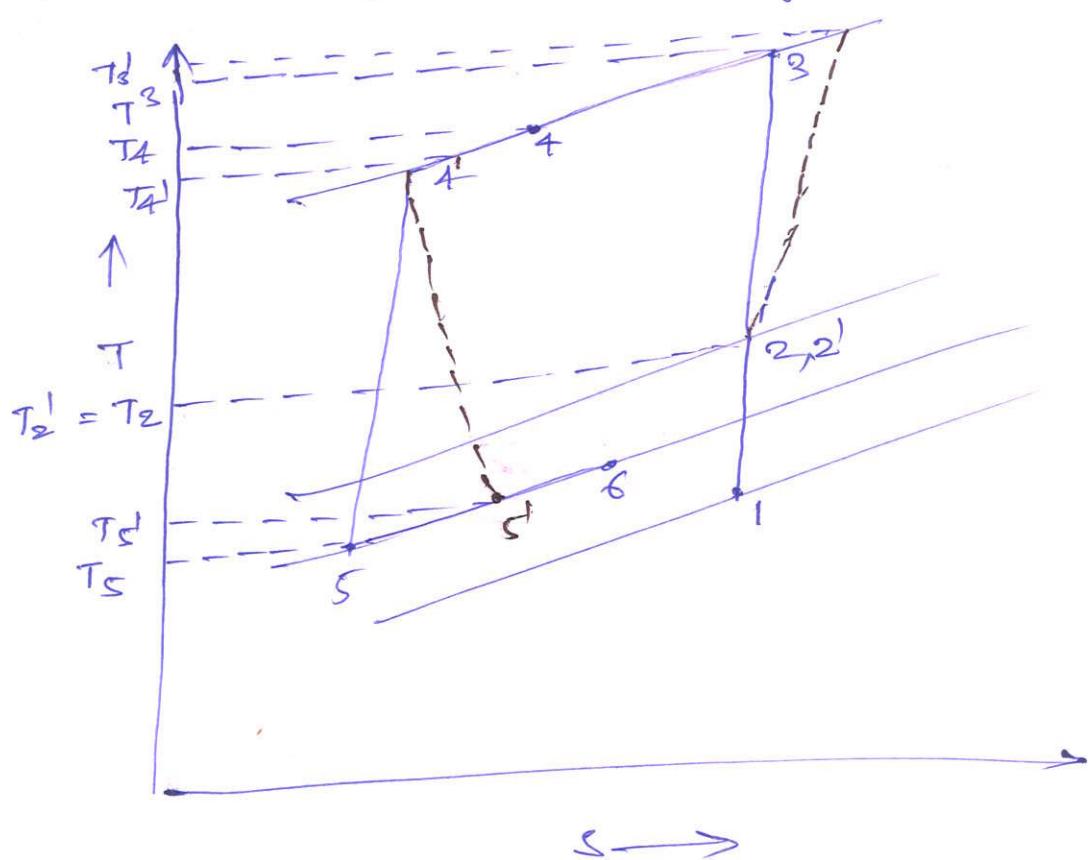
$$= 0.33 \text{ N}$$

Simple air evaporative cooling system

(12)



Simple air evaporative cooling system is shown above fig.
It is similar to simple air cooling system except that the addition of an evaporator between the heat exchanger and cooling turbine.



If 'Q' tonnes of refrigeration is the cooling load in the cabin

$$Q = m c_p \Delta T$$

$$Q = m c_p (T_6 - T_5) \text{ kJ/min}$$

$$m = \frac{Q}{c_p (T_6 - T_5)} \text{ kg/min.}$$

Power required

$$W = m c_p \Delta T$$

$$W = m c_p (T_5 - T_2)$$

$$P = \frac{m c_p (T_5 - T_2)}{60}$$

$$\text{C.O.P of system} = \frac{Q}{m c_p (T_5 - T_2)} = \frac{Q}{60 \times P} \text{ H.}$$

(1) A boot strap cooling system of IOTR capacity is used in an aeroplane. The ambient air temperature and pressure are 20°C and 0.85 bar respectively. The pressure of air increases from 0.85 bar to 1 bar due to ramming action of air. The pressure of air discharged from the main compressor is 3 bar . The discharge pressure of air from the auxiliary compressor is 4 bar . The isentropic efficiency of each of the compressor is 80% , while that of turbine is 85% . 50% of the enthalpy of air discharged from the main compressor is removed in the 1st heat exchanger and 30% of the enthalpy of air discharged from the auxiliary compressor is removed in the second heat-exchanger using rammed air. Assuming ramming action to be isentropic, the required cabin pressure of 0.9 bar , and temperature of air leaving the cabin not more than 20°C . Find

- (1) the power required to operate the system.
 (2) the C.O.P of the system. Draw the schematic and temperature - entropy diagram of system. Take $\gamma = 1.4$ and $C_p = \frac{1\text{ kJ}}{\text{kg.K}}$

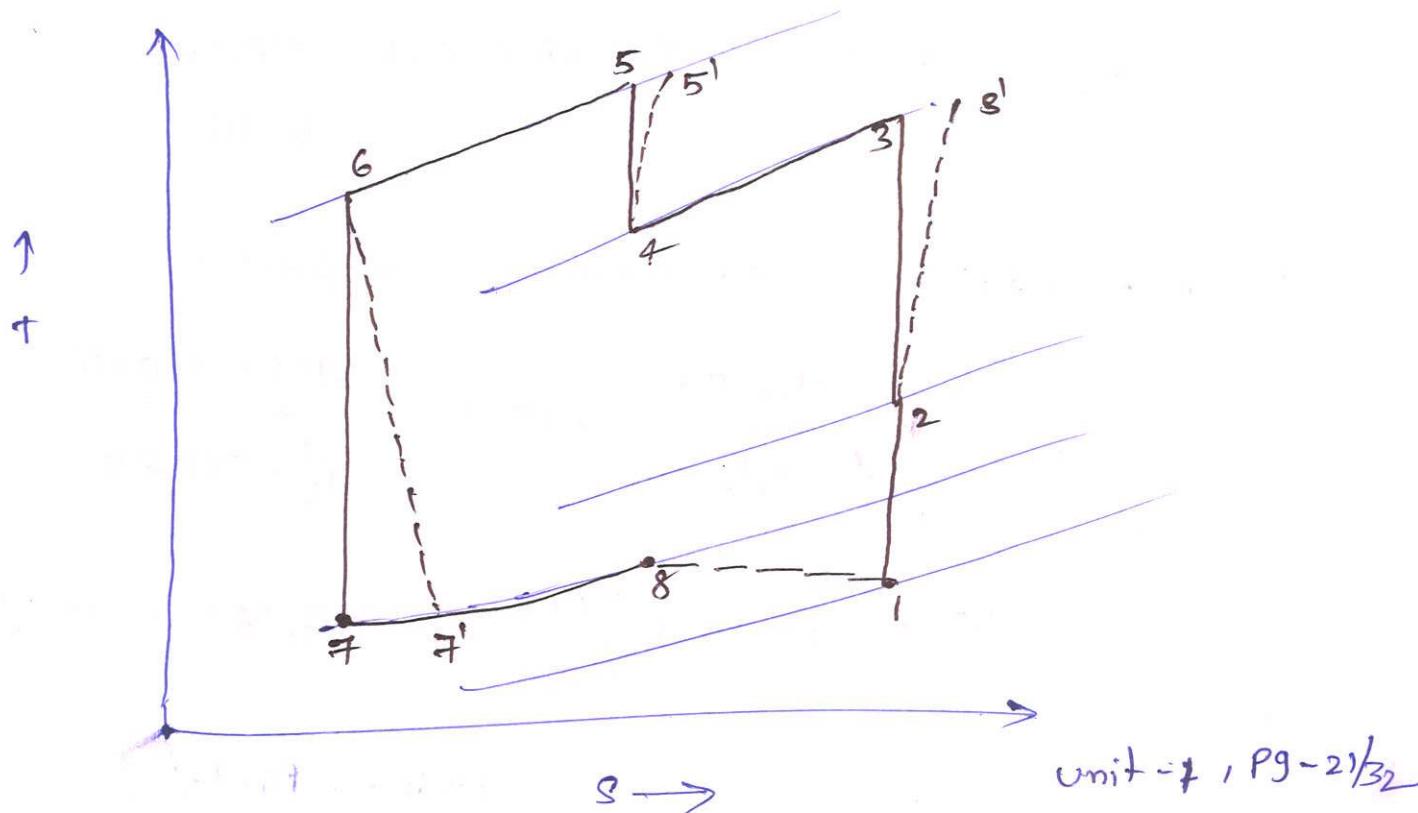
$$Q = \text{IOTR}, T_1 = 20^\circ\text{C} = 20 + 273 = 293\text{ K}$$

$$P_1 = 0.85\text{ bar}, P_2 = 1\text{ bar}; P_3 = P'_3 = P_4 = 3\text{ bar}$$

$$P_5 = P'_5 = P_6 = 4\text{ bar}, \eta_C = \eta_T = 80\% = 0.8$$

$$\eta_T = 85\% = 0.85; P_7 = P'_7 = P_8 = 0.9\text{ bar} \text{ and}$$

$$T_8 = 20^\circ\text{C} + 273 = 293\text{ K}, \gamma = 1.4; C_p = \frac{1\text{ kJ}}{\text{kg.K}}$$



$$\underline{1-2} \quad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{1-1}{\gamma}} = \left(\frac{1}{0.85} \right)^{\frac{1.04-1}{1.04}} = (1.176)^{0.286} = 1.04 F.$$

$$T_2 = T_1 \times 1.04 F = 298 \times 1.04 F = 306.8 K = 38.8^\circ C.$$

$$\underline{2-3} \quad \frac{T_3}{T_2} = \left(\frac{P_3}{P_2} \right)^{\frac{1-1}{\gamma}} = \left(\frac{2}{1} \right)^{\frac{1.04-1}{1.04}} = (2)^{0.286} = 1.2 F$$

$$T_3 = T_2 \times 1.2 F = 306.8 \times 1.2 F = 420.8 K \\ = 147.7^\circ C$$

$$\eta_{c1} = \frac{\text{Isentropic increase in temp}}{\text{actual increase in temp}} = \frac{T_3 - T_2}{T_{31} - T_2}$$

$$0.8 = \frac{420.8 - 306.8}{T_{31} - 306.8} \Rightarrow \frac{112.5}{T_{31} - 306.8} = 0.8$$

$$T_{31} = 306.8 + \frac{112.5}{0.8} = 448.7 K \\ = 175.7^\circ C$$

\therefore 50% of enthalpy of air discharged from the main compressor is removed in the 1st heat exchanger. Therefore temp of air leaving the 1st heat exchanger

$$T_4 = 0.5 \times 175.7^\circ C = 360.85 K.$$

Now for the isentropic process 4-5,

$$\frac{T_5}{T_4} = \left(\frac{P_5}{P_4} \right)^{\frac{1-1}{\gamma}} = \left(\frac{2}{1} \right)^{\frac{0.4}{1.04}} = (1.83)^{0.286} = 1.085$$

$$T_5 = T_4 \times 1.085 = 360.85 \times 1.085 = 391.5 K \\ = 118.5^\circ C.$$

Isentropic efficiency of auxiliary compressor.

$$\eta_{p2} = \frac{T_5 - T_4}{T_{51} - T_4} \Rightarrow 0.8 = \frac{391.5 - 360.85}{T_{51} - 360.85}$$

$$T_{51} = 360.85 + \frac{30.65}{0.8} = 399.16 K = 126.16^\circ C.$$

(16)

since 20% of enthalpy of air discharged from the auxiliary compressor is removed in the second heat exchanger.

: temp of air leaving the second H.E

$$T_6 = 0.7 \times 126.16 = 88.2^\circ\text{C} = 361.3\text{K}$$

For the Isentropic process G-F

$$\frac{T_F}{T_6} = \left(\frac{P_F}{P_6}\right)^{\frac{1}{k}} = \left(\frac{0.9}{4}\right)^{\frac{1.4-1}{1.4}} = 0.225^{0.286}$$

$$T_F = T_6 \times 0.653 = 361.3 \times 0.653 \\ = 236\text{K.} \\ = -37^\circ\text{C.}$$

turbine efficiency

$$\eta_T = \frac{\text{actual increase in temp}}{\text{Isentropic increase in temp}}$$

$$0.85 = \frac{361.2 - T_F'}{361.2 - 236} = \frac{361.2 - T_F'}{125.3}$$

$$T_F' = 361.2 - 0.85 \times 125.3$$

$$T_F' = 254.8\text{K} = -18.2^\circ\text{C.}$$

(1) power required to operate the system,

$$W = m \cdot c_p (T_8 - T_F')$$

$$P = \frac{m \cdot c_p (T_8 - T_F')}{60}$$

$$10 \times 210 = m \cdot c_p (T_8 - T_F')$$

$$m = \frac{210 \times 10}{1(293 - 254.8)} = 55 \text{ kg/min}$$

$$P = \frac{55 \times 1 \times (448.9 - 306.8)}{60} = 130\text{K.W}$$

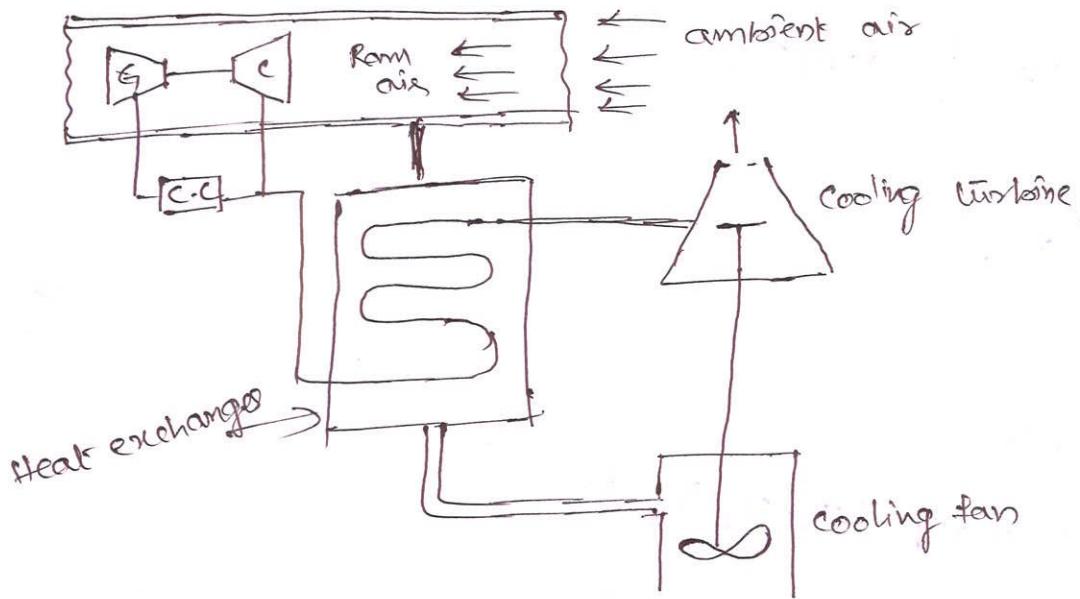
C.O.P of the system

$$\text{C.O.P} = \frac{N}{W} = \frac{210 \times 10}{130} = 0.271$$

Methods of air Refrigeration systems :-

- (i) simple air cooling system
- (ii) simple air evaporative cooling system.
- (iii) Boot strap air cooling system
- (iv) Boot strap air evaporative cooling system &
- (v) Reduced ambient air cooling system and
- (vi) Regenerative air cooling system .

Simple air cooling system:-



1-2 process is called Ramming process.

If V is the aircraft velocity ~~relative~~ relative to the aircraft in m/s.

$$K.E = \frac{V^2}{2000} \text{ KJ/kg.}$$

$$h_2 - h_1 = \frac{V^2}{2000}$$

$$CPT_2 - CPT_1 = \frac{V^2}{2000}$$

$$T_2 = T_1 + \frac{V^2}{2000 c_p}$$

$$\frac{T_2}{T_1} = 1 + \frac{V^2}{2000 c_p T_1}$$

We know that $c_p - c_v = R$.

$$c_p \left(1 - \frac{c_v}{c_p}\right) = R \quad \text{or} \quad c_p \left(1 - \frac{1}{\gamma}\right) = R$$

$$c_p = \frac{R\gamma}{\gamma - 1}$$

$$\frac{T_2}{T_1} = 1 + \frac{V^2(\gamma-1)}{2000\delta RT_1}$$

$$\frac{T_2}{T_1} = 1 + \frac{V^2(\gamma-1)}{2\delta RT_1}$$

$$\frac{T_2}{T_1} = 1 + \frac{V^2(\gamma-1)}{2a^2}$$

$a = \text{acoustic velocity}$

$$= \sqrt{\gamma RT_1}$$

$$\frac{T_2}{T_1} = \frac{T_2'}{T_1} = 1 + \frac{\gamma-1}{2} \times M^2$$

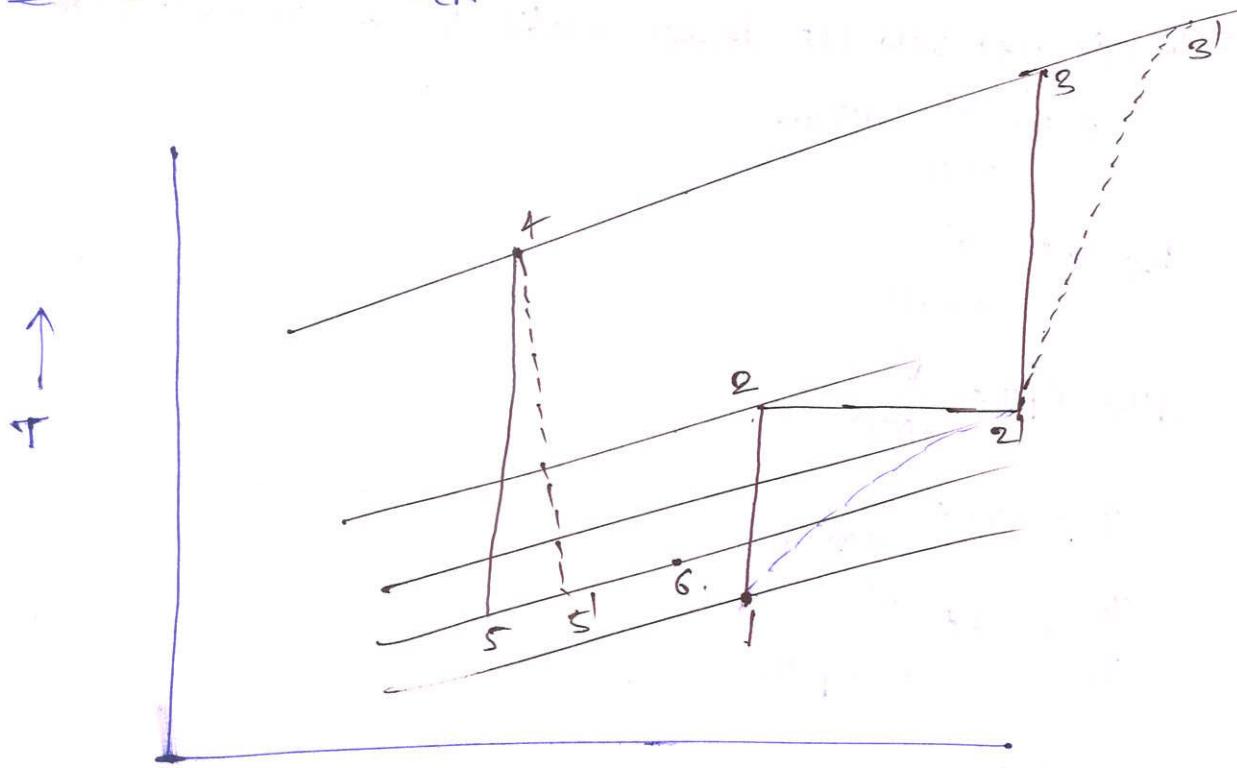
$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1} \right)^{\gamma/(\gamma-1)}$$

compression process:

$$W_c = mcp (T_2' - T_2)$$

cooling process:

$$Q_R = mcp (T_3 - T_4)$$



$S \rightarrow$

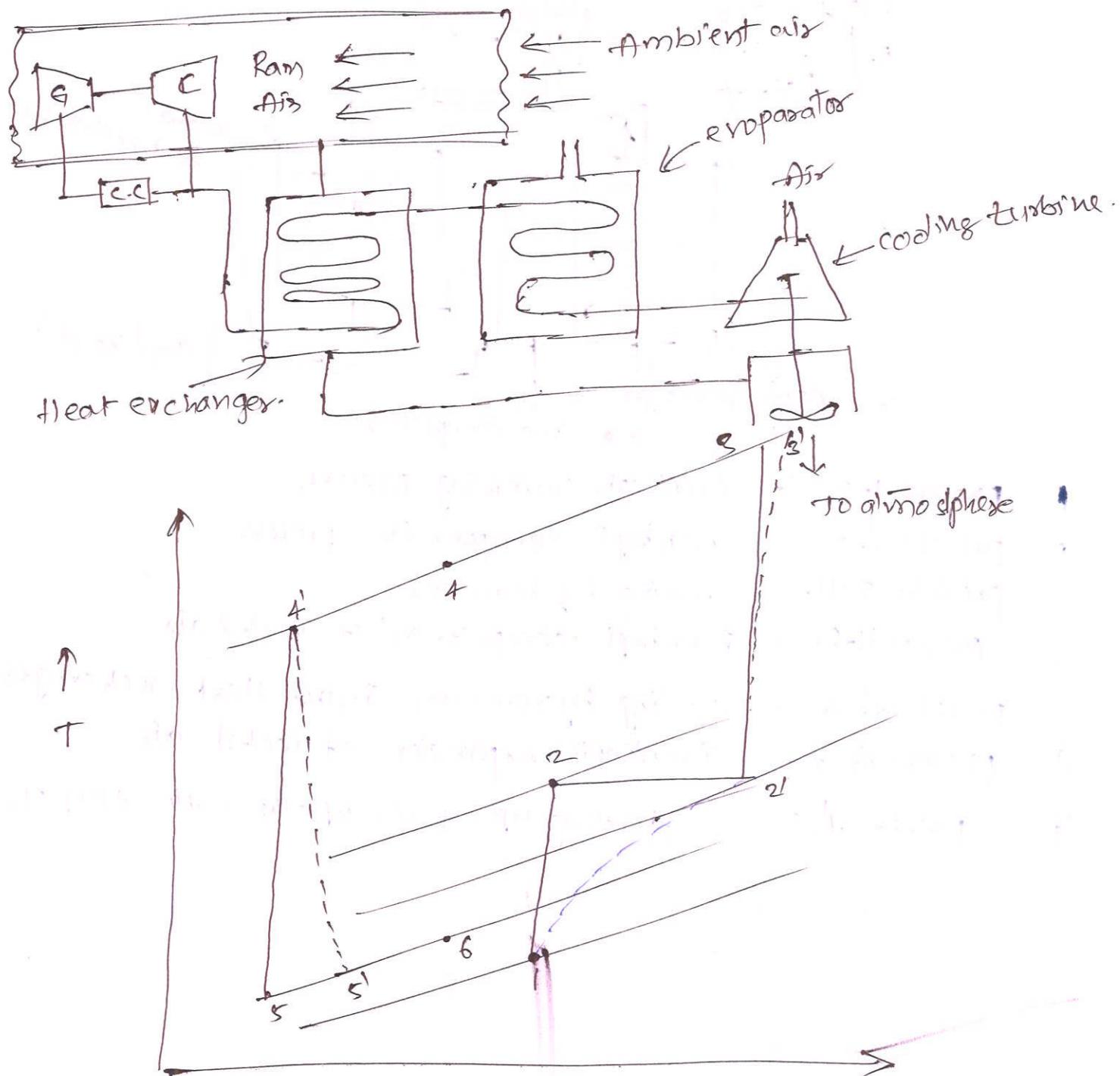
expansion process $W_f = mcp(T_4 - T_5)$

Refrigeration process $R_E = mcp(T_6 - T_5)$

$$C.O.P = \frac{\text{Refrigeration effect produced}}{\text{Work done.}}$$

$$= \frac{mcp(T_6 - T_5)}{mcp(T_3' - T_2')} = \frac{T_6 - T_5}{T_3' - T_2'}$$

Simple Air Evaporative Cooling system: simple air evaporative cooling system is same that of simple air cooling system but difference is it has an evaporator.

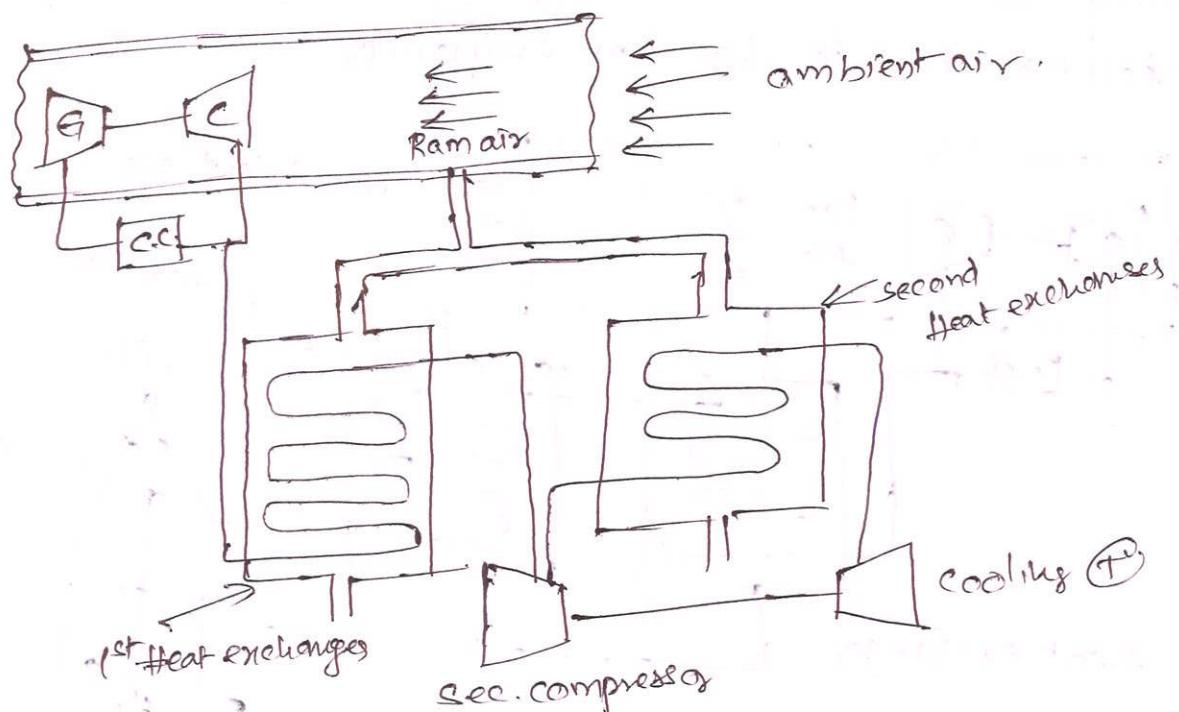


$$m_a = \frac{210Q}{c_p(T_6 - T_5)}$$

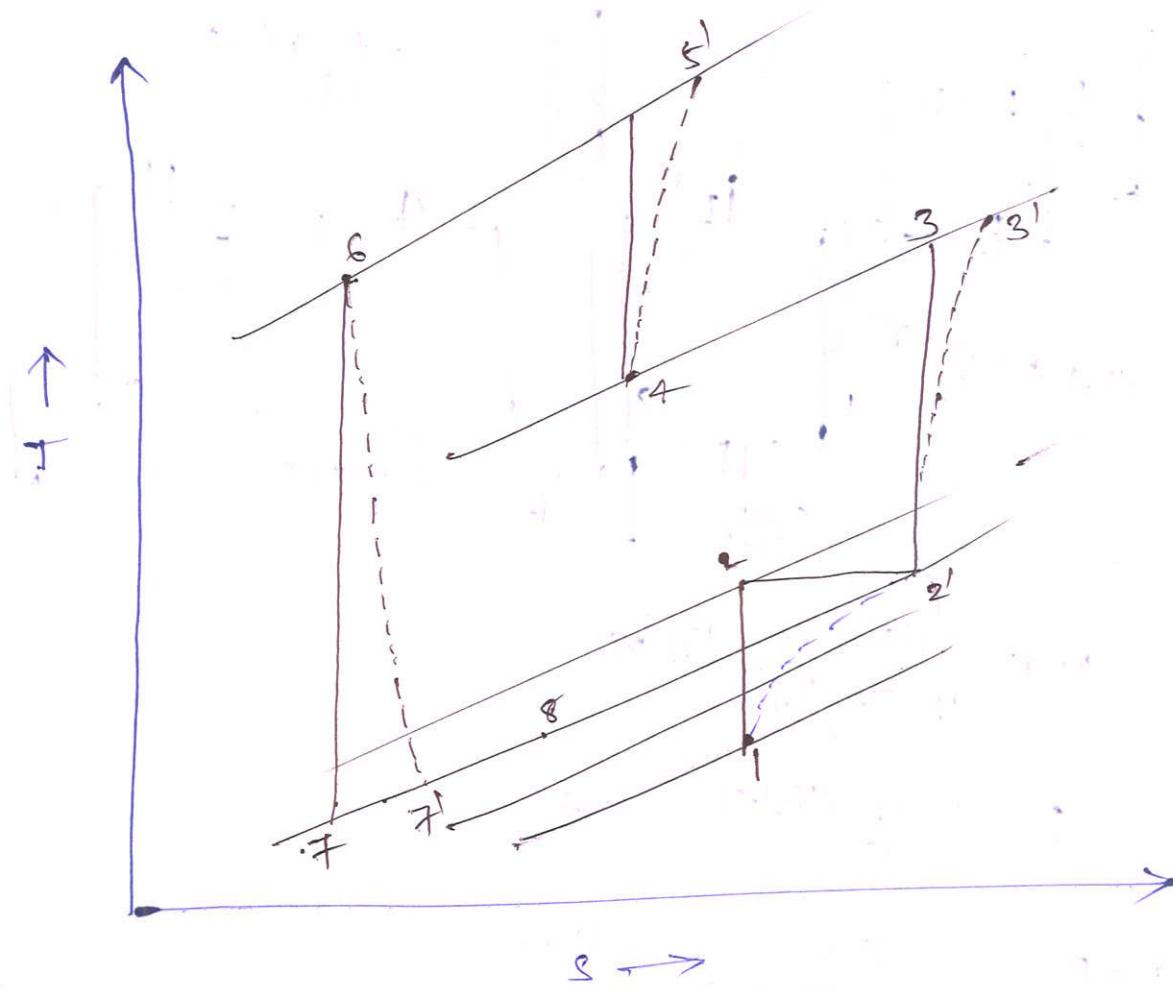
$$P = \frac{m_a c_p (T_3^1 - T_2)}{60}$$

$$\text{C.O.P of Ref system} = \frac{210Q}{m_a c_p (T_3^1 - T_2)} = \frac{210Q}{P \times 60}$$

Boot strap air cooling system: Boot strap air cooling system. This cooling system has two heat exchangers instead of one and a cooling turbine drives a secondary compressor instead of cooling fan.



1. process 1-2 → isentropic ramming process.
2. process 2-3 → isentropic compression process.
3. process 3'-4 → cooling by ram air
4. process 4-5 → isentropic compression of cooled air
5. process 5-6 → cooling by ram air in the heat exchangers.
6. process 6-7 → isentropic expansion of cooled air
7. process 7-8 → heating up dr air upto the cabin temp. T_8



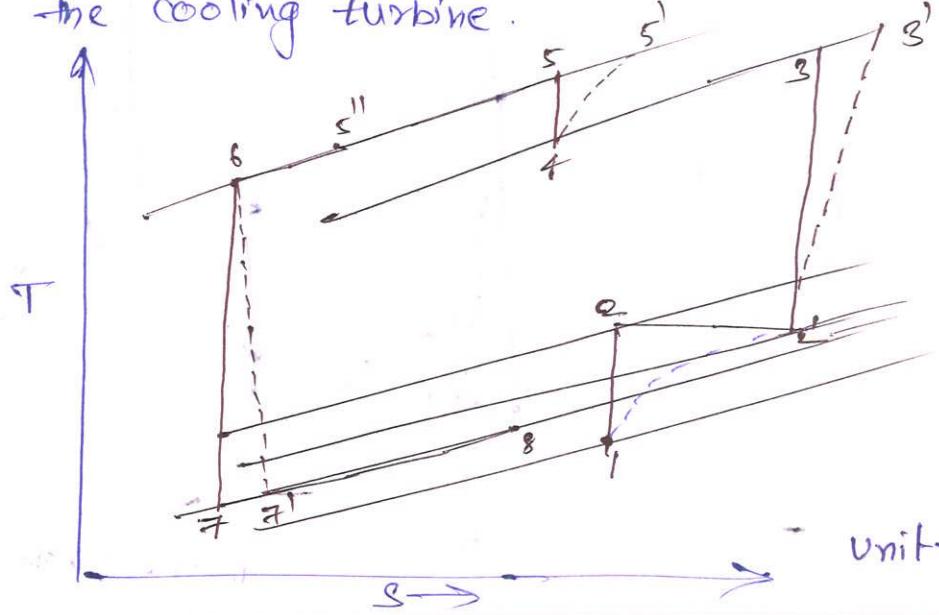
If Q tonnes of refrigeration is the cooling load in the cabin then the quantity of air required for the refrigeration purpose will be

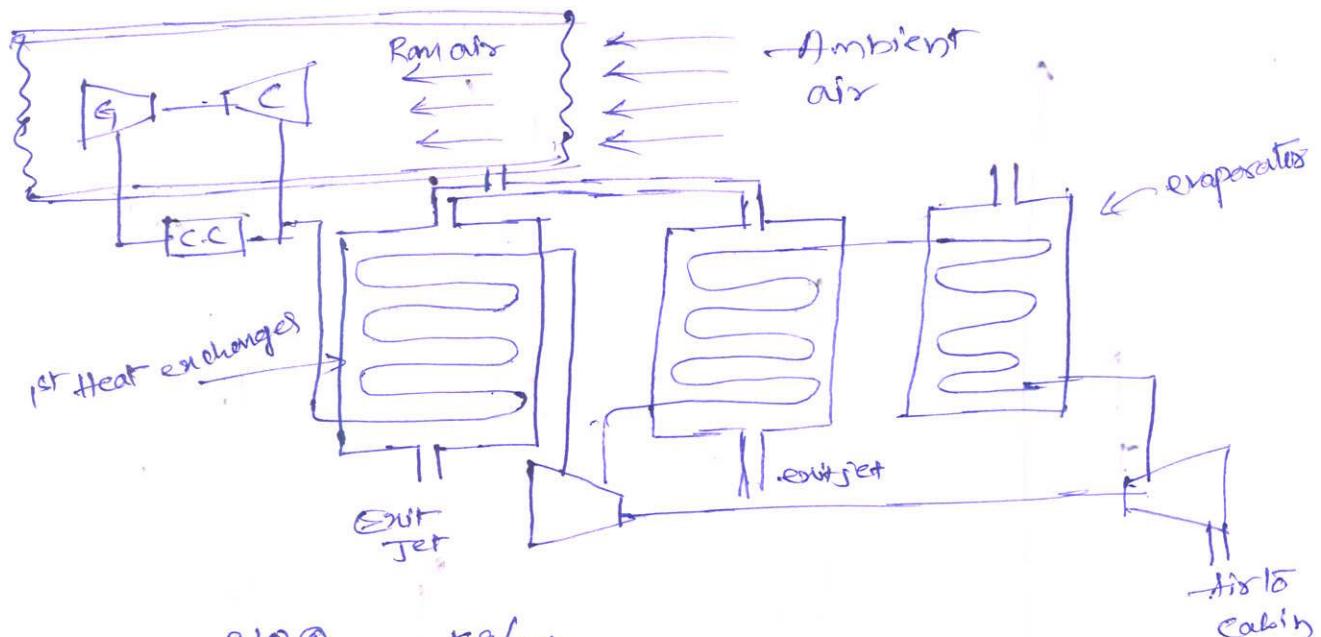
$$m_a = \frac{210 Q}{c_p(T_8 - T_1)} \text{ kg/min}$$

$$P = \frac{m_a c_p (T_8 - T_2)}{60} \text{ k.w.}$$

Boot-strap Air evaporative cooling system:

A boot-strap air cycle evaporative cooling system is similar to the boot-strap air cycle cooling system except that the addition of an evaporator between the second heat exchanger and the cooling turbine.



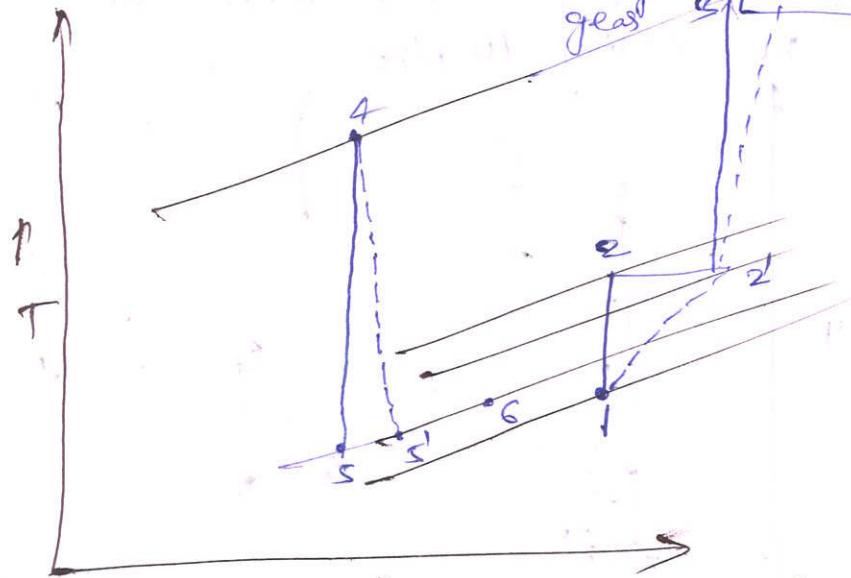
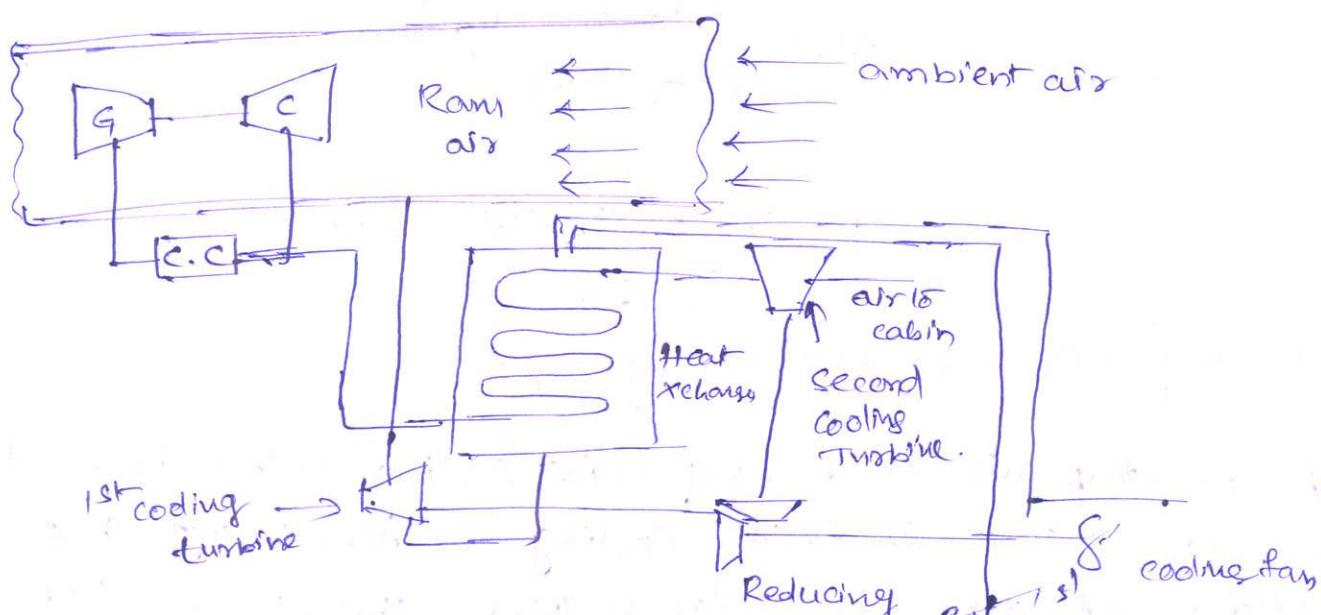


$$m_a = \frac{210 @}{c_p (T_8 - T_7)} \text{ kg/min}$$

$$P = \frac{m_a c_p (T_3 - T_2)}{60} \text{ k.W}$$

$$\text{C.O.P} = \frac{210 @}{m_a c_p (T_3 - T_2)} = \frac{210 @}{P \times 60}$$

Reduced ambient air cooling system:



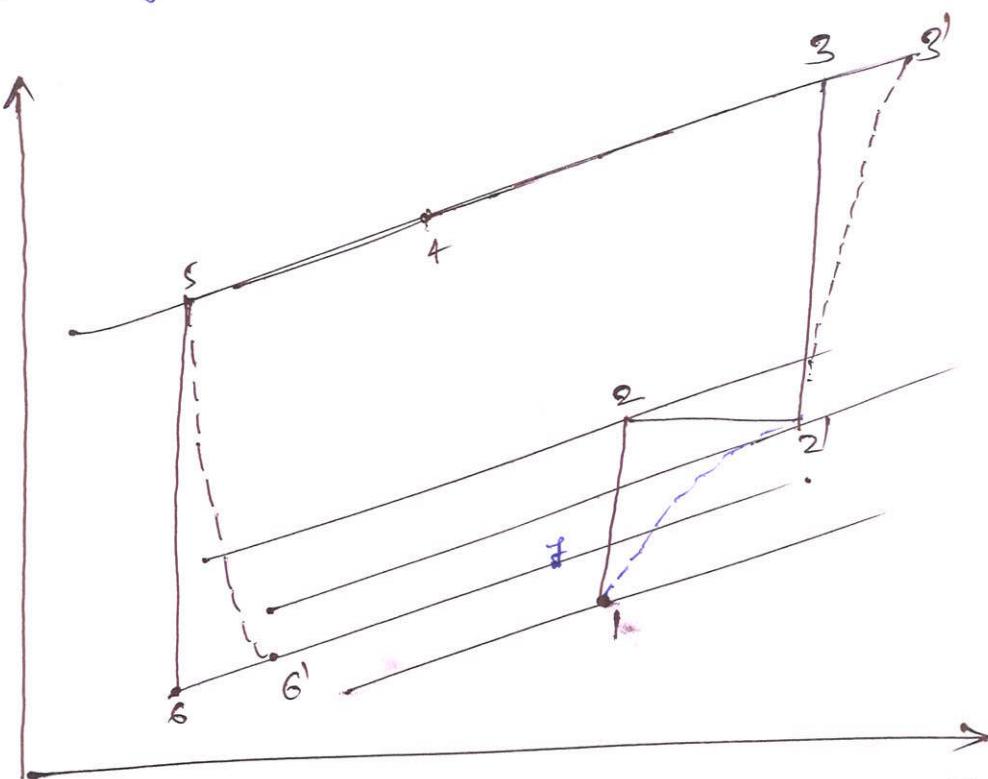
$$m_a = \frac{210 \text{ Q}}{c_p(T_6 - T_5)} \text{ kg/min}$$

power required for the refrigeration system is given by

$$\dot{P} = \frac{m_a c_p (T_3 - T_2)}{60} \text{ k.W.}$$

$$\text{C.O.P of the system} = \frac{210 \text{ Q}}{m_a c_p (T_2 - T_1)} = \frac{210 \text{ Q}}{P \times 60}.$$

Regenerative air cooling system: The regenerative air cooling system is the modification of a simple air cooling system with the addition of regenerative heat exchanger.



1. process 1-2 represents isentropic ramming of air.
2. process 2-3 represents isentropic compression of air in the main compressor and 2-3' represents actual compression.
3. process 3-4 represents cooling of compressed air.
4. process 4-5 represents cooling of air in the regenerative heat exchanger.
5. process 5-6 represents isentropic expansion of air in the cooling turbine upto the cabin pressure and process 5-6' represents actual expansion of air in the cooling turbine.
6. process 6-7 represents heating of air upto cabin temperature T_f .

$$m_a = \frac{210Q}{c_p(T_1 - T_6)} \text{ kg/min}$$

$$m_2 c_p (T_8 - T_6) = m_1 c_p (T_4 - T_5)$$

$$m_2 = \frac{m_1 (T_4 - T_5)}{(T_8 - T_6)}$$

$$P = \frac{m_1 c_p (T_3 - T_2)}{60} \text{ kW}$$

$$C.O.P = \frac{210Q}{m_1 c_p (T_3 - T_2)} = \frac{210Q}{60 \times P} \text{ // }$$