UNIT – I: Air Refrigeration

Introduction to Refrigeration :

Refrigeration may be defined as the process of achieving and maintaining a temperature below that of the surroundings, the aim being to cool some product or space to the required temperature.

One of the most important applications of refrigeration has been the preservation of perishable food products by storing them at low temperatures. Refrigeration systems are also used extensively for providing thermal comfort to human beings by means of air conditioning.

Air Conditioning refers to the treatment of air so as to simultaneously control its temperature, moisture content, cleanliness, odour and circulation, as required by occupants, a process, or products in the space.

The subject of refrigeration and air conditioning has evolved out of human need for food and comfort, and its history dates back to centuries. The history of refrigeration is very interesting since every aspect of it, the availability of refrigerants, the prime movers and the developments in compressors and the methods of refrigeration all are a part of it.

Necessity:

Refrigeration deals with cooling of bodies or fluids to temperatures lower than those of surroundings. This involves absorption of heat at a lower temperature and rejection to higher temperature of the surroundings.

In olden days, the main purpose of refrigeration was to produce ice, which was used for cooling beverages, food preservation and refrigerated transport etc.

Now-a-days refrigeration and air conditioning find so many applications that they have become very essential for mankind, and without refrigeration and air conditioning the basic fabric of the society will be adversely affected.

Refrigeration and air conditioning are generally treated in a single subject due to the fact that one of the most important applications of refrigeration is in cooling and dehumidification as required for summer air conditioning.

Of course, refrigeration is required for many applications other than air conditioning, and air conditioning also involves processes other than cooling and dehumidification. The temperature range of interest in refrigeration extends down to about $–100^{o}$C. At lower temperatures cryogenic systems are more economical.

Now-a-days refrigeration has become an essential part of food chain- from post harvest heat removal to processing, distribution and storage.

Refrigeration has become essential for many chemical and processing industries to improve the standard, quality, precision and efficiency of many manufacturing processes. Ever-new applications of refrigeration arise all the time. Some special applications require small capacities but are technically intriguing and challenging.

Air-conditioning is one of the major applications of refrigeration. Air-conditioning has made the living conditions more comfortable, hygienic and healthy in offices, work places and homes. Air-conditioning involves cooling and dehumidification in summer months; this is essentially done by refrigeration.

It also involves heating and humidification in cold climates, which is conventionally done by a boiler unless a heat pump is used. The major applications of refrigeration can be grouped into following four major equally important areas.

1. Food processing, preservation and distribution
2. Chemical and process industries
3. Special Applications
4. Comfort air-conditioning

Applications

1. *Storage of Raw Fruits and Vegetables*: It is well-known that some bacteria are responsible for degradation of food, and enzymatic processing cause ripening of the fruits and vegetables. The growth of bacteria and the rate of enzymatic processes are reduced at low temperature. This helps in reducing the spoilage and improving the shelf life of the food. Table 3.1 shows useful storage life of some plant and animal tissues at various temperatures. it is possible to preserve various food products for much longer periods under frozen conditions.

Food Product	**Average useful storage life (days)**		
	0 °C	**22 °C**	**38 °C**
Meat	6-10	1	< 1
Fish	2-7	1	< 1
Poultry	5-18	1	< 1
Dry meats and fish	> 1000	> 350 & < 1000	> 100 & < 350
Fruits	2 - 180	1 – 20	1 – 7
Dry fruits	> 1000	> 350 & < 1000	> 100 & < 350
Leafy vegetables	3 - 20	1 – 7	1 – 3
Root crops	90 - 300	7 – 50	2 – 20
Dry seeds	> 1000	> 350 & < 1000	> 100 & < 350

Fish: In India, iced fish is still transported by rail and road, and retail stores store it for short periods by this method. Freezing of fish aboard the ship right after catch results in better quality than freezing it after the ship docks. In some ships, it is frozen along with seawater since it takes months before the ships return to dock. Long-term preservation of fish requires cleaning, processing and freezing.

Meat and poultry: These items also require refrigeration right after slaughter during processing, packaging. Short-term storage is done at 0 °C. Long-term storage requires freezing and storage at -25 °C.

Dairy Products**:** The important dairy products are milk, butter, buttermilk and ice cream. To maintain good quality, the milk is cooled in bulk milk coolers immediately after being taken from cow. Bulk milk cooler is a large refrigerated tank that cools it between 10 to 15 °C. Then it is transported to dairy farms, where it is pasteurized. Pasteurization involves heating it to 73 °C and holding it at this temperature for 20 seconds. Thereafter, it is cooled to 3 to 4 °C.

Beverages**:** Production of beer, wine and concentrated fruit juices require refrigeration. The taste of many drinks can be improved by serving them cold or by adding ice to them. To preserve the taste and flavor of juice, the water is driven out of it by boiling it at low temperature under reduced pressure. The concentrate is frozen and transported at –20 °C.

Candy: Use of chocolate in candy or its coating with chocolate requires setting at 5-10^{o}C otherwise it becomes sticky. Further, it is recommended that it be stored at low temperature for best taste.

Processing and distribution of frozen food: Many vegetables, meat, fish and poultry are frozen to sustain the taste, which nearly duplicates that of the fresh product.

Applications of refrigeration in chemical and process industries

The industries like petroleum refineries, petrochemical plants and paper pulp industries etc. require very large cooling capacities. The requirement of each industry-process wise and equipment-wise is different hence refrigeration system has to be customized and optimized for individual application. The main applications of refrigeration in chemical and process industries involve the following categories.

1. ***Separation of gases*****:** In petrochemical plant, temperatures as low as –150^{o}C with refrigeration capacities as high as 10,000 Tons of Refrigeration (TR) are used for separation of gases by fractional distillation.

2. ***Condensation of Gases*****:** some gases that are produced synthetically, are condensed to liquid state by cooling, so that these can be easily stored and transported in liquid state. For example, in synthetic ammonia plant, ammonia is condensed at –10 to 10^{o}C before filling in the cylinders, storage and shipment. This low temperature requires refrigeration.

3. ***Dehumidification of Air:*** Low humidity air is required in many pharmaceutical industries. It is also required for air liquefaction plants. This is also required to prevent static electricity and prevents short circuits in places where high voltages are used. The air is cooled below its dew point temperature, so that some water vapour condenses out and the air gets dehumidified.

4. ***Solidification of Solute*****:** One of the processes of separation of a substance or pollutant or impurity from liquid mixture is by its solidification at low temperature. Lubricating oil is de-waxed in petroleum industry by cooling it below –25^{o}C. Wax solidifies at about –25^{o}C.

5. ***Storage as liquid at low pressure****:* Liquid occupies less space than gases. Most of the refrigerants are stored at high pressure. This pressure is usually their saturation pressure at atmospheric temperature. For some gases, saturation pressure at room temperature is very high hence these are stored at relatively low pressure and low temperature. For example natural gas is stored at 0.7 bar gauge pressure and –130^{o}C. Heat gain by the cylinder walls leads to boiling of some gas, which is compressed, cooled and expanded back to 0.7 bar gauge.

6. ***Removal of Heat of Reaction*****:** In many chemical reactions, efficiency is better if the reaction occurs below room temperature. This requires refrigeration. If these reactions are exothermic in nature, then more refrigeration capacities are required. Production of viscose rayon, cellular acetate and synthetic rubber are some of the examples. Fermentation is also one of the examples of this.

7. ***Cooling for preservation***: Many compounds decompose at room temperature or these evaporate at a very fast rate. Certain drugs, explosives and natural rubber can be stored for long periods at lower temperatures.

8. ***Recovery of Solvents*****:** In many chemical processes solvents are used, which usually evaporate after reaction. These can be recovered by condensation at low temperature by refrigeration system. Some of the examples are acetone in film manufacture and carbon tetrachloride in textile production.

Special applications of refrigeration

In this category we consider applications other than chemical uses. These are in manufacturing processes, applications in medicine, construction units etc.

1. ***Cold Treatment of Metals*****:** The dimensions of precision parts and gauge blocks can be stabilized by soaking the product at temperature around – 90 °C. The hardness and wear resistance of carburized steel can be increased by this process. Keeping the cutting tool at –100 °C for 15 minutes can also increase the life of cutting tool. In deep drawing process the ductility of metal increases at low temperature. Mercury patterns frozen by refrigeration can be used for precision casting.

2. ***Medical:*** Blood plasma and antibiotics are manufactured by freeze-drying process where water is made to sublime at low pressure and low temperature. This does not affect the tissues of blood. Centrifuges refrigerated at –10 °C, are used in the manufacture of drugs. Localized refrigeration by liquid nitrogen can be used as anesthesia also.

3***. Ice Skating Rinks***: Due to the advent of artificial refrigeration, sports like ice hockey and skating do not have to depend upon freezing weather. These can be played in indoor stadium where water is frozen into ice on the floor. Refrigerant or brine carrying pipes are embedded below the floor, which cools and freezes the water to ice over the floor.

4. ***Construction*****:** Setting of concrete is an exothermic process. If the heat of setting is not removed the concrete will expand and produce cracks in the structure. Concrete may be cooled by cooling sand, gravel and water before mixing them or by passing chilled water through the pipes embedded in the concrete. Another application is to freeze the wet soil by refrigeration to facilitate its excavation.

5***. Desalination of Water*****:** In some countries fresh water is scarce and seawater is desalinated to obtain fresh water. Solar energy is used in some cases for desalination. An alternative is to freeze the seawater. The ice thus formed will be relatively free of salt. The ice can be separated and thawed to obtain fresh water.

6. ***Ice Manufacture:*** This was the classical application of refrigeration. Ice was manufactured in plants by dipping water containers in chilled brine and it used to take about 36 hours to freeze all the water in cans into ice. The ice thus formed was stored in ice warehouses. Now that small freezers and icemakers are available. Hotels and restaurants make their own ice, in a hygienic manner. Household refrigerators also have the facility to make ice in small quantities. The use of ice warehouses is dwindling because of this reason. Coastal areas still have ice plants where it is used for transport of iced fish.

Refrigeration systems are also required in remote and rural areas for a wide variety of applications such as storage of milk, vegetables, fruits, foodgrains etc., and also for storage of vaccines etc. in health centers. One typical problem with many of the rural and remote areas is the continuous availability of electricity. Since space is not constraint, and most of these areas in tropical countries are blessed with alternate energy sources such as solar energy, biomass etc., it is preferable to use these clean and renewable energy sources in these areas.

Thermal energy driven absorption systems have been used in some instances. Vapour compression systems that run on photovoltaic (PV) cells have also been developed for small applications. Figure 3.5 shows the schematic of solar PV cell driven vapour compression refrigeration system for vaccine storage.

Methods of Refrigeration:

Refrigeration is defined as “the process of cooling of bodies or fluids to temperatures lower than those available in the surroundings at a particular time and place”. It should be kept in mind that refrigeration is not same as “cooling”, even though both the terms imply a decrease in temperature.

In general, cooling is a heat transfer process down a temperature gradient, it can be a natural, spontaneous process or an artificial process.

However, refrigeration is not a spontaneous process, as it requires expenditure of exergy (or availability). Thus cooling of a hot cup of coffee is a spontaneous cooling process (not a refrigeration process), while converting a glass of water from room temperature to say, a block of ice, is a refrigeration process (non-spontaneous). “All refrigeration processes involve cooling, but all cooling processes need not involve refrigeration”.

Refrigeration is a much more difficult process than heating, this is in accordance with the second laws of thermodynamics. This also explains the fact that people knew ‘how to heat’, much earlier than they learned ‘how to refrigerate’. All practical refrigeration processes involve reducing the temperature of a system from its initial value to the required temperature that is lower than the surroundings, and then maintaining the system at the required low temperature.

The second part is necessary due to the reason that once the temperature of a system is reduced, a potential for heat transfer is created between the system and surroundings, and in the absence of a “perfect insulation” heat transfer from the surroundings to the system takes place resulting in increase in system temperature. In addition, the system itself may generate heat (e.g. due to human beings, appliances etc.), which needs to be extracted continuously. Thus in practice refrigeration systems have to first reduce the system temperature and then extract heat from the system at such a rate that the temperature of the system remains low. Theoretically refrigeration can be achieved by several methods. All these methods involve producing temperatures low enough for heat transfer to take place from the system being refrigerated to the system that is producing refrigeration.

Methods of producing low temperatures

1. **Ice Refrigeration**

Ice was the only refrigeration means available for many years. The usual ice refrigerator consists of an insulated cabinet equipped with a tray at the top, for holding an ice blocks. Shelves for food are located below the ice compartment. Air surrounding these blocks gets cooled and descends down since it becomes denser. Warmer air at lower level is replaced by the cold dense air flows up.
Cold air flows downward from the ice compartment and cools the food on the shelves below. Air returns from the bottom of the cabinet up, the sides and back of the cabinet which is warmer, flows over the ice, and again flows down over the shelves to be cooled.

2. **Evaporative Refrigeration**

3. **Refrigeration By expansion of Air**

4. **Refrigeration By Throttling of the gas**

5. **Vapour Refrigeration systems**

6. **Vapour Absorption system**

7. **Steam jet Refrigeration systems**

8. **Refrigeration by using liquid gasses**

9. **Dry Ice Refrigeration**

UNIT-1

Refrigeration: The process of cooling of bodies or fluids to temperatures lower than those available in the surroundings at a particular time and place.

Refrigeration is not same as Cooling:

⇒ Cooling can be spontaneous and the final temperature need not be lower than the surroundings.

⇒ Refrigeration is not spontaneous and the final temperature should be lower than the surroundings.

Ex: (i) Cooling of a hot cup of coffee (cooling process)

(ii) Cooling of a glass of water by adding Ice (Refrigeration)

Air Conditioning:- Treatment of air so as to simultaneously control its temperature, moisture content, quality and circulation as required by occupants, a process or products in the space.

Application of Refrigeration.

⇒ Food Processing and preservation

⇒ Chemical and process Industries

⇒ Comfort and Industrial Air Conditioning

⇒ Miscellaneous.

Units of Refrigeration:-

The practical unit of refregeration is expressed in terms of tonne of refregeration. A tonne of refregration is defined as the amount of refrigeration effect produced by the uniform melting of one tonne (1000 kg) of ice from and at 0°C in 24 hours.

Since the latent heat of ice is 335 kJ/kg,

$$1\ TR = 1000 \times 335\ kJ \text{ in 24 hours}$$

$$= \frac{1000 \times 335}{24 \times 60} = 232.6\ kJ/min$$

~~= 3.5 kJ/s~~

In actual practice one tonne of refrigeration is taken as equivalent to 210 kJ/min or 3.5 kW (i.e 3.5 kJ/s)

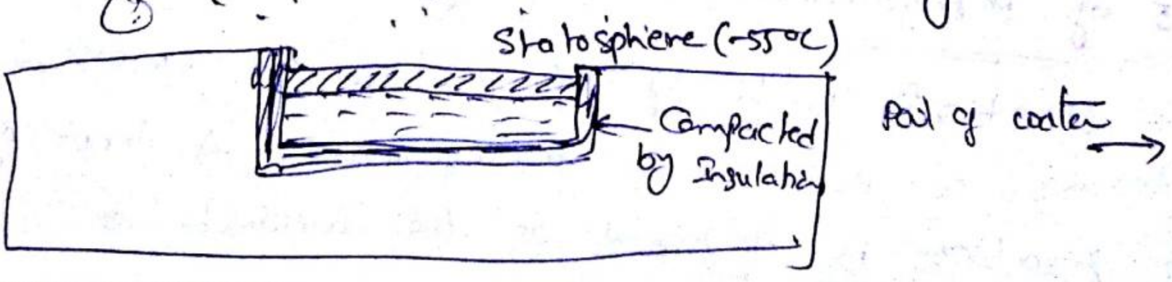
History of refrigeration can be broadly divided into two phases

(i) Age Natural refrigeration
↳ from pre-historic times to the begining of 19th century

(ii) Age of artificial refrigeration
↳ from 19th century onwards.

Natural Refrigeration methods:

1. Use of natural ice, that is
(a) Transported from colder regions. (Polar)
(b) Harvested in winter and stored for summer.
(c) Produced by Nocturnal cooling



Refrigerants:- these are the substances (working fluid) which are used for producing lower temperatures. i.e., these substances absorb heat from the storage space for maintaining lower temperatures.

Examples:- NH_3, CO_2, Air, water etc.,

Refrigeration Effect:- (RE)

The amount of heat that is to be removed from the storage space inorder to maintain lower temp is known as "refrigeration Effect (RE)".

Unit of Refrigeration (TR) → Ton of Refrigeration

It actually represents heat transfer rate one ton of refrigeration is the amount of heat that is to be removed 1 tonne of water [(American tonne) = 2000 lb = 907 kg] at 0°c in order to convert it into ice at 0°c in 1 day.

$$1\,TR = m \times \text{Latent Heat of water} \qquad LH_{H_2O} = 334\ \frac{kJ}{kg}$$

$$= \frac{907}{24 \times 60 \times 60} \times 334$$

$$\boxed{1\,TR = 3.5\ kW}$$

$$\boxed{\begin{array}{c} 210\ kJ/min\ \text{(or)} \\ 3.5\ kJ/sec \end{array}}$$

$$C.O.P = \frac{N}{W}$$

$$W = \frac{N}{COP} = \frac{210}{COP}\ kJ/min$$

$$= \frac{210}{60 \times COP} = \frac{3.5}{COP}\ kJ/s$$

power required per ton of refrigeration $= \frac{3.5}{COP}\ kW$

Co-efficient of performance of a Refrigerator

The COP is the ratio of heat extracted in the refrigerator to the work done on the refrigerant. It is also known as theoretical coefficient of performance. Mathematically

$$\text{Theoretical COP} = \frac{Q}{W}$$

Q = Amount of heat extracted in the refrigerator

W = Amount of work done.

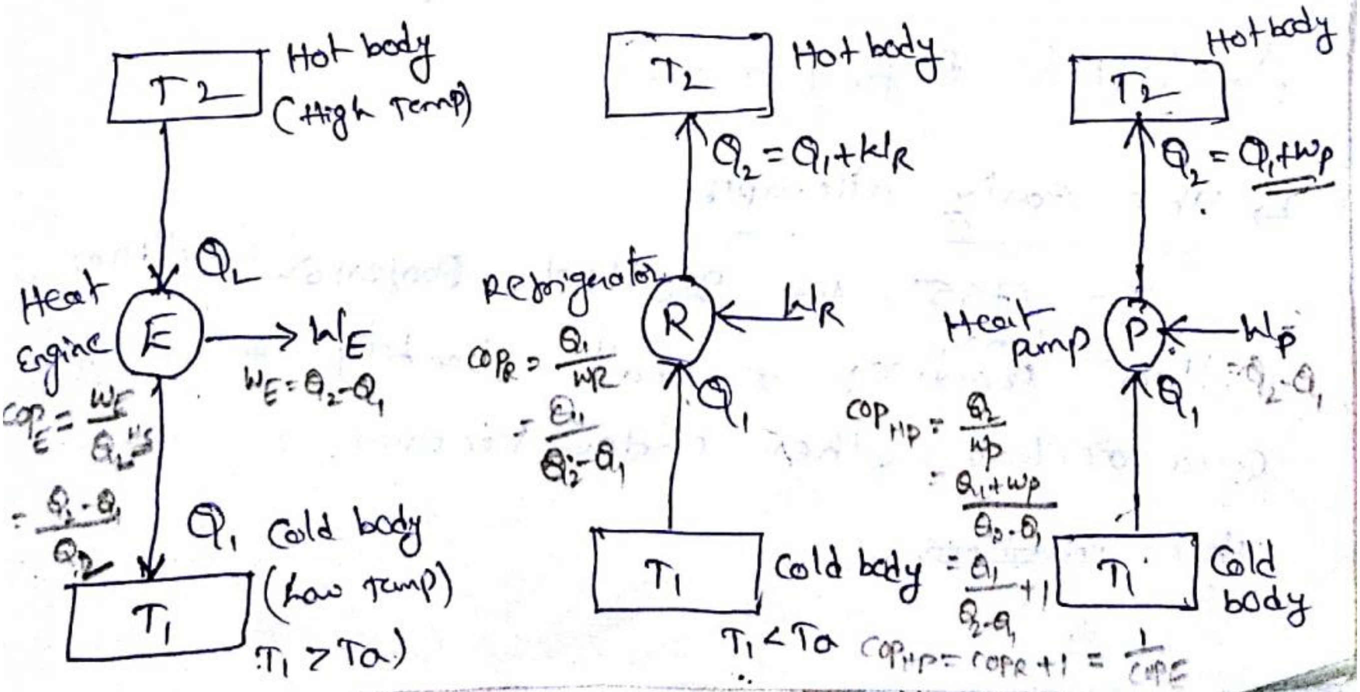
Note:- 1. For per unit mass $COP = \frac{q}{w}$

2. The COP is the reciprocal of the efficiency

$$COP = \frac{1}{\eta}$$

3. $$\text{Relative COP} = \frac{\text{Actual COP}}{\text{Theoretical COP}}$$

Difference b/w a Heat Engine, Refrigerator and Heat Pump:



→ In a Heat Engine the heat supplied to the Engine is converted into useful work. If Q_2 is the heat supplied to the engine and Q_1 is the heat rejected from the Engine then the net work done by the Engine is given by $W_E = Q_2 - Q_1$

$$\eta_E \text{ or } (C.O.P)_E = \frac{\text{Work done}}{\text{Heat supplied}} = \frac{W_E}{Q_2} = \frac{Q_2 - Q_1}{Q_2}$$

⇒ A Refrigerator is a reversed heat engine which either cool or maintain the temperature of a body (T_1) lower than the atmospheric temperature (T_a). This is done by extracting the heat (Q_1) from a cold body and delivering it to a hot body (Q_2). ~~In doing so~~

$$W_R = Q_2 - Q_1$$

$$(C.O.P)_R = \frac{Q_1}{W_R} = \frac{Q_1}{Q_2 - Q_1}$$

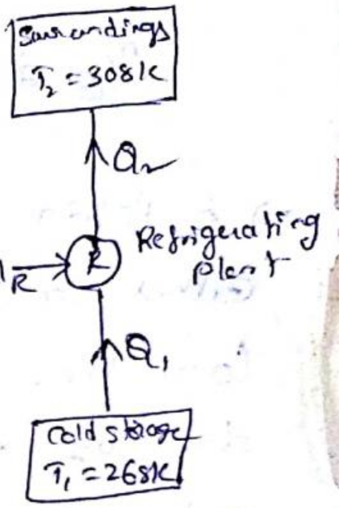
The COP of Refrigerator is expressed by the ratio of amount of heat taken from cold body (Q_1) to the amount of work required to be done on the system (W_R).

⇒ Any Refrigerating system is a heat pump which extracts heat (Q_1) from cold body and delivers it to a hot body. Thus there is no difference between the cycle of operating of heat pump and a refrigerator. The performance of heat pump is expressed by the ratio of the amount of heat delivered to the hot body (Q_2) to the amount of W.D on the system. (W_P)

$$W_P = Q_2 - Q_1$$

$$(C.O.P)_P = \frac{Q_2}{W_P} = \frac{Q_2}{Q_2 - Q_1} = \frac{Q_1}{Q_2 - Q_1} + 1 = (C.O.P)_R + 1$$

⇒ A Cold storage is to be maintained at -5°C while the surroundings are at 35°C. The heat leakage from the surroundings into the cold storage is estimated to be 29 kW. The actual COP of the refrigeration plant is one-third of an ideal plant working between the same temperatures. Find the power required to drive the plant.



Sol: G.D

$T_1 = -5°C = -5+273 = 268K$

$T_2 = 35°C = 35+273 = 308K$

$Q_1 = 29\ kW$

$(C.O.P)_{actual} = \frac{1}{3}(C.O.P)_{ideal}$

R.T: $W_R = ?$

F.U = $(C.O.P)_{ideal} = \frac{T_1}{T_2 - T_1}$

$(C.O.P)_{actual} = \frac{Q_1}{W_R}$

Calculations:

$(C.O.P)_{ideal} = \frac{T_1}{T_2 - T_1} = \frac{268}{308-268} = 6.7$

$(C.O.P)_{actual} = \frac{1}{3}(C.O.P)_{ideal} = \frac{1}{3} \times 6.7 = 2.233$

$(C.O.P)_{actual} = \frac{Q_1}{W_R}$

$W_R = \frac{Q_1}{(C.O.P)_{actual}}$

$= \frac{29}{2.233} = 12.987\ kW$

$\boxed{\therefore W_R = 12.987\ kW}$

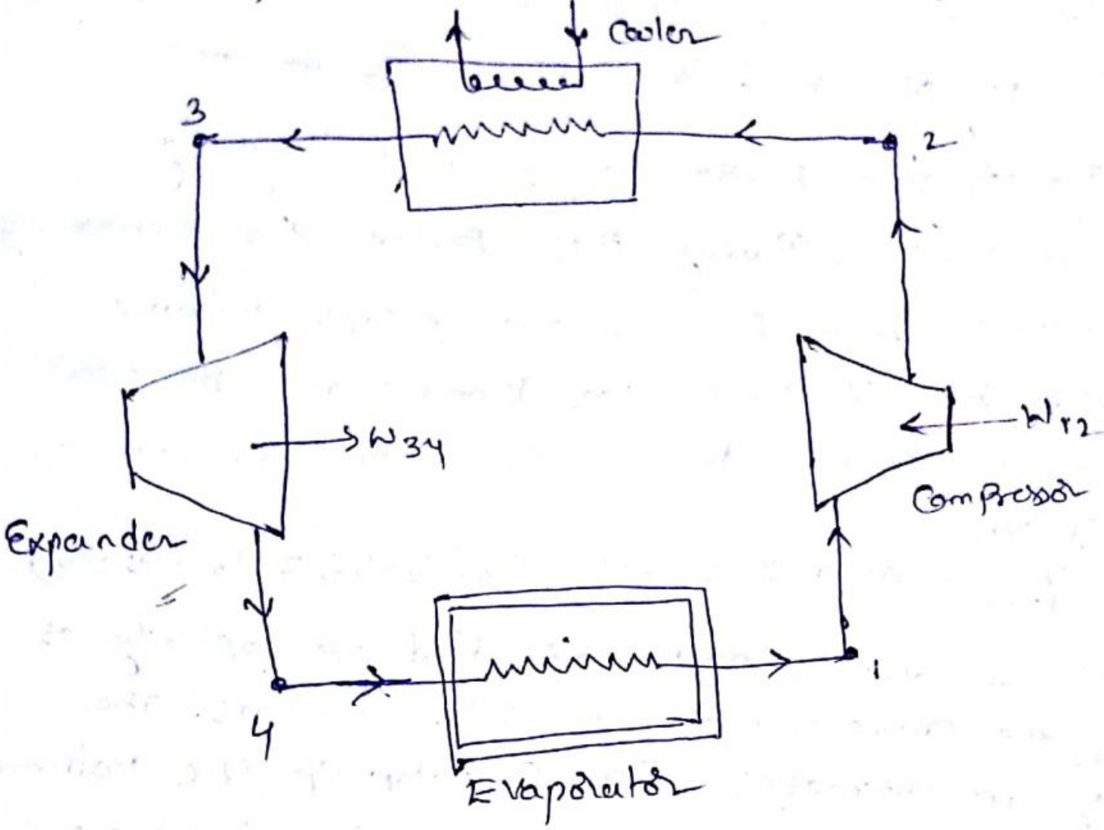
$(COP)_R = \frac{T_1}{T_2 - T_1}$

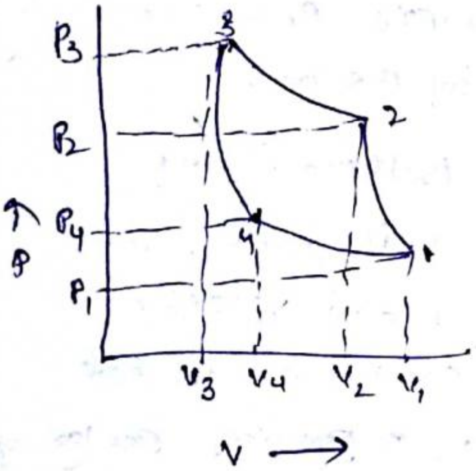
$(COP)_P = \frac{T_2}{T_2 - T_1}$

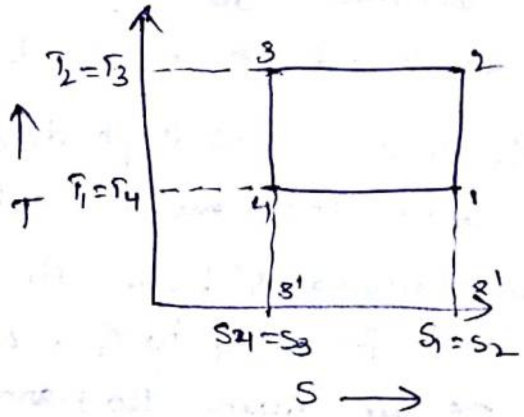
$(COP)_E = \frac{T_2 - T_1}{T_2}$

$T_2 > T_1$

Reversed Carnot Cycle:- If the Carnot cycle is reversed, it becomes ideal refrigeration cycle.







The reversed Carnot cycle is shown on P-V and T-s diagrams as shown in fig, Using air as the refrigerant and operates as follows.

Process 1-2 : Isentropic Compression Process

Process 2-3 : Isothermal Compression Process

Process 3-4 : Isentropic Expansion Process

Process 4-1 : Isothermal Expansion Process.

Process 1-2: Air enters the compressor at point 1. and compressed isentropically by external energy. Temperature increases from $\overset{T_1 \text{ to } T_2}{(T_2 \text{ to } T_1)}$. In this operation no heat is absorbed or rejected by the air.

Process 2-3:- The air is now compressed isothermally (i.e const temp $T_2 = T_3$). During this process the pressure of air increases from P_2 to P_3 and specific volume decreases from V_2 to V_3. We know that the heat rejected by the air during isothermal compression per kg of air

$$q_R = q_{2-3} = \text{Area } 2-3-3'-2' = T_3(S_2 - S_3) = T_2(S_2 - S_3).$$

Process 3-4: The air is now expanded isentropically as shown by the curve 3-4 on P-V and T-S diagrams. The pressure of air decreases from P_3 to P_4. Specific volume increases from V_3 to V_4 and the temperature decreases from T_3 to T_4. We know that during isentropic expansion no heat is absorbed or rejected by the air.

Process 4-1: The air is now expanded isothermally as shown by the curve 4-1 on P-V and T-S diagrams. The pressure of air decreases from P_4 to P_1 and specific volume increases from V_4 to V_1. We know that the heat absorbed by the air during isothermal expansion per kg of air. $q_A = q_{4-1} = \text{Area } 4-1-2'-3' = T_4(S_1 - S_4) = T_1(S_2 - S_3)$

W.K.T W.D during the cycle per kg of air

$$W_R = H.R - H.O. = q_R - q_A = q_{2-3} - q_{4-1}$$

$$= T_2(S_2 - S_3) - T_1(S_2 - S_3) = (T_2 - T_1)(S_2 - S_3)$$

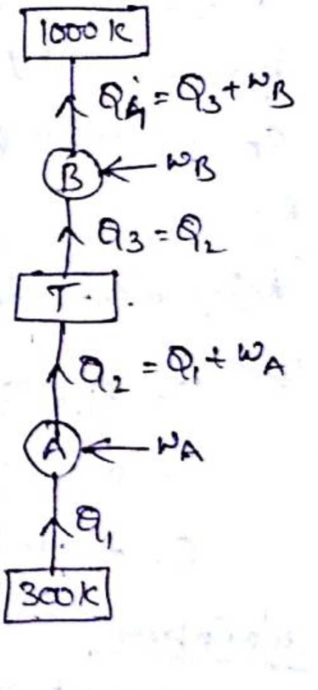
$$(C.O.P)_R = \frac{H.O}{W.D} = \frac{T_1(S_2 - S_3)}{(T_2 - T_1)(S_2 - S_1)} = \frac{T_1}{T_2 - T_1}$$

Note: $(C.O.P)_P = (C.O.P)_R + 1 = \frac{T_1}{T_2 - T_1} + 1 = \frac{T_2}{T_2 - T_1}$

$$(C.O.P)_E = \frac{W_R}{q_R} = \frac{(T_2 - T_1)(S_2 - S_3)}{T_2(S_2 - S_3)} = \frac{T_2 - T_1}{T_2} = \frac{1}{(C.O.P)_P}$$

Two Refrigerators A and B operate in series. I-5

The refrigerator A absorbs energy at the rate of 1 kJ/s from a body at temperature 300K and rejects energy as heat to a body at temperature T. The refrigerator B absorbs the same quantity of energy which is rejected by the refrigerator A from the body at temperature T, and rejects energy as heat to a body at temperature 1000 K. If both the refrigerators have the same C.O.P calculate 1. The temperature T of the body (2) The C.O.P of the refrigerators (3) The rate at which energy is rejected as heat to the body at 1000 K.



Sol: G.D

$Q_1 = 1\,kJ/s$, $T_1 = 300K$; $T_2 = T$; $T_3 = 1000\,K$

R.T $T = ?$, $(C.O.P)_A = (C.O.P)_B = ?$, $Q_4 = ?$

F.U: $(C.O.P)_A = \frac{T_1}{T_2 - T_1}$; $(C.O.P)_B = \frac{T_2}{T_3 - T_2}$

$(C.O.P)_A = \frac{Q_1}{W_A} \Rightarrow W_A = \frac{Q_1}{(C.O.P)_A}$

$Q_2 = Q_1 + W_A$

$(C.O.P)_B = \frac{Q_3}{W_B} \Rightarrow W_B = \frac{Q_3}{(C.O.P)_B}$

$Q_4 = Q_3 + W_B$

C.L:

(i) $(C.O.P)_A = \frac{T_1}{T_2 - T_1} = \frac{300}{T - 300} \longrightarrow ①$ $(C.O.P)_B = \frac{T_2}{T_3 - T_2} = \frac{T}{1000 - T} \rightarrow ②$

$\frac{300}{T-300} = \frac{T}{1000-T} \Rightarrow 300 \times 1000 - 300T = T^2 - 300T \Rightarrow T = 547.7\,K$

(ii) $(C.O.P)_A = (C.O.P)_B = \frac{300}{547.7 - 300} = 1.21$

(iii) $W_A = \frac{Q_1}{(C.O.P)_A} = \frac{1}{1.21} = 0.826\,kJ/s$; $Q_2 = Q_1 + W_A = 1 + 0.826 = 1.826\,kJ/s$

$W_B = \frac{Q_3}{(C.O.P)_B} = \frac{1.826}{1.21} = 1.51\,kJ/s$; $Q_4 = Q_3 + W_B = 1.826 + 1.51$

$= 3.336\,kJ/s$

— o —

⇒ Five hundread kgs 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 the storage temperature in 10 hours. The latent heat of freezing is 105 kJ/kg and specific heat of fruit is 1.256 kJ/kg k. Find the refrigeration capacity of the plant.

Sol: G.D

$m = 500\ kg$

$T_2 = 20°C = 20+273 = 293k$

$T_1 = -5°C = -5+273 = 268\ k$

$h_{fg} = 105\ kJ/kg$

$C_F = 1.256\ kJ/kg\ k$

R.T

Refrigeration Capacity of the plant = ?

F.U

$Q = Q_1 + Q_2$

$Q_1 = mC_F\,(T_2 - T_1)$

$Q_2 = m\,h_{fg}$

Calculations:

w.k.T heat removed from the fruits in 10 hours:

$$Q_1 = m\,C_p\,(T_2 - T_1)$$
$$= 500 \times 1.256\,(293-268)$$
$$= 15700\ kJ$$

Total latent heat of freezing

$$Q_2 = m\,h_{fg} = 500\times105 = 52500\ kJ$$

∴ Total heat removed in 10 hours

$$Q = Q_1 + Q_2 = 15700 + 52500$$
$$= 68200\ kJ$$

Total heat removed in one minute

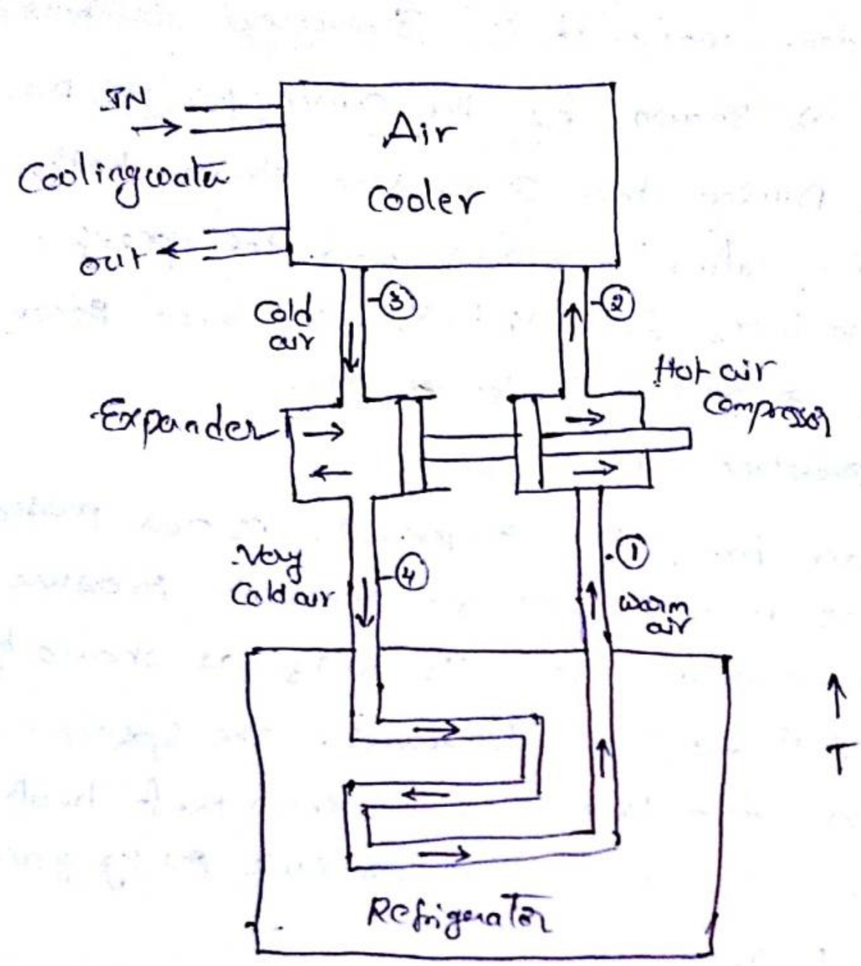
$$= \frac{68200\ \cancel{\times 60}}{10\times60}$$
$$= 113.7\ kJ/min$$

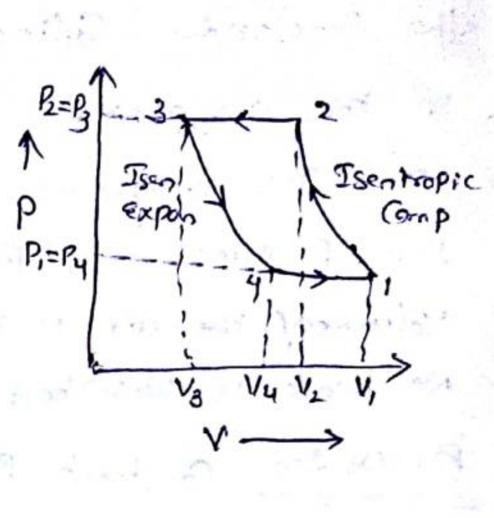
∴ Refrigeration Capacity of the plant

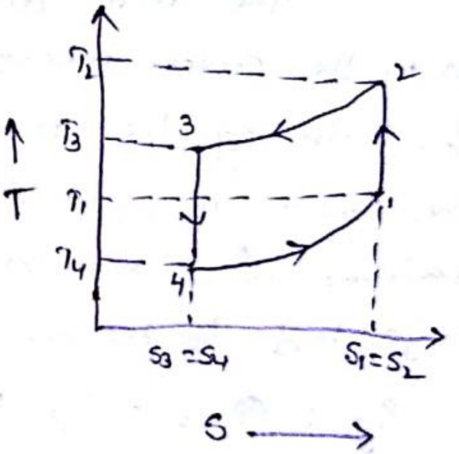
$$= \frac{113.7}{210}$$
$$= 0.541\ TR$$

$\boxed{\because 1TR = 210\ kJ/min}$

Bell coleman Cycle or Reversed Brayton or Joule cycle







It is Modified Reverse Carnot Cycle

Air refrigeration System working on reversed Brayton Cycle. Elements of the systems are 1. Compressor 2. Cooler 3. Expander 4. Refrigerator. In this System work gained from expander is employed for Compression of air, thus less external work is needed for operation of the system. In this Cycle there are four processes.

1. Isentropic Compression process
2. Process 2-3: Constant Pressure Cooling Process
3. Process 3-4: Isentropic Expansion Process
4. Process 4-1 : Constant pressure Expansion Process

Process 1-2: Isentropic Compression Process.

The cold air from the refrigerator is drawn into the compressor cylinder where it is compressed isentropically in the compressor as shown by the curve 1-2 on P-V and T-S diagrams. During this compression stroke both the pressure and temperature increases and the specific volume of the air is reduces from V_1 to V_2. In this process no heat is absorbed or rejected by the air.

Process 2-3: Constant pressure cooling process

The warm air from the compressor is now passed in to the cooler where it is cooled at constant pressure P_3. reducing the temperature from T_2 to T_3 as shown by the curve 2-3 on P-V and T-S diagrams. The specific volume also reduces from V_2 to V_3. We know that heat rejected by the air during constant pressure per kg of air.

$$q_R = Q_{2-3} = C_p(T_2 - T_3)$$

Process 3-4: Isentropic Expansion Process:

The air from the cooler is drawn in to the expander cylinder where it is expanded isentropically from pressure P_3 to P_4 which is equal to the atmospheric pressure. The temperature of air during expansion falls from T_3 to T_4 and the specific volume of air at entry to the refrigerator increases from V_3 to V_4. shown by the curve 3-4 on P-V and T-S diagrams.

Process 4-1: Constant Pressure Expansion Process

The cold air from the expander is now passed to the refrigerator where it is expanded at constant pressure P_4. The temperature of air increases T_4 to T_1. Due to heat from the refrigerator the specific volume of the air changes as shown by the curve 4-1 in P-V & T-S diagram. from V_4 to V_1. We know that the heat absorbed by the air during constant pressure expansion per kg of air is

$$q_A = q_{4-1} = C_p(T_1 - T_4)$$

We know that workdone during the cycle per kg of air

$$= \text{Heat rejected} - \text{Heat absorbed}$$
$$= q_R - q_A$$
$$= C_p(T_2 - T_3) - C_p(T_1 - T_4) = C_p\left[(T_2 - T_3) - (T_1 - T_4)\right]$$

∴ Co-efficient of performance

$$C.O.P = \frac{\text{Heat absorbed}}{\text{Workdone}} = \frac{q_A}{q_R - q_A}$$

$$= \frac{C_p(T_1 - T_4)}{C_p\left[(T_2 - T_3) - (T_1 - T_4)\right]} = \frac{T_1 - T_4}{(T_2 - T_3) - (T_1 - T_4)}$$

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

We know that for isentropic compression process 1-2

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

lly 3-4 process.

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

$P_2 = P_3$ and $P_1 = P_4$. then

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \frac{T_3}{T_4}$$

$$\frac{T_2}{T_3} = \frac{T_1}{T_4} \longrightarrow ②$$

$$\therefore C.O.P = \frac{T_4\left(\frac{T_1}{T_4} - 1\right)}{(T_3 - T_4)\left(\frac{T_1}{T_4} - 1\right)} = \frac{T_4}{T_3 - T_4} = \frac{T_4}{T_4\left(\frac{T_3}{T_4} - 1\right)}$$

$$= \frac{1}{\left(\frac{T_3}{T_4}\right) - 1} = \frac{1}{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1} = \frac{1}{(r_p)^{\frac{\gamma-1}{\gamma}} - 1}$$

∴ r_p = Compression or Expansion ratio $= \frac{P_2}{P_1} = \frac{P_3}{P_4}$.

Note:- 1. Some times the Compression and Expansion Process take place according to the law $pv^n = Const$. In such case the C.O.P =

$$C.O.P = \frac{T_1 - T_4}{\frac{n}{n-1} \times \frac{\gamma-1}{\gamma}\left[(T_2 - T_3) - (T_1 - T_4)\right]} \longrightarrow (i)$$

2. In this case the values of T_2 and T_4 are to be obtained from the following relations

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} \quad \text{and} \quad \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}}$$

3. For isentropic Compression or expansion $n = \gamma$ therefore the equation (i) may be written as

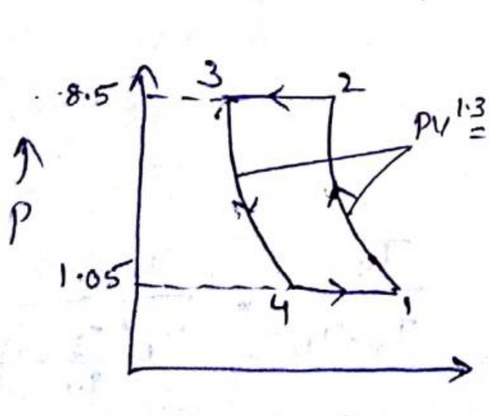
$$C.O.P = \frac{T_1 - T_4}{(T_2 - T_3) - (T_1 - T_4)}$$

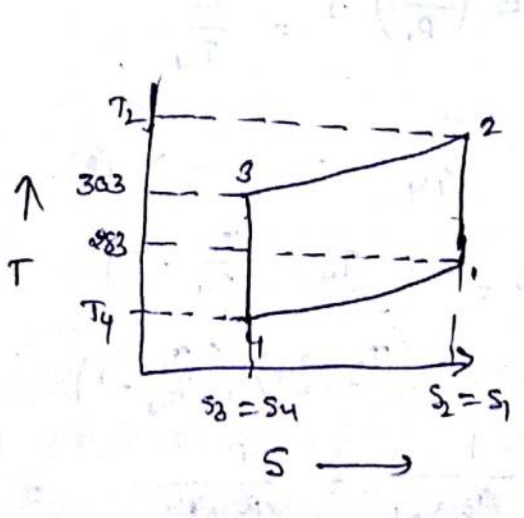
⇒ A refrigerator working on Bell-coleman cycle operates between pressure limits of 1.05 bar and 8.5 bar. Air is drawn from the cold chamber at 10°C. Compressed and then it is cooled to 30°C before entering the expansion cylinder. The expansion and compression follows the law $pv^{1.3} = Const$. Determine the theoretical C.O.P of the system.

G.D: $P_1 = P_4 = 1.05$ bar ; $P_2 = P_3 = 8.5$ bar ; $T_1 = 10$

$T_1 = 10°C = 10 + 273 = 283K$; $T_3 = 30°C = 30 + 273 = 303K$.

$n = 1.3$; $\gamma = 1.4$





R.T: C.O.P = ?

F.U: $$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{T_3}{T_4}\right)$$

$$C.O.P = \frac{T_1 - T_4}{\left(\frac{n}{n-1}\right)\left(\frac{\gamma-1}{\gamma}\right)\left[(T_2 - T_3) - (T_1 - T_4)\right]}$$

Calculations:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.3-1}{1.3}} = (8.1)^{0.231} = 1.62$$

$$T_2 = 1.62 \times T_1 = 283 \times 1.62 = 458.5\,K$$

$$\frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{\frac{n-1}{n}} = \left(\frac{8.5}{1.05}\right)^{\frac{1.3-1}{1.3}} = (8.1)^{0.231} = 1.62$$

$$T_4 = T_3/1.62 = 303/1.62 = 187\,K$$

Theoretical Co-efficient of Performance

$$C.O.P = \frac{T_1 - T_4}{\left(\frac{n}{n-1}\right)\left(\frac{\gamma-1}{\gamma}\right)\left[(T_2 - T_3) - (T_1 - T_4)\right]}$$

$$= \frac{283 - 187}{\left(\frac{1.3}{1.3-1}\right)\left(\frac{1.4-1}{1.4}\right)\left[(458.5 - 303) - (283 - 187)\right]}$$

$$= \frac{96}{1.24 \times 59.5}$$

$$= 1.3$$

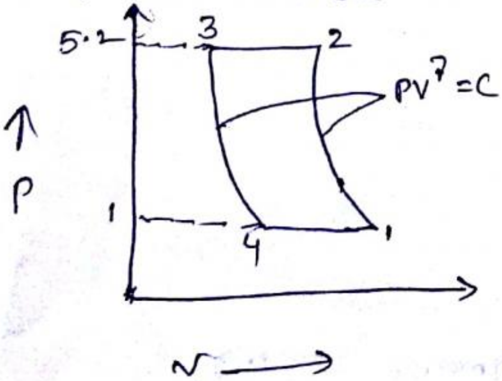
Answer:

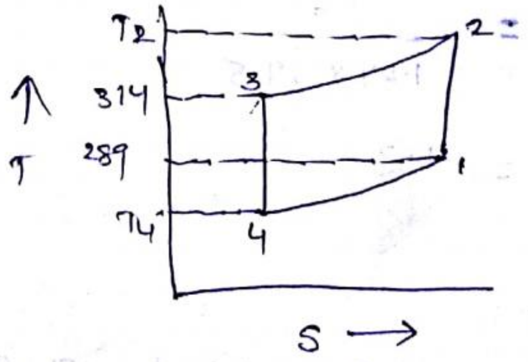
Theoretical Co-efficient of Performance = 1.3.

⇒ A refrigerating machine of 6 tonnes capacity working on Bell-Coleman cycle has an upper limit of pressure of 5.2 bar. The pressure and temperature at the start of compression are 1 bar and 16°C respectively. The compressed air is cooled at constant pressure to a temperature of 41°C enters the expansion cylinder. Assuming both expansion and compression processes to be isentropic with $\gamma = 1.4$. Calculate 1. Co-efficient of performance
2. Quantity of air in circulation per minute
3. Piston displacement of compressor and expander
4. Bore of compressor and expansion cylinders, the unit runs at 240 rpm. and is double acting. Stroke length is 200mm
5. Power required to drive the unit. for air take $\gamma = 1.4$ and $C_p = 1.003$ kJ/kgK.

Sol: G.D

$Q = 6TR = 6 \times 210 = 1260$ kJ/min ; $P_2 = P_3 = 5.2$ bar
$P_1 = P_4 = 1$ bar $= 1 \times 10^5$ N/m^2 ; $T_1 = 16°C = 16+273 = 289$ K
$T_3 = 41°C = 41+273 = 314$ K ; $\gamma = 1.4$, $N = 240$ rpm, $L = 200$ mm
$C_p = 1.003$ kJ/kgK





R.T:
1. $COP = ?$
2. $m_a = ?$
3. $v_1 = ?$, $v_4 = ?$
4. $D = ?$, $d = ?$
5. $P = ?$

F.U :

$$\left(\frac{T_2}{T_1}\right) = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{T_3}{T_4}\right)$$

$$C.O.P = \frac{T_4}{T_3 - T_4}$$

$$m_a = \frac{\text{Heat Extracted}}{\text{Capacity}} \text{ kg/min}$$

Heat extracted $= C_p (T_1 - T_4)$ kJ/kg

$C_p - C_v = R_a \Rightarrow 1 - \frac{1}{\gamma} = \frac{R_a}{C_p} \Rightarrow R_a = C_p\left(\frac{\gamma-1}{\gamma}\right)$

$P_1 V_1 = m_a R_a T_1 \Rightarrow V_1 = \frac{m_a R_a T_1}{P_1}$ $(\because R_a = 287)$

Process 4-1 $\frac{V_4}{T_4} = \frac{V_1}{T_1} \Rightarrow V_4 = \frac{V_1 T_4}{T_1}$

$V_1 = \left[\frac{\pi}{4} D^2 \times L \times 2\right] N$ $(\because 2 \text{ D Double acting})$

$V_4 = \left[\frac{\pi}{4} d^2 \times L \times 2\right] N$

COP. ~~Power~~ $= \frac{\text{Heat absorbed}}{\text{Work done}} \Rightarrow W.D = \frac{H.A}{60 \times C.O.P}$ ~~kJ/min~~ kW

Heat absorbed $= m_a C_p (T_1 - T_4)$

Calculations:-

(1) Co-efficient of Performance:-

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5.2}{1}\right)^{\frac{1.4-1}{1.4}} = (5.2)^{0.286} = 1.6$$

$T_2 = 1.6 \times T_1 = 1.6 \times 289 = 462.4\,K$

$T_4 = \frac{T_3}{1.6} = \frac{314}{1.6} = 196.25\,K$

$$C.O.P = \frac{T_4}{T_3 - T_4} = \frac{196.25}{314 - 196.25} = 1.674$$

(2) Quantity of air in circulation per minutes:

Heat Extracted $= C_p(T_1 - T_4) = 1.003(289 - 196.25)$

$= 93$ kJ/kg.

Capacity $= 6TR = 6 \times 210 = 1260$ kJ/min

mass of air in circulation

$$m_a = \frac{1260}{93} = 13.548 \text{ kg/min}$$

(3) Piston displacement of compressor and expander:

$$R_a = C_p\left(\frac{\gamma-1}{\gamma}\right) = 1.003\left(\frac{1.4-1}{1.4}\right) = 0.287 \text{ kJ/kg K}$$

$= 287$ J/kg K

$$V_1 = \frac{m_a R_a T_1}{P_1}$$

$$= \frac{13.548 \times 287 \times 289}{1 \times 10^5} = 11.237 \text{ m}^3\text{/min}$$

$$V_4 = V_1 \times \frac{T_4}{T_1} \quad 11.237 \times \frac{196.25}{289} = 7.63 \text{ m}^3\text{/min}$$

(4) Bore of compressor and Expension cylinders:

$$V_1 = \left[\frac{\pi}{4} D^2 \times L \times 2\right] N = \frac{\pi}{4}$$

$$11.237 = \frac{\pi}{4} \times D^2 \times 0.2 \times 2 \times 240 = 75.4 D^2$$

$$D^2 = \frac{11.237}{75.4} = 0.149$$

$D = 0.386$ m $= 386$ mm

$$V_4 = \left(\frac{\pi}{4} d^2 L \times 2\right) N$$

$$7.63 = \frac{\pi}{4} d^2 \times 0.2 \times 2 \times 240 = 75.4 d^2$$

$$d^2 = \frac{7.63}{75.4} = 0.1012$$

$d = 0.318$ m $= 318$ mm

(5) Power required to drive the unit:-

Heat Absorbed $= m_a C_p (T_1 - T_4)$

$= 13.548 \times 1.003 \times (289 - 196.25)$

$= 1260$ kJ/min

Work done $= \dfrac{\text{Heat Absorbed}}{\text{C.O.P}}$

$= \dfrac{1260}{1.674} = 752.7$ kJ/min

Power required to drive the unit $= \dfrac{752.7}{60}$ kJ/sec

$= 12.54$ kW

Answers:-

① Coefficient of performance $= 1.674$

② Quantity of air in circulation per minute = 13.548 kg/min

= 13.548 kg/min

③ Piston displacement of Compressor and Expander

$V_1 = 11.237$ m³/min

$V_4 = 7.63$ m³/min

④ Bore of Compressor and expansion Cylinder

$D = 386$ mm

$d = 318$ mm

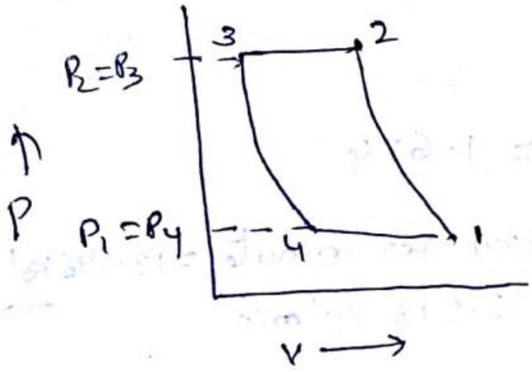
⑤ Power required to drive the unit = 12.54 kW

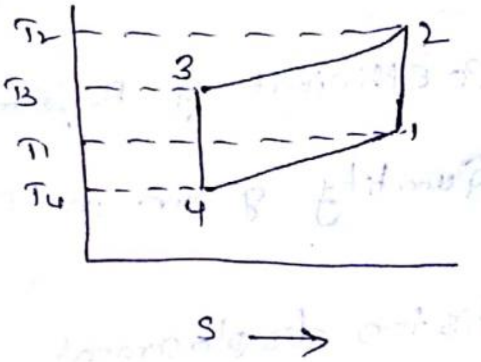
= x =

⇒ An air refrigeration used for food storage provides 25TR. The temperature of air entering the Compressor is 7°c and the temperature at exit of cooler is 27°c. Find 1. C.O.P of the Cycle 2. Power per tonne of refrigeration required by the Compressor. The quantity of air Circulated in the system is 3000 kg/h. The Compression and expansion both follows the law $pv^{1.3}$ = Const and take $\gamma = 1.4$ and $C_p = 1$ kJ/kg K for air.

G.D $Q = 25TR$, $T_1 = 7°C = 7+273 = 280K$

$T_3 = 27°C = 27+273 = 300K$, $m_a = 3000 kg/h = 50 kg/min$





R.T: (i) C.O.P of the cycle = ?

(ii) Power per tonne of refrigeration = ?

F.U

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

$$\frac{T_3}{T_4} = \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

Heat Extracted from the refrigerator $= m_a C_p (T_1 - T_4)$

Heat absorbed during the Const Pressure 4-1 process

$= m_a C_p (T_1 - T_4)$

$$\text{Work done/min} = \frac{\text{Heat absorbed}}{C.O.P}$$

$$\text{power} = \frac{W.D}{60 \times 25} \text{ kW/TR}$$

C.L Heat Extracted from the refrigerator = 25×210 = 5250 kJ/min ←①

therefore Heat extracted from the refrigerator

$= m_a C_p (T_1 - T_4) = 50 \times 1 (280 - T_4)$

$= 50(280 - T_4)$ kJ/min →②

Equating Eq ① & ②

$50(280 - T_4) = 5250$

$280 - T_4 = \frac{5250}{50} = 105$

$T_4 = 280 - 105 = 175$ K

W.K.T $\frac{T_3}{T_4} = \frac{T_2}{T_1} \Rightarrow T_2 = \frac{T_3 \times T_1}{T_4} = \frac{280 \times 300}{175} = 480$ k

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

$$= \frac{280 - 175}{\frac{1.3}{1.3 - 1} \times \frac{1.4 - 1}{1.4} \left[(480 - 300) - (280 - 175) \right]} = 1.13$$

Heat absorbed $= m_a C_p (T_1 - T_4)$

$= 50 \times 1 (280 - 175) = 5250$ kJ/min

Work done /min $= \frac{\text{Heat Absorbed}}{C.O.P} = \frac{5250}{1.13} = 4646$ kJ/min

Power per tone of refrigeration

$= \frac{4646}{60 \times 25} = 3.1$ kW/TR

Answers:

(i) C.O.P = 1.13

(ii) Power = 3.1 kW/TR

Open and Dense air Systems:

In closed (dense air) system the air refrigerant is contained within the component parts of the system. at all times and refrigerator with usually pressures above atmospheric pressure.

In open system the refrigerator is replaced by the actual space to be cooled with the air expanded to atmospheric pressure, circulated through the cold room and then compressed to the cooler pressure. The pressure of operation is limitted to operation at atmospheric pressure in the refrigerator.

The Advantages of closed system over open system:

=> As suction to compressor is at high pressure sizes of Expander and compressor are uses in closed system.

=> In open system air picks up moisture from products kept in refrigerated chamber, moisture may freeze during expansion and may choke the valves.

=> In open system the expansion of refrigerant can be carried only upto atmospheric pressure but for closed system there is no such restriction.

Refrigeration System Used in Aircraft:

The air cycle continues to be favoured for aircraft refrigeration. The main considerations involved in an aircraft application in order of importance are weight, space and operating power. through the power per ton of refrigeration is considerably more for air cycle refrigeration than vapour compression system, the bulk and weight advantanges of air cycle system due to no heat exchanger at cold end and a common turbo compressor for both the engine and refrigeration plant, result in a greater overall power saving in the aircraft.

The advantages of an air cycle with regard to its application in aircraft refrigeration are

- => Small amounts of leakage are tolerable with air as refrigerant.
- => Availability of the refrigerant in mid air is an important consideration.
- => Intial compression of the air is obtained by the ram effect due to the high kinetic energy of the ambient air relative to the aircraft.

The air cycle systems for aircraft refrigeration.

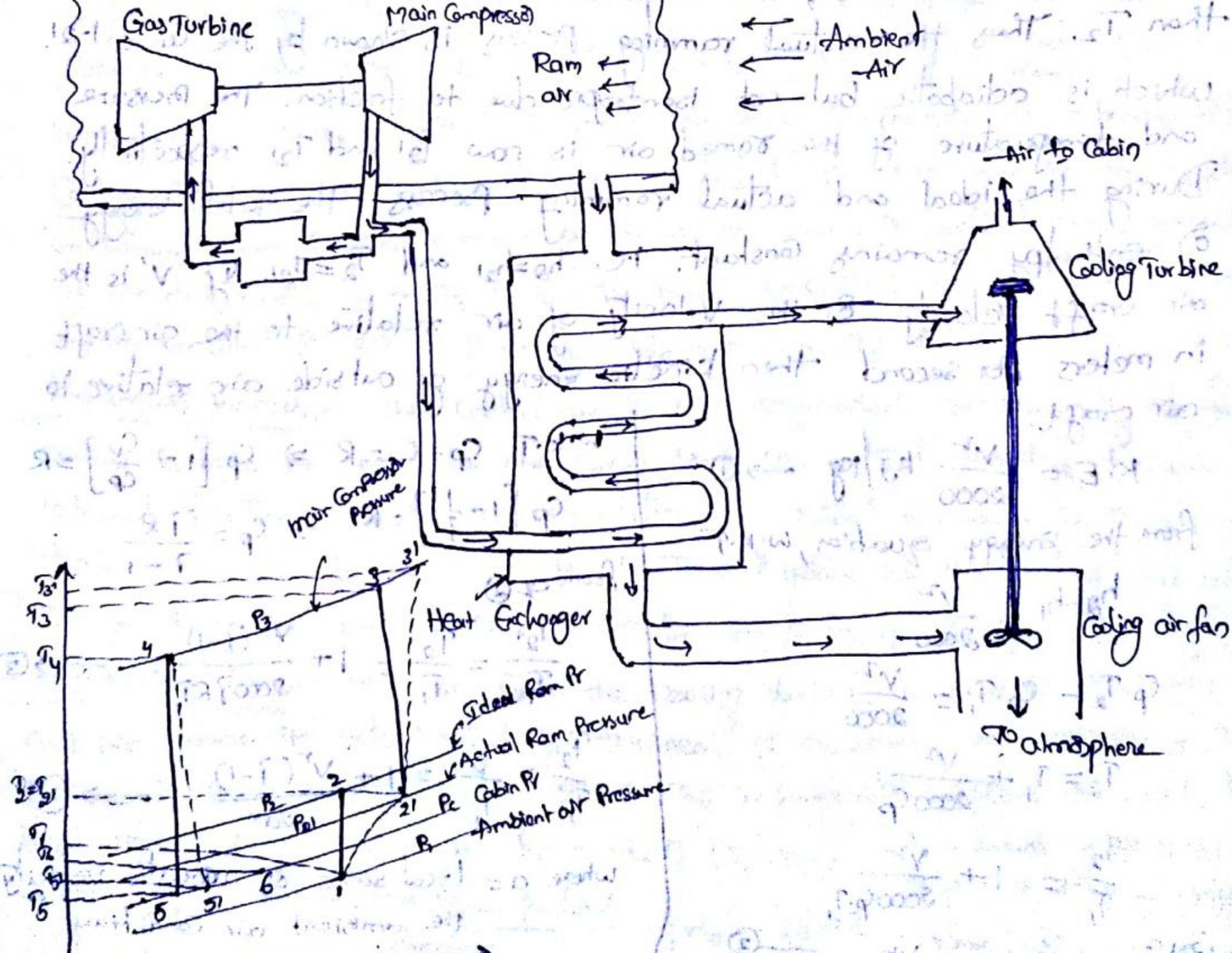
1. Simple system
2. Boot strap system
3. Regenerative system
4. Reduced ambient system.

Methods of Air Refrigeration Systems:-

The various methods of air refrigeration system used for aircrafts these days are as follows.

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

1. Simple Air Cooling System:-



A simple air cooling system for aircrafts, as shown in figure. The main components of this system are the main compressor driven by a gas turbine, a heat exchanger, a cooling turbine and a cooling air fan. The air required for refrigeration system is beld off from the main compressor. This high pressure and high temperature air is cooled initially in the heat exchanger where ram air is used for cooling. It is further cooled in the cooling turbine by the process of expansion. The work of this turbine is used to drive the cooling fan which draws cooling air through the heat exchanger. This system is good for ground surface cooling and for low flight speeds.

Ramming Process:- Let the pressure and temperature of ambient air is rammed isentropically from P_1 and T_1 to P_2 and T_2 respectively. The ideal ramming action is shown by the ~~curve~~ vertical line 1-2 in T-s diagram. In actual practice because of internal friction due to irreversibilities, the temperature of the rammed air is more than T_2. Thus the actual ramming process is shown by the curve 1-2'. which is adiabatic but not isentropic due to friction. The pressure and temperature of the rammed air is now $P_{2'}$ and $T_{2'}$ respectively. During the ideal and actual ramming process the total energy or enthalpy remains constant. i.e. $h_2 = h_{2'}$ and $T_2 = T_{2'}$. If 'V' is the air craft velocity or the velocity of air relative to the air craft in meters per second then kinetic energy of outside air relative to air craft.

$$K.E = \frac{V^2}{2000}\ kJ/kg \longrightarrow ①$$

from the energy equation, w.k.T

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

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

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

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

(or) $$\frac{T_{2'}}{T_1} = 1 + \frac{V^2}{2000 C_p T_1} \quad \boxed{\because T_2 = T_{2'}} \quad ②$$

w.k.T $C_p - C_v = R \Rightarrow C_p\left[1 - \frac{C_v}{C_p}\right] = R$

$$C_p\left[1 - \frac{1}{\gamma}\right] = R \Rightarrow C_p = \frac{\gamma R}{\gamma - 1}$$

from eq ②

$$\frac{T_{2'}}{T_1} = \frac{T_2}{T_1} = 1 + \frac{V^2(\gamma - 1)}{2000 \gamma R T_1} \longrightarrow ③$$

$$\frac{T_2}{T_1} = \frac{T_{2'}}{T_1} = 1 + \frac{V^2(\gamma - 1)}{2a^2} \longrightarrow ④$$

where a = Local sonic or acoustic velocity at the ambient air conditions.

$= \sqrt{\gamma R T_1}$ where R in J/kgK.

The Eq ④ may further be written as

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

where M = mach number of the flight. It is defined as the ratio of aircraft velocity (V) to the local sonic velocity (a)

The temperature $T_2 = T_{2'}$ is called the stagnation temperature of the ambient air entering the main compressor. The stagnation pressure after isentropic compression P_2 is given by $\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}}$

$$\text{Ram Efficiency } \eta_R = \frac{\text{Actual Rise in Pressure}}{\text{Isentropic rise in Pressure}} = \frac{P_{2'} - P_1}{P_2 - P_1}$$

Compression Process:- The isentropic compression of air in the main compressor is represented by the line 2'-3. In actual practice because of internal friction due to irreversibilities, the actual compression is represented by the curve 2'-3'. The workdone during compression process is given by $W_C = m_a C_p (T_{3'} - T_{2'})$; $\eta_C = \frac{T_3 - T_2}{T_{3'} - T_2}$

where m_a = Mass of air bled from the main compressor for refrigeration purpose.

Cooling Process:- The compressed air is cooled by the ram air in the heat Exchanger. This process is shown by the curve 3'-4. ~~In actual~~ The temperature of air decreases from $T_{3'}$ to T_4. The heat rejected in the heat exchanger during cooling process is given by $Q_R = m_a C_p (T_{3'} - T_4)$

Expansion Process:- The cooled air is now expanded isentropically in the cooling turbine as shown by the curve 4-5. In actual practice because of internal friction due to irreversibilities the actual expansion in the cooling turbine is shown by the curve 4-5'. The workdone by the cooling turbine during this expansion process given by $W_T = m_a C_p (T_4 - T_{5'})$; $\eta_T = \frac{T_4 - T_{5'}}{T_4 - T_5}$

Refrigeration Process:- The air from the cooling turbine is sent to the cabin and cock pit where it gets heated by the heat of equipment and occupancy. This process is shown by the curve 5'-6. The refrigeration effect produced or heat absorbed is given by $R_E = m_a C_p (T_6 - T_{5'})$

T_6 = Inside temp of cabin

$T_{5'}$ = Exit temp of cooling Turbine.

W.K.T, $COP = \frac{\text{Refrigeration Effect Produced}}{\text{Workdone}}$

$$= \frac{m_a C_p (T_6 - T_{5'})}{m_a C_p (T_{3'} - T_{2'})} = \frac{T_6 - T_{5'}}{T_{3'} - T_{2'}}$$

$$m_a = \frac{210Q}{C_p (T_6 - T_{5'})} \text{ kg/min}$$

$$P = \frac{m_a C_p (T_{3'} - T_{2'})}{60} \text{ kW}$$

$$COP = \frac{210Q}{m_a C_p (T_{3'} - T_{2'})}$$

$$COP = \frac{210Q}{P \times 60}$$

⇒ A Simple air cooled System is used for an aeroplane having a load of 10 Tonnes. The atmospheric pressure and temperature are 0.9 bar and 10°c respectively. The pressure increases to 1.013 bar due to ramming. The temperature of the air is reduced by 50°C in the heat Exchanger. The pressure in the cabin is 1.01 bar and the temperature of air leaving the Cabin is 25°C. Determine 1. Power required to take the load of cooling in the cabin. and 2. COP of the system. Assume that all the Expansions and Compressions are isentropic. the pressure of the compressed air is 3.5 bar.

Sol:- G.D

$Q = 10TR$

$P_1 = 0.9$ bar

$T_1 = 10°C = 10+273 = 283K$

$P_2 = 1.013$ bar

$P_5 = P_6 = 1.01$ bar

$T_6 = 25°C$

$= 25+273 = 298K$

$P_3 = 3.5$ bar

R.T

Power $(P) = ?$

$COP = ?$

F.U:- $P = \frac{m_a C_p (T_3 - T_2)}{60}$

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

$COP = \frac{210 Q}{P \times 60}$

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

$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$

$T_4 = T_3 - 50°C$

$\frac{T_5}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$

Calculations:-

$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.013}{0.9}\right)^{\frac{1.4-1}{1.4}} = (1.125)^{0.286} = 1.034$

$T_2 = T_1 \times 1.034 = 283 \times 1.034 = 292.6 K$

$\frac{T_3}{T_2} = \left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.013}\right)^{\frac{1.4-1}{1.4}} = (3.45)^{0.286} = 1.425$

$T_3 = T_2 \times 1.425 = 292.6 \times 1.425 = 417 K = 144°C$

$T_4 = 144 - 50 = 94°C = 94+273 = 367 K$

$\frac{T_5}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.01}{3.5}\right)^{\frac{1.4-1}{1.4}} = (0.288)^{0.286} = 0.7$

$T_5 = 0.7 \times 367 = 257 K$

$m_a = \frac{210 Q}{C_p (T_6 - T_5)} = \frac{210 \times 10}{1(287-257)} = 51.2$ kg/min

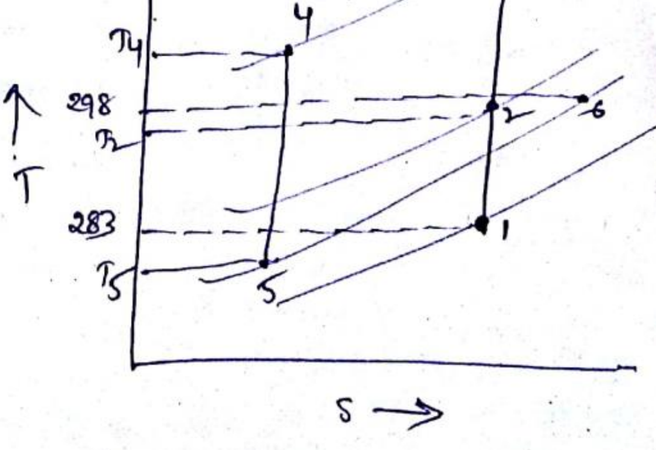
$P = \frac{m_a C_p (T_3 - T_2)}{60} = \frac{51.2 \times 1 (417 - 292.6)}{60} = 106 kW$

$COP = \frac{210 Q}{P \times 60} = \frac{210 \times 10}{106 \times 60} = 0.33$

Ans:-

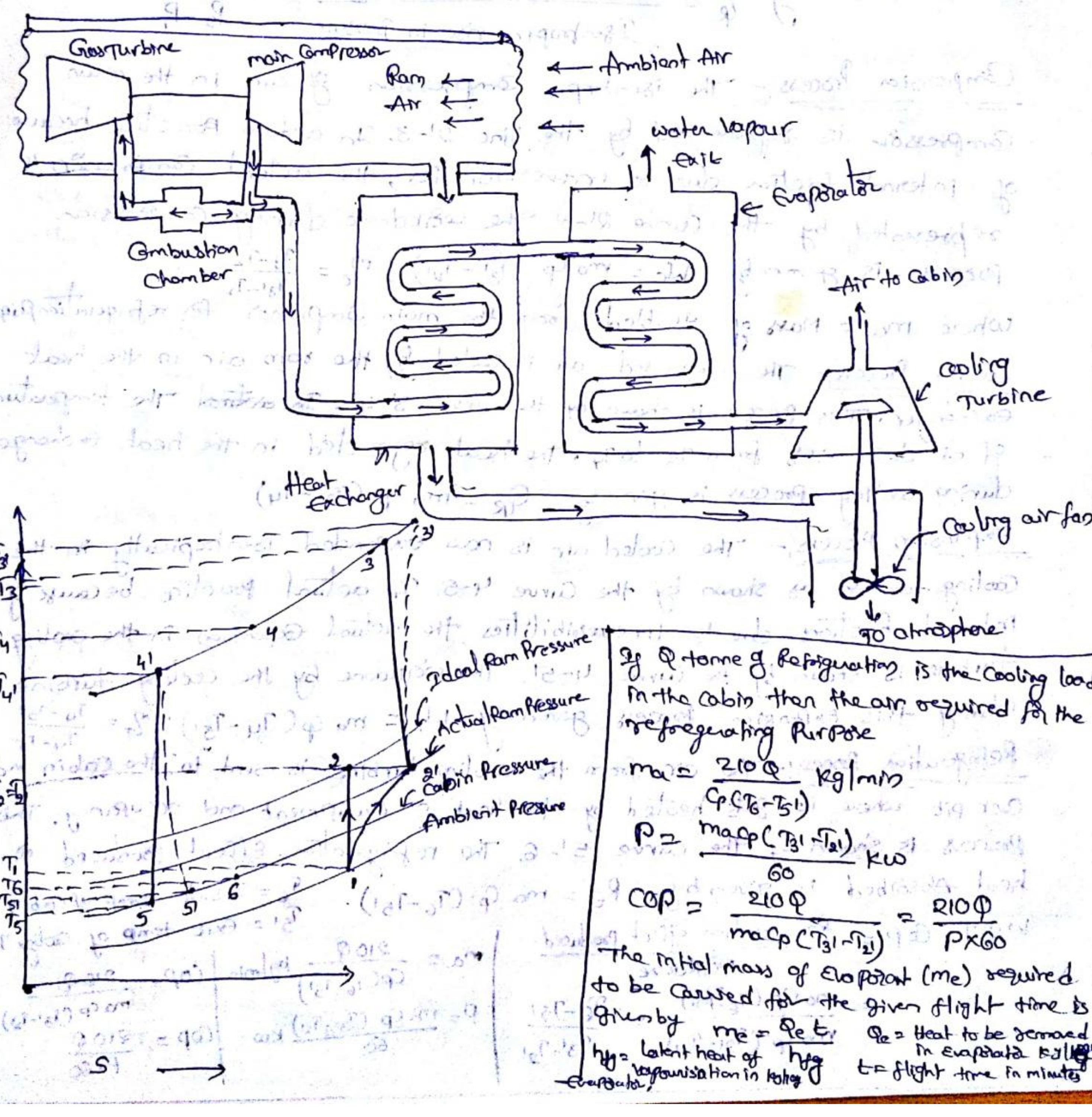
$P = 106 kW$

$COP = 0.33$



2. Simple Air Evaporative Cooling system:-

A simple air evaporative cooling system as shown in fig. It is similar to the simple air cooling system except that the addition of an evaporator between the heat exchanger and cooling turbine. The evaporator provides an additional cooling effect through evaporation of a refrigerant such as water. At high altitudes the evaporative cooling may be obtained by using alcohol or ammonia. The water alcohol and ammonia have different refrigerating effects at different altitudes. At 20,000 meters height water boiles at 40°c, alcohol at 9°c and Ammonia at -70°c.



If Q tonne of Refrigeration is the cooling load in the cabin then the air required for the refrigerating purpose

$$m_a = \frac{210Q}{C_p(T_6 - T_{5'})} \text{ kg/min}$$

$$P = \frac{m_a C_p (T_{3'} - T_{2'})}{60} \text{ kW}$$

$$COP = \frac{210Q}{m_a C_p (T_{3'} - T_{2'})} = \frac{210Q}{P \times 60}$$

The initial mass of evaporant (m_e) required to be carried for the given flight time is given by

$$m_e = \frac{Q_e\, t}{h_{fg}}$$

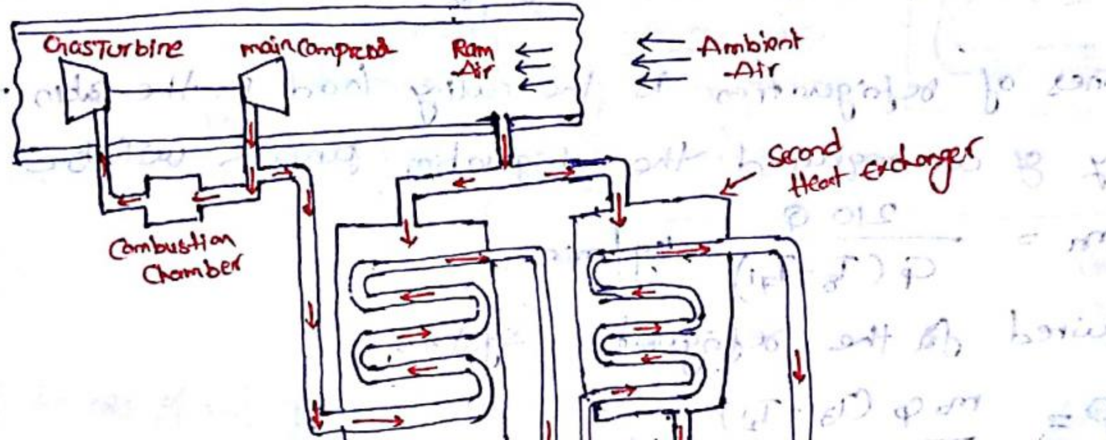
Q_e = Heat to be removed in evaporator kJ/min

h_{fg} = Latent heat of vapourisation in kJ/kg evaporator,

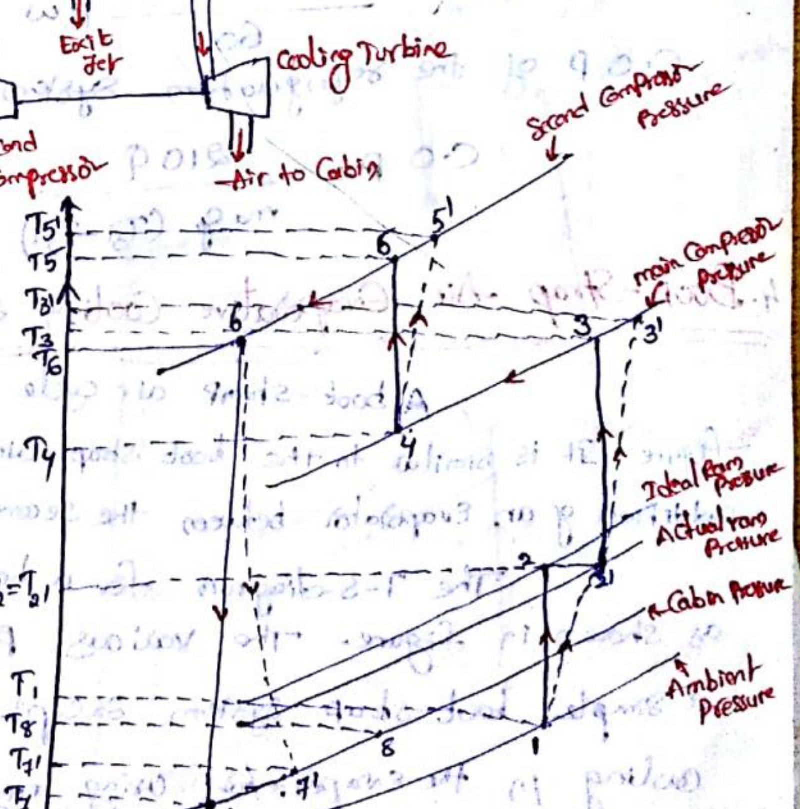
t = flight time in minutes

3. Boot Strap Air Cooling System:-

A boot strap air cooling systems as shown in figure. This cooling system has two Exchangers instead of one and a cooling turbine drives a secondary compressor instead of cooling fan. The air bled from the main compressor is first cooled by the ram air in the first heat exchanger. This cooled air after compression in the secondary compressor is led to the second heat exchanger, where it is again cooled by the ram air before passing to the cooling turbine. this type of cooling system is mostly used in transport type of aircraft.



The T-S diagram for a boot strap air cycle cooling system as shown in figure. The various processes are as follows.



⇒ The Process 1-2 represents the isentropic ramming of ambient air from Pressure P_1 and Temperature T_1 to Pressure P_2 and Temperature T_2. The Process 1-2' represents actual ramming process because of internal friction due to irreversibility.

⇒ The Process 2'-3 represents the isentropic compression of air in the main compressor and the process 2'-3' represents actual compression of air because of internal friction due to irreversibilities.

⇒ Process 3'-4 represents the cooling by ram air in the first heat exchanger. The pressure drop in the heat exchanger is neglected.

⇒ The Process 4-5 represents the Isentropic compression of cooled air from first heat Exchanger in the secondary Compressor. The process 4-5' represents the actual Compression Process because of internal friction due to irreversibility.

⇒ Process 5'-6 represents the Cooling by ram air in the second heat Exchanger. The pressure drop in the heat Exchanger is neglected.

⇒ The Process 6-7 represents the Isentropic Expansion of cooled air in the Cooling turbine upto the Cabin Pressure. The Process 6-7' represents actual expansion of the cooled air in the Cooling turbine.

⇒ The Process 7'-8 represents the heating of air upto the cabin temperature T8.

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

$$m_a = \frac{210\,Q}{C_p\,(T_8 - T_{7'})}\ \text{kg/min}$$

Power required for the refrigeration system

$$P = \frac{m_a\,c_p\,(T_{3'} - T_{2'})}{60}\ \text{kW}$$

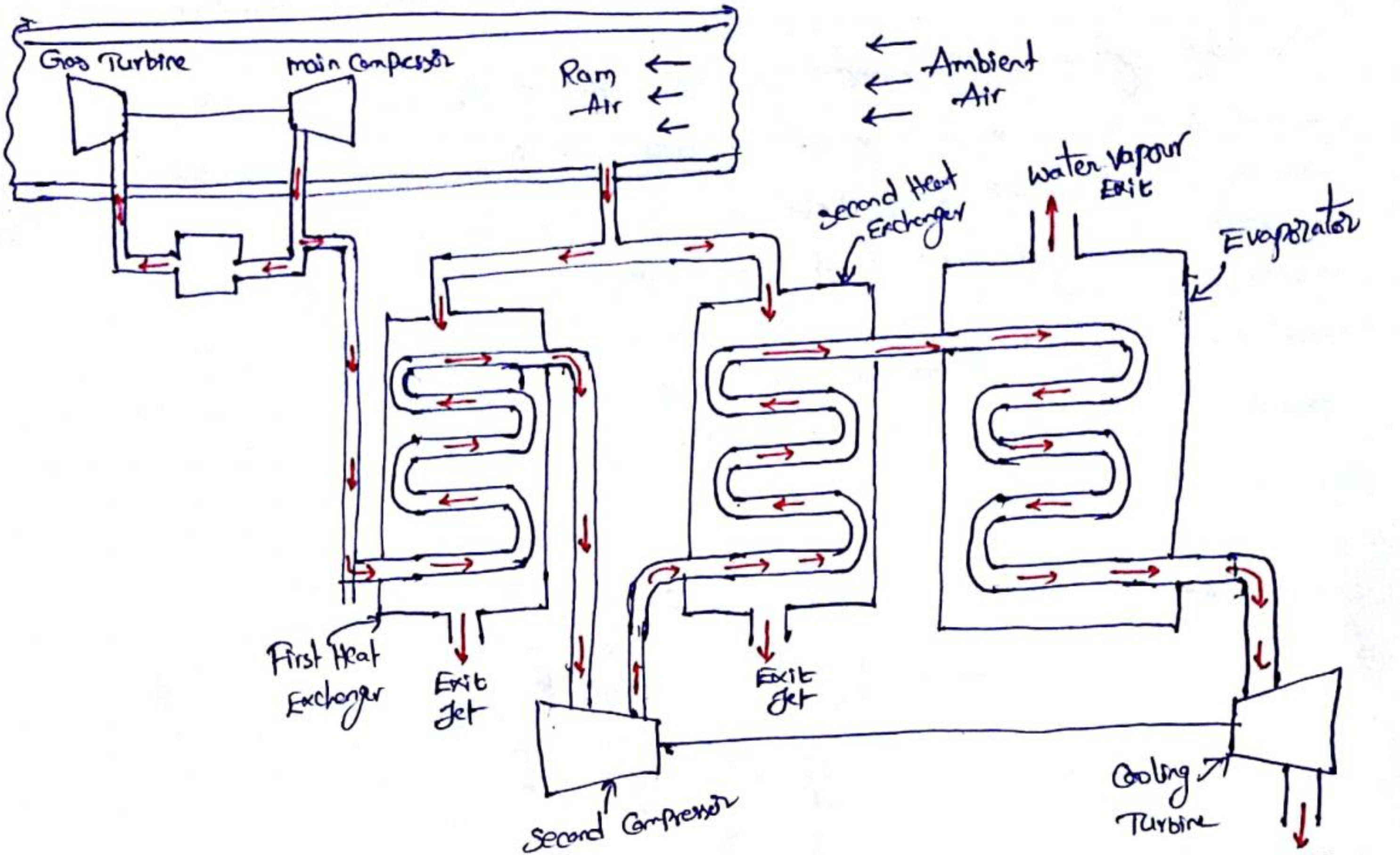
C.O.P of the refrigeration system

$$\text{C.O.P} = \frac{210\,Q}{m_a\,c_p\,(T_{3'} - T_{2'})} = \frac{210\,Q}{P \times 60}$$

4. Boot-Strap Air Evaporative Cooling System:-

A boot-strap air cycle evaporative cooling system as shown in figure. It is similar to the boot strap air cycle cooling system Except that the addition of an Evaporator between the second heat Exchanger and Cooling Turbine.

The T-S-diagram for a boot-strap air Evaporative Cooling System as shown in figure. The various processes of this cycle are same as a simple boot-strap system except the process 5'-6 which represents cooling in the Evaporator using any suitable Evaporant.



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

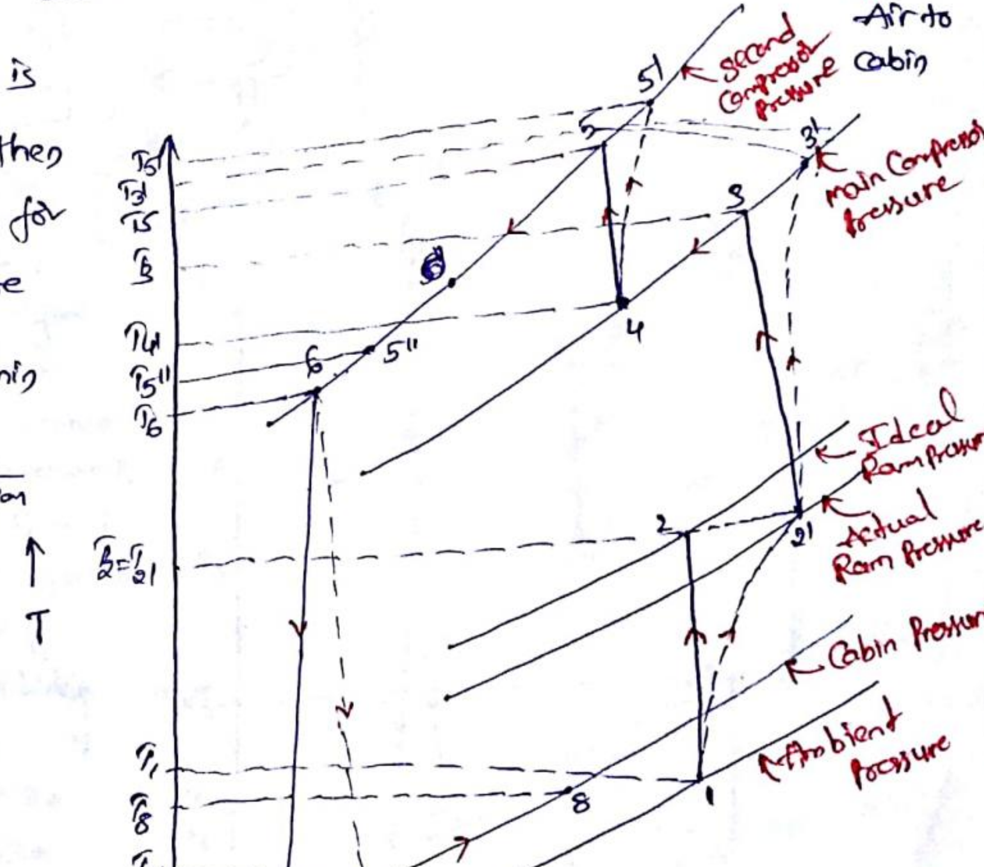
$$m_a = \frac{210\,Q}{c_p(T_8 - T_{7'})} \text{ kg/min}$$

Power required for the refrigeration system is given by

$$P = \frac{m_a c_p (T_{3'} - T_{2'})}{60} \text{ kW}$$

$$C.O.P = \frac{210\,Q}{m_a c_p (T_{3'} - T_{2'})}$$

$$= \frac{210\,Q}{P \times 60}$$



Example 3.2. *An aircraft refrigeration plant has to handle a cabin load of 30 tonnes. The atmospheric temperature is 17°C. The atmospheric air is compressed to a pressure of 0.95 bar and temperature of 30°C due to ram action. This air is then further compressed in a compressor to 4.75 bar, cooled in a heat exchanger to 67°C, expanded in a turbine to 1 bar pressure and supplied to the cabin. The air leaves the cabin at a temperature of 27°C. The isentropic efficiencies of both compressor and turbine are 0.9. Calculate the mass of air circulated per minute and the C.O.P. For air,* $c_p = 1.004$ *kJ/kg K and* $c_p / c_v = 1.4$

Solution. Given : $Q = 30$ TR ; $T_1 = 17°\text{C} = 17 + 273 = 290$ K ; $p_2 = 0.95$ bar ; $T_2 = 30°\text{C} = 30 + 273 = 303$ K ; $p_3 = p_{3'} = 4.75$ bar ; $T_4 = 67°\text{C} = 67 + 273 = 340$ K ; $p_5 = p_{5'} = 1$ bar ; $T_6 = 27°\text{C} = 27 + 273 = 300$ K ; $\eta_C = \eta_T = 0.9$; $c_p = 1.004$ kJ/kg K ; $c_p / c_v = \gamma = 1.4$

The *T-s* diagram for the simple air refrigeration cycle with the given conditions is shown in Fig. 3.4.

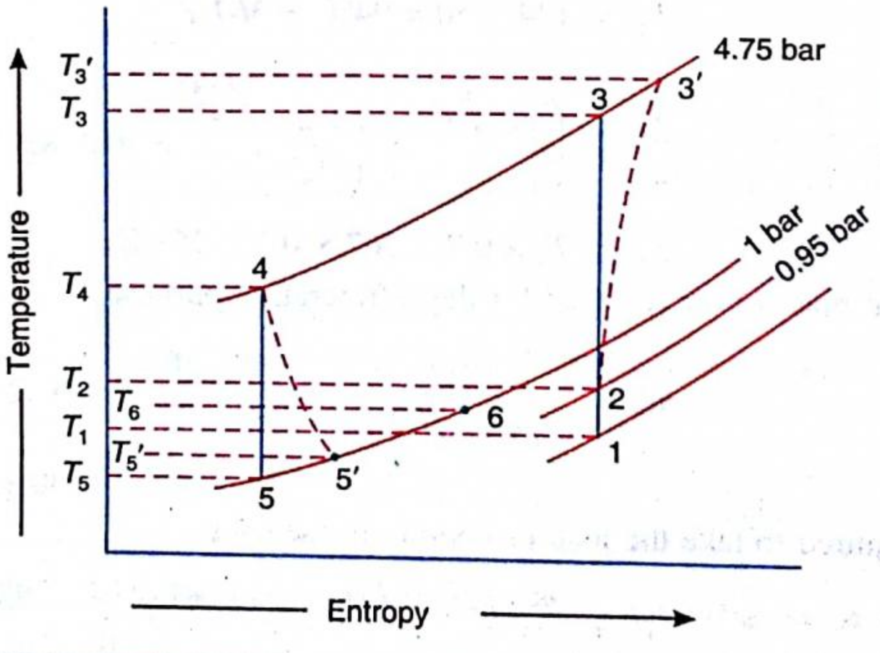


Fig. 3.4

Let T_3 = Temperature of the air after isentropic compression in the compressor,

$T_{3'}$ = Actual temperature of the air leaving the compressor,

T_5 = Temperature of the air leaving the turbine after isentropic expansion, and

$T_{5'}$ = Actual temperature of the air leaving the turbine.

We know that for isentropic compression process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.75}{0.95}\right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.584$$

$$\therefore \quad T_3 = T_2 \times 1.584 = 303 \times 1.584 = 480 \text{ K}$$

and isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.9 = \frac{480 - 303}{T_{3'} - 303} = \frac{177}{T_{3'} - 303}$$

$$\therefore \quad T_{3'} - 303 = 177/0.9 = 196.7 \text{ or } T_{3'} = 303 + 196.7 = 499.7 \text{ K}$$

Now for the isentropic expansion process 4-5,

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.75}{1}\right)^{\frac{1.4-1}{1.4}} = (4.75)^{0.286} = 1.561$$

$$\therefore \quad T_5 = T_4 / 1.561 = 340 / 1.561 = 217.8 \text{ K}$$

and isentropic efficiency of the turbine,

$$\eta_T = \frac{\text{Actual increase in temperature}}{\text{Isentropic increase in temperature}} = \frac{T_4 - T_{5'}}{T_4 - T_5}$$

$$0.9 = \frac{340 - T_{5'}}{340 - 217.8} = \frac{340 - T_{5'}}{122.2}$$

$$\therefore \quad T_{5'} = 340 - 0.9 \times 122.2 = 230 \text{ K}$$

Mass of air circulated per minute

We know that mass of air circulated per minute,

$$m_a = \frac{210\,Q}{c_p(T_6 - T_{5'})} = \frac{210 \times 30}{1.004\,(300 - 230)} = 89.64 \text{ kg/min } \textbf{Ans.}$$

C.O.P.

We know that

$$\text{C.O.P.} = \frac{210\,Q}{m_a c_p (T_{3'} - T_2)} = \frac{210 \times 30}{89.64 \times 1.004\,(499.7 - 303)} = 0.356 \ \textbf{Ans.}$$

Example 3.3. *An aircraft moving with speed of 1000 km/h uses simple gas refrigeration cycle for air-conditioning. The ambient pressure and temperature are 0.35 bar and −10°C respectively. The pressure ratio of compressor is 4.5. The heat exchanger effectiveness is 0.95. The isentropic efficiencies of compressor and expander are 0.8 each. The cabin pressure and temperature are 1.06 bar and 25°C. Determine temperatures and pressures at all points of the cycle. Also find the volume flow rate through compressor inlet and expander outlet for 100 TR. Take* $c_p = 1.005$ *kJ/kg K ;* $R = 0.287$ *kJ/kg K and* $c_p / c_v = 1.4$ *for air.*

Solution. Given : $V = 1000 \text{ km/h} = 277.8 \text{ m/s}$; $p_1 = 0.35$ bar ; $T_1 = -10°\text{C} = -10 + 273 = 263$ K ; $p_3 / p_2 = 4.5$; $\eta_E = 0.95$; $\eta_C = \eta_T = 0.8$; $p_5 = p_{5'} = 1.06$ bar ; $T_6 = 25°\text{C} = 25 + 273 = 298$ K ; $Q = 100$ TR ; $c_p = 1.005$ kJ/kg K ; $R = 0.287$ kJ / kg K = 287 J / kg K ; $c_p / c_v = \gamma = 1.4$

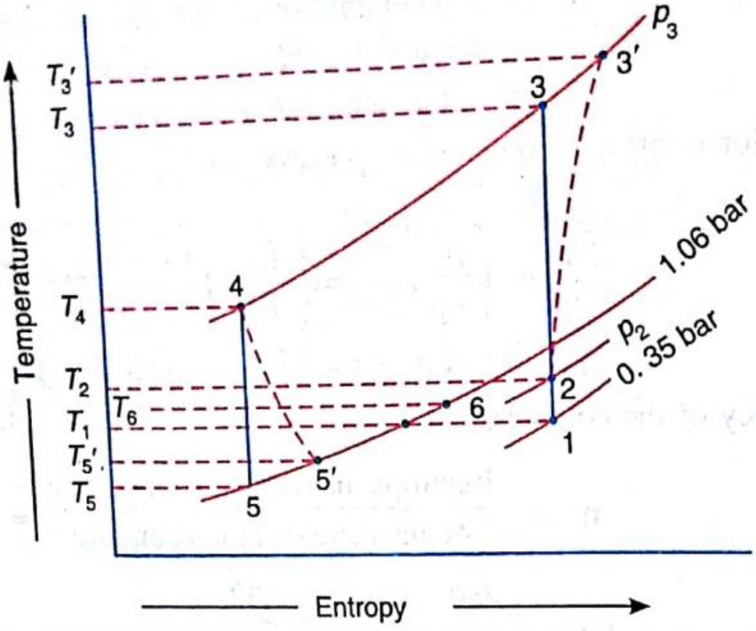


Fig. 3.5

Temperatures and pressures at all points of the cycle

The *T-s* diagram for the simple gas refrigeration cycle with the given conditions is shown in Fig. 3.5.

Let T_2 and p_2 = Stagnation temperature and pressure of the ambient air entering the compressor,

T_3 and p_3 = Temperature and pressure of the air leaving the compressor after isentropic compression,

$T_{3'}$ = Actual temperature of the air leaving the compressor,

T_4 = Temperature of the air leaving the heat exchanger or entering the expander,

p_4 = Pressure of the air leaving the heat exchanger or entering the expander = $p_3 = p_{3'}$,

T_5 = Temperature of the air leaving the expander after isentropic expansion,

$T_{5'}$ = Actual temperature of the air leaving the expander.

We know that
$$T_2 = T_1 + \frac{V^2}{2000\, c_p} = 263 + \frac{(277.8)^2}{2000 \times 1.005}$$
$$= 263 + 38.4 = 301.4 \text{ K } \textbf{Ans.}$$

and
$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{301.4}{263}\right)^{\frac{1.4}{1.4-1}} = (1.146)^{3.5} = 1.611$$

$\therefore$
$$p_2 = p_1 \times 1.611 = 0.35 \times 1.611 = 0.564 \text{ bar } \textbf{Ans.}$$

Since $p_3 / p_2 = 4.5$ (Given), therefore
$$p_3 = p_2 \times 4.5 = 0.564 \times 4.5 = 2.54 \text{ bar } \textbf{Ans.}$$

We know that for isentropic compression process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = (4.5)^{\frac{1.4-1}{1.4}} = (4.5)^{0.286} = 1.537$$

$$\therefore \quad T_3 = T_2 \times 1.537 = 301.4 \times 1.537 = 463.3 \text{ K}$$

We also know that isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic temperature rise}}{\text{Actual temperature rise}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.8 = \frac{463.3 - 301.4}{T_{3'} - 301.4} = \frac{161.9}{T_{3'} - 301.4}$$

$$T_{3'} - 301.4 = 161.9/0.8 = 202.4$$

$$\therefore \quad T_{3'} = 301.4 + 202.4 = 503.8 \text{ K } \textbf{Ans.}$$

Effectiveness of the heat exchanger (η_H),

$$0.95 = \frac{T_{3'} - T_4}{T_{3'} - T_2} = \frac{503.8 - T_4}{503.8 - 301.4} = \frac{503.8 - T_4}{202.4}$$

$$\therefore \quad T_4 = 503.8 - 0.95 \times 202.4 = 311.5 \text{ K } \textbf{Ans.}$$

and $p_4 = p_3 = 2.54$ bar **Ans.**

Now isentropic efficiency of the expander,

$$\eta_E = \frac{\text{Actual temperature rise}}{\text{Isentropic temperature rise}} = \frac{T_4 - T_{5'}}{T_4 - T_5}$$

$$0.8 = \frac{311.5 - T_{5'}}{311.5 - 243} = \frac{311.5 - T_{5'}}{68.5}$$

$$\therefore \quad T_{5'} = 311.5 - 0.8 \times 68.5 = 256.7 \text{ K } \textbf{Ans.}$$

Volume flow rate

Let v_2 = Volume flow rate through the compressor inlet, and
$v_{5'}$ = Volume flow rate through the expander outlet.

We know that mass flow rate of air,

$$m_a = \frac{210\,Q}{c_p(T_6 - T_{5'})} = \frac{210 \times 100}{1.005\,(298 - 256.7)} = 506 \text{ kg/min}$$

and

$$p_2 v_2 = m_a R T_2$$

$$\therefore \quad v_2 = \frac{m_a R T_2}{p_2} = \frac{506 \times 287 \times 301.4}{0.564 \times 10^5} = 776 \text{ m}^3/\text{min } \textbf{Ans.}$$

... (*R* is taken in J/kg K and p_2 is taken in N/m²)

Similarly

$$p_{5'} v_{5'} = m_a R\, T_{5'}$$

$$\therefore \quad v_{5'} = \frac{m_a R T_{5'}}{p_{5'}} = \frac{506 \times 287 \times 256.7}{1.06 \times 10^5} = 351.7 \text{ m}^3/\text{min } \textbf{Ans.}$$

Example 3.4. *The cock pit of a jet plane flying at a speed of 1200 km/h is to be cooled by a simple air cooling system. The cock pit is to be maintained at 25°C and the pressure in the cock pit is 1 bar. The ambient air pressure and temperature are 0.85 bar and 30°C. The other data available is as follows :*

Cock-pit cooling load = 10 TR ; Main compressor pressure ratio = 4 ; Ram efficiency = 90% ; Temperature of air leaving the heat exchanger and entering the cooling turbine = 60°C ; Pressure drop in the heat exchanger = 0.5 bar ; Pressure loss between the cooler turbine and cock pit = 0.2 bar.

Assuming the isentropic efficiencies of main compressor and cooler turbine as 80%, find the quantity of air passed through the cooling turbine and C.O.P. of the system. Take $\gamma = 1.4$ *and* $c_p = 1$ *kJ/kg K.*

Solution. Given : $V = 1200 \text{ km/h} = 333.3 \text{ m/s}$; $T_6 = 25°\text{C} = 25 + 273 = 298 \text{ K}$; $p_6 = 1$ bar ; $p_1 = 0.85$ bar ; $T_1 = 30°\text{C} = 30 + 273 = 303$ K ; $Q = 10$ TR ; $p_3 / p_{2'} = 4$; $\eta_R = 90\% = 0.9$; $T_4 = 60°\text{C} = 60 + 273 = 333$ K ; $p_4 = (p_{3'} - 0.5)$ bar ; $p_5 = p_{5'} = p_6 + 0.2 = 1 + 0.2 = 1.2$ bar ; $\eta_C = \eta_T = 80\% = 0.8$; $\gamma = 1.4$; $c_p = 1$ kJ/kg K

The *T-s* diagram for the simple air cooling system with the given conditions is shown in Fig. 3.6.

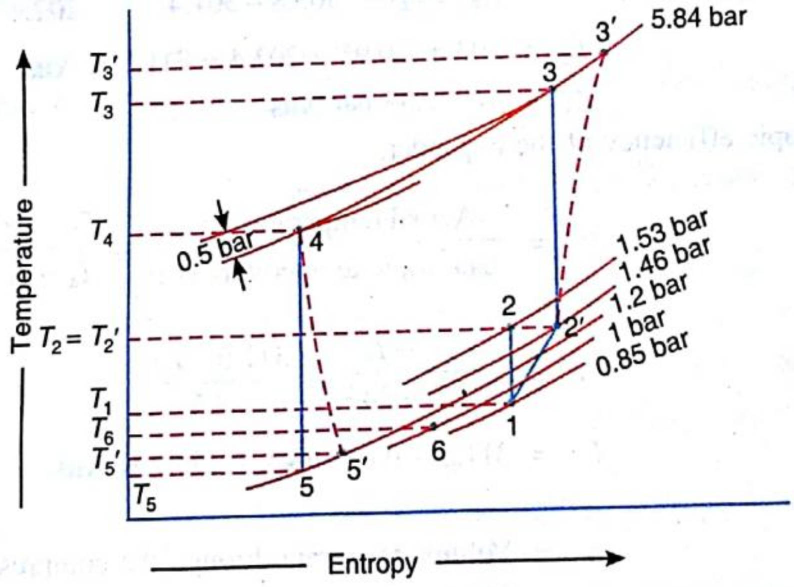


Fig. 3.6

Let $T_{2'}$ = Stagnation temperature of the ambient air entering the main compressor = T_2,

p_2 = Pressure of air after isentropic ramming, and

$p_{2'}$ = Stagnation pressure of air entering the main compressor.

We know that
$$T_2 = T_{2'} = T_1 + \frac{V^2}{2000\, c_p} = 303 + \frac{(333.3)^2}{2000 \times 1}$$
$$= 303 + 55.5 = 358.5 \text{ K}$$

and
$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{358.5}{303}\right)^{\frac{1.4}{1.4-1}} = (1.183)^{3.5} = 1.8$$

$\therefore$
$$p_2 = p_1 \times 1.8 = 0.85 \times 1.8 = 1.53 \text{ bar}$$

We know that ram efficiency,

$$\eta_R = \frac{\text{Actual pressure rise}}{\text{Isentropic pressure rise}} = \frac{p_{2'} - p_1}{p_2 - p_1}$$

$$0.9 = \frac{p_{2'} - 0.85}{1.53 - 0.85} = \frac{p_{2'} - 0.85}{0.68}$$

$$\therefore \quad p_{2'} = 0.9 \times 0.68 + 0.85 = 1.46 \text{ bar}$$

Now for the isentropic process $2' - 3$,

$$\frac{T_3}{T_{2'}} = \left(\frac{p_3}{p_{2'}}\right)^{\frac{\gamma-1}{\gamma}} = (4)^{\frac{1.4-1}{1.4}} = (4)^{0.286} = 1.486$$

$$\therefore \quad T_3 = T_{2'} \times 1.486 = 358.5 \times 1.486 = 532.7 \text{ K}$$

and isentropic efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic temperature rise}}{\text{Actual temperature rise}} = \frac{T_3 - T_{2'}}{T_{3'} - T_{2'}}$$

$$0.8 = \frac{532.7 - 358.5}{T_{3'} - 358.5} = \frac{174.2}{T_{3'} - 358.5}$$

$$\therefore \quad T_{3'} = \frac{174.2}{0.8} + 358.5 = 576 \text{ K}$$

Since the pressure ratio of the main compressor ($p_3 / p_{2'}$) is 4, therefore pressure of air leaving the main compressor,

$$p_3 = p_{3'} = 4\, p_{2'} = 4 \times 1.46 = 5.84 \text{ bar}$$

Pressure drop in the heat exchanger

$$= 0.5 \text{ bar}$$

∴ Pressure of air after passing through the heat exchanger or at entrance to the cooling turbine,

$$p_4 = p_{3'} - 0.5 = 5.84 - 0.5 = 5.34 \text{ bar}$$

Also there is a pressure loss of 0.2 bar between the cooling turbine and the cock pit. Therefore pressure of air leaving the cooling turbine,

$$p_5 = p_{5'} = p_6 + 0.2 = 1 + 0.2 = 1.2 \text{ bar}$$

Now for the isentropic process 4-5,

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5.34}{1.2}\right)^{\frac{1.4-1}{1.4}} = (4.45)^{0.286} = 1.53$$

$$\therefore \quad T_5 = T_4 / 1.53 = 333 / 1.53 = 217.6 \text{ K}$$

We know that isentropic efficiency of the cooling turbine,

$$\eta_T = \frac{\text{Actual temperature rise}}{\text{Isentropic temperature rise}} = \frac{T_4 - T_{5'}}{T_4 - T_5}$$

$$0.8 = \frac{333 - T_{5'}}{333 - 217.6} = \frac{333 - T_{5'}}{115.4}$$

$$\therefore \quad T_{5'} = 333 - 0.8 \times 115.4 = 240.7 \text{ K}$$

Example 3.6. *A simple evaporative air refrigeration system is used for an aeroplane to take 20 tonnes of refrigeration load. The ambient air conditions are 20°C and 0.9 bar. The ambient air is rammed isentropically to a pressure of 1 bar. The air leaving the main compressor at pressure 3.5 bar is first cooled in the heat exchanger having effectiveness of 0.6 and then in the evaporator where its temperature is reduced by 5°C. The air from the evaporator is passed through the cooling turbine and then it is supplied to the cabin which is to be maintained at a temperature of 25°C and at a pressure of 1.05 bar. If the internal efficiency of the compressor is 80% and that of cooling turbine is 75% ,determine :*

1. Mass of air bled off the main compressor; 2. Power required for the refrigerating system; and 3. C.O.P. of the refrigerating system.

Solution. Given : $Q = 20$ TR ; $T_1 = 20°\text{C} = 20 + 273 = 293$ K ; $p_1 = 0.9$ bar ; $p_2 = 1$ bar ; $p_3 = p_{3'} = 3.5$ bar ; $\eta_H = 0.6$; $T_6 = 25°\text{C} = 25 + 273 = 298$ K ; $p_6 = 1.05$ bar ; $\eta_C = 80\% = 0.8$; $\eta_T = 75\% = 0.75$

The *T-s* diagram for the simple evaporative air refrigeration system with the given conditions is shown in Fig. 3.10.

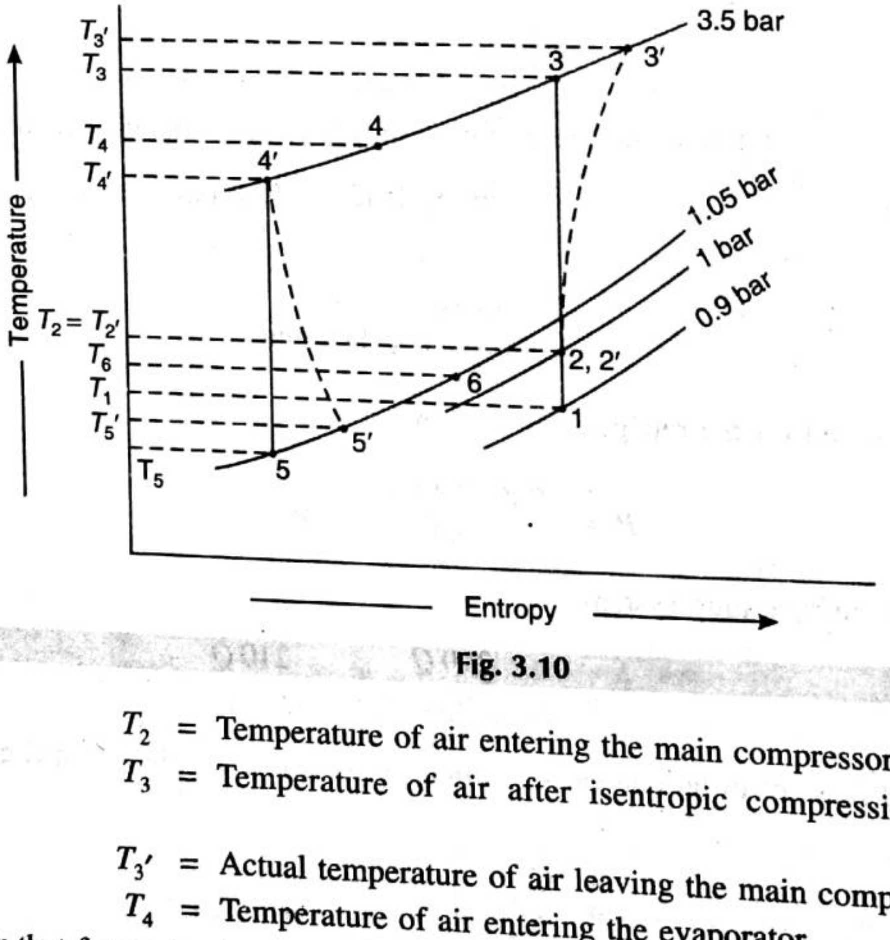


Fig. 3.10

Let T_2 = Temperature of air entering the main compressor,

T_3 = Temperature of air after isentropic compression in the main compressor,

$T_{3'}$ = Actual temperature of air leaving the main compressor, and

T_4 = Temperature of air entering the evaporator.

We know that for an isentropic ramming process 1-2,

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{0.9}\right)^{\frac{1.4-1}{1.4}} = (1.11)^{0.286} = 1.03 \qquad \ldots \text{(Taking } \gamma = 1.4)$$

$$\therefore \quad T_2 = T_1 \times 1.03 = 293 \times 1.03 = 301.8 \text{ K}$$

Now for the isentropic compression process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1}\right)^{\frac{1.4-1}{1.4}} = (3.5)^{0.286} = 1.43$$

$$\therefore \quad T_3 = T_2 \times 1.43 = 301.8 \times 1.43 = 431.6 \text{ K}$$

We know that efficiency of the compressor,

$$\eta_C = \frac{\text{Isentropic increase in temperature}}{\text{Actual increase in temperature}} = \frac{T_3 - T_2}{T_{3'} - T_2}$$

$$0.8 = \frac{431.6 - 301.8}{T_{3'} - 301.8} = \frac{129.8}{T_{3'} - 301.8}$$

$$\therefore \quad T_{3'} = 301.8 + 129.8/0.8 = 464 \text{ K}$$

Effectiveness of the heat exchanger (η_H),

$$0.6 = \frac{T_{3'} - T_4}{T_{3'} - T_{2'}} = \frac{464 - T_4}{464 - 301.8} = \frac{464 - T_4}{162.2} \qquad \ldots (\because T_{2'} = T_2)$$

$$\therefore \quad T_4 = 464 - 0.6 \times 162.2 = 366.7 \text{ K} = 93.7°\text{C}$$

Since the temperature of air in the evaporator is reduced by 5°C, therefore the temperature of air leaving the evaporator and entering the cooling turbine,

$$T_{4'} = T_4 - 5 = 93.7 - 5 = 88.7°\text{C} = 361.7 \text{ K}$$

Now for the isentropic expansion process 4′– 5,

$$\frac{T_{4'}}{T_5} = \left(\frac{p_3}{p_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.05}\right)^{\frac{1.4-1}{1.4}} = (3.33)^{0.286} = 1.41$$

$$\therefore \quad T_5 = T_{4'} / 1.41 = 361.7/1.41 = 256.5 \text{ K}$$

Efficiency of the cooling turbine,

$$\eta_T = \frac{\text{Actual increase in temperature}}{\text{Isentropic increase in temperature}} = \frac{T_{4'} - T_{5'}}{T_{4'} - T_5}$$

$$0.75 = \frac{361.7 - T_{5'}}{361.7 - 256.5} = \frac{361.7 - T_{5'}}{105.2}$$

$$\therefore \quad T_{5'} = 361.7 - 0.75 \times 105.2 = 282.8 \text{ K}$$

1. ***Mass of air bled off the main compressor***

We know that mass of air bled off the main compressor,

$$m_a = \frac{210\,Q}{c_p(T_6 - T_{5'})} = \frac{210 \times 20}{1\,(298 - 282.8)} = 276 \text{ kg / min } \textbf{Ans.}$$

2. ***Power required for the refrigerating system***

We know that power required for the refrigerating system,

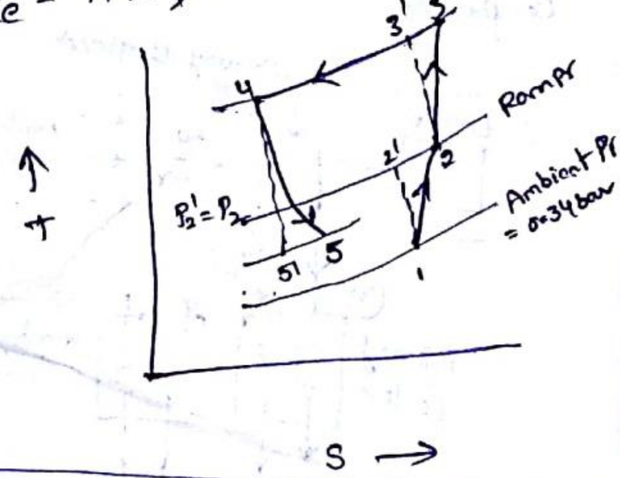
$$P = \frac{m_a c_p (T_{3'} - T_{2'})}{60} = \frac{276 \times 1\,(464 - 301.8)}{60} = 746 \text{ kW } \textbf{Ans.}$$

3. ***C.O.P. of the refrigerating system***

We know that C.O.P. of the refrigerating system

$$= \frac{210\,Q}{P \times 60} = \frac{210 \times 20}{746 \times 60} = 0.094 \textbf{ Ans.}$$

⇒ Air craft is flying at an altitude of 8000m at a speed of 900 km/hr. The pressure and temperature of air at this altitude are 0.34 bar and 263K respectively. The air is compressed by an air compressor with a compression ratio of 5. The cabin pressure is 1.013 bar and temperature is 300K. Determine the power required for pressurization excluding ram work, extra power required for refrigeration purpose and refrigeration capacity of the system if the air flow rate is 1 kg/s. Take the following data $\eta_c = 82\%$, $\eta_e = 77\%$, ϵ (effectiveness of H.E) $= 0.8$, η_r (ram effect) $= 84\%$.



G.D

Altitude = 8000m

Speed (V) = 900 km/hr

$= \frac{900 \times 1000}{3600} = 250 m/s$

$P_1 = 0.34$ bar

$T_1 = 263$ K

$\frac{P_3}{P_2} = 5$ (∵ 2-3 Comp Process)

Cabin Pressure $P_5 = 1.013$ bar

$T_{cabin} = 300$ k

$m = 1$ kg/s

$\eta_c = 82\% = 0.82$

$\eta_e = 77\% = 0.77$

$\epsilon = 0.8$

$\eta_r = 84\% = 0.84$

R.T Power = ?

Refrigeration capacity = ?

S.O $T_2' = T_1 + \frac{V^2}{2C_p} = 294K$

$\frac{P_2'}{P_1} = \left(\frac{T_2'}{T_1}\right)^{\frac{\gamma-1}{\gamma}} \Rightarrow P_2 = \left(\frac{T_2'}{T_1}\right)^{\frac{\gamma-1}{\gamma}} \cdot P_1 = 0.5 bar$

(1-2) $T_2 = T_1\left[1 + \frac{1}{\eta_r}\left\{\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\}\right] = 300K$

(2-3) $T_3 = T_2\left[1 + \frac{1}{\eta_c}\left\{\left(\frac{P_3}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right\}\right] = 514K$

$\epsilon = \frac{T_3 - T_4}{T_3 - T_2} \Rightarrow T_4 = T_3 - \epsilon(T_3 - T_2) = 343K$

$T_5 = T_4\left[1 - \eta_e\left\{1 - \frac{1}{\left(\frac{P_4}{P_5}\right)^{\frac{\gamma-1}{\gamma}}}\right\}\right] = 282K$

work of Pressurization Excluding ram work

$= \frac{m C_p T_2}{\eta_c}\left[\left(\frac{P_{cabin}}{P_2}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] = 88 kW$

Power required for refrigeration purposes (Excluding Ram work)

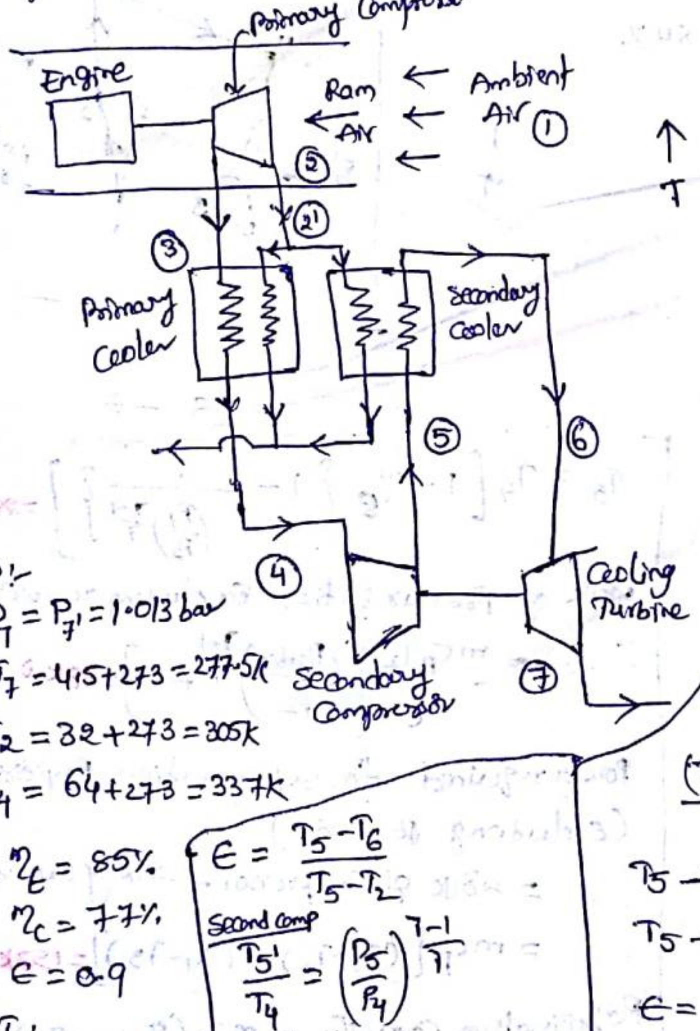
= work of Compressor − work of Expander

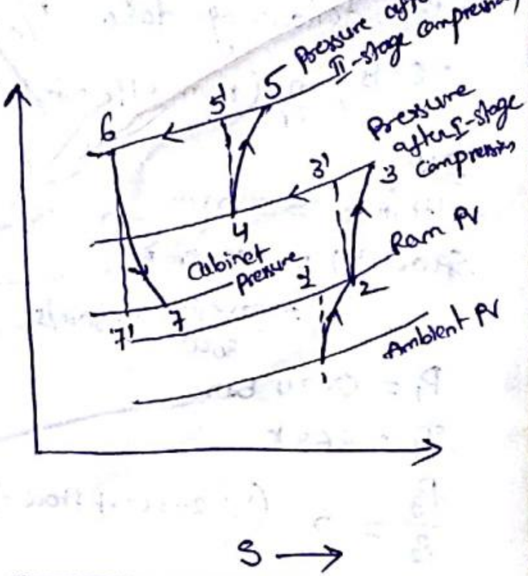
$= mC_p\left[(T_3 - T_2) - (T_4 - T_5)\right] = 153 kW$

Refrigeration capacity $= mC_p(T_{cabin} - T_5)$

$= 18 kW = \frac{18}{3.5} \doteq 5.12 TR$

⇒ A boot strap system is used for an air plane. The pressure in the cabin is maintained at 1.013 bar and the air enters the cabin at 4.5°C. The temperature of air is used for cooling in the heat exchanger is 32°C. The compressed air leaves the primary heat exchanger at 64°C. Taking the following data $\eta_t = 85\%$, η_c (secondary compressor) $= 77\%$, ϵ (secondary H.E) $= 0.9$. Determine (i) the temperature of air entering the cooling turbine (ii) the pressures of air at discharge from primary and secondary compressors.





G.D:-

$P_7 = P_{7'} = 1.013$ bar

$T_7 = 4.5 + 273 = 277.5K$

$T_2 = 32 + 273 = 305K$

$T_4 = 64 + 273 = 337K$

$\eta_t = 85\%$

$\eta_c = 77\%$

$\epsilon = 0.9$

R.T:

$T_6 = ?$

$P_4 = ?$

$P_5 = ?$

F.U

$$\eta_t = \frac{T_6 - T_7}{T_6 - T_{7'}}$$

$$\eta_c = \frac{T_{5'} - T_4}{T_5 - T_4}$$

$$\epsilon = \frac{T_5 - T_6}{T_5 - T_2}$$

Second comp

$$\frac{T_{5'}}{T_4} = \left(\frac{P_5}{P_4}\right)^{\frac{\gamma-1}{\gamma}}$$

Expansion process

$$\frac{T_6}{T_{7'}} = \left(\frac{P_5}{P_7}\right)^{\frac{\gamma-1}{\gamma}}$$

Cooling turbine work = secondary compressor work

$$(T_6 - T_{7'})\eta_t = (T_5 - T_4)$$

$$0.77 = \frac{T_{5'} - 337}{371.11 - 337}$$

$$\boxed{T_{5'} = 363.26K}$$

Calculations

$$\eta_t = \frac{T_6 - T_7}{T_6 - T_{7'}}$$

$$(T_6 - T_{7'}) = \frac{T_6 - 277.5}{0.85} \rightarrow ①$$

$$\frac{(T_5 - T_4)}{0.85} = \frac{T_6 - 277.5}{0.85}$$

$$T_5 - 337 = T_6 - 277.5$$

$$T_5 - T_6 = 59.5 = 0 \longrightarrow ②$$

$$\epsilon = \frac{T_5 - T_6}{T_5 - T_2} = \frac{59.5}{T_5 - 305}$$

$$0.9 \times T_5 - 0.9 \times 305 = 59.5$$

$$\boxed{T_5 = 371.11K}$$

$$T_6 = T_5 - 59.5 \Rightarrow \boxed{T_6 = 311.61K}$$

Eq①

$$T_{7'} = T_6 - \frac{T_6 - 277.5}{0.85}$$

$$= 311.61 - \frac{311.61 - 277.5}{0.85}$$

$$\boxed{T_{7'} = 271.48K}$$