REFRIGERATION AND AIR CONDITIONING

B.TECH. VII SEMESTER
MECHANICAL ENGINEERING

PREPARED BY:
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TEXT BOOKS

1. S. C. Arora, Domkundwar, ―A Course in Refrigeration and Air-conditioning
2. C. P. Arora, ―Refrigeration and Air Conditioning

UNIT – I

INTRODUCTION TO REFRIGERATION AND VAPOR COMPRESSION REFRIGERAION

At the end of the unit students are able to:

	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	Relate the performance of a vapour compression refrigeration cycles under specified inlet and outlet conditions.	Remember
CO2	Identify the modifications required in an impossible reversed Carnot cycle to convert it into practical cycle for refrigeration applications.	Understand
CO3	Demonstrate the working principle and coefficient of performance of a heat pump, heat engine and refrigerator.	Understand
CO4	Analyze theoritical, practical aircraft refrigeration cycles with T-S diagrams, by stating merits, limitations, etc.	Analyze

Introduction

- 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.

Introduction

- **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.**

- **Refrigeration also defined as continued extraction of heat from a body which is kept at a temperature lower than the surrounding temperature.**

Introduction

- If we remove bucket of water from a tank, the surrounding water rushes in to fill the cavity. Similarly heat rushes in, to replace the heat removed. Therefore, the insulation is provided to prevent the rush in heat.

- Therefore, the refrigeration involves in pumping of heat from lower temperature to higher temperature but heat has a natural tendency to flow from higher temperature to lower temperature.

- According to second law of thermodynamics heat can flow from a lower temperature to higher temperature with the aid of an external agency, so refrigeration works on the principle of second law of thermodynamics.

Thermodynamic Laws:

- **First law of thermodynamics:**

When a closed system undergoes a thermodynamic cycle, the net heat transfer is equal to the net work transfer.

$$\oint \delta Q = \oint \delta W$$

(OR)

The energy can neither be created nor destroyed but it can be transferred from one form of energy into another.

Thermodynamic Laws:

- **Second law of thermodynamics:**

  i. Kelvin-Plank statement

  It is impossible to construct a device that operates in a cyclic process and produce no effect other than to receive heat from a single reservoir to convert it into equivalent amount of work. In other words it is impossible to construct an engine whose sole purpose is to convert all amount of heat into equal amount of work.

  ii. Clausius statement

  It states that heat cannot flow from a body at lower temperature to a body at higher temperature without any aid of external energy.

Thermodynamic Laws:

- **Sensible Heat:**

  When a substance heated and the temperatures rises as the heat is added the increase in heat is called sensible heat.

- **Latent heat:**

  The amount of heat required to change the phase of substance from one state to another with no change in temperature is called latent heat.

  Latent heat of ice = 335 KJ/Kg, it means 1 kg of ice requires 335 KJ of heat to change into water at 0^0C & atmospheric pressure. This heat is called latent heat of fusion or melting.

Thermodynamic Laws:

Latent heat of water = 2257 KJ/Kg, it requires 2257 KJ of heat to become gas at 100^0C & atmospheric pressure. This heat is called latent heat of vaporization or condensation.

- **Specific heat:**

The amount of heat required to raise the temperature of 1^0K of unit mass of any substance KJ/Kg K**.**

Substance	Specific Heat
Water	4.187
Ice	2.110
Steam	2.094
Air	1.0

UNIT OF REFRIGERATION

- **Unit of refrigeration is TR (ton of refrigeration)**

  It is defined as the amount of refrigeration effect produced by uniform melting of one ton of ice at 0^0C with in 24 hours.

1 TR	**=**	**1000 Kg of ice**	
	=	**1000 x 335 KJ/Kg**	**: LH of ice = 335 KJ/Kg**
	=	**335000 KJ / 24 hrs.**	
	=	**335000 / (24 x 60) KJ/min.**	
	=	**232.6 KJ/min. (or)**	
	=	**3.8 KW**	

But in actual practice it is considered as 210 KJ/min. or 3.5 KW

Natural Refrigeration

- **In olden days refrigeration was achieved by natural means such as the use of ice or evaporative cooling. In earlier times, ice was either:**

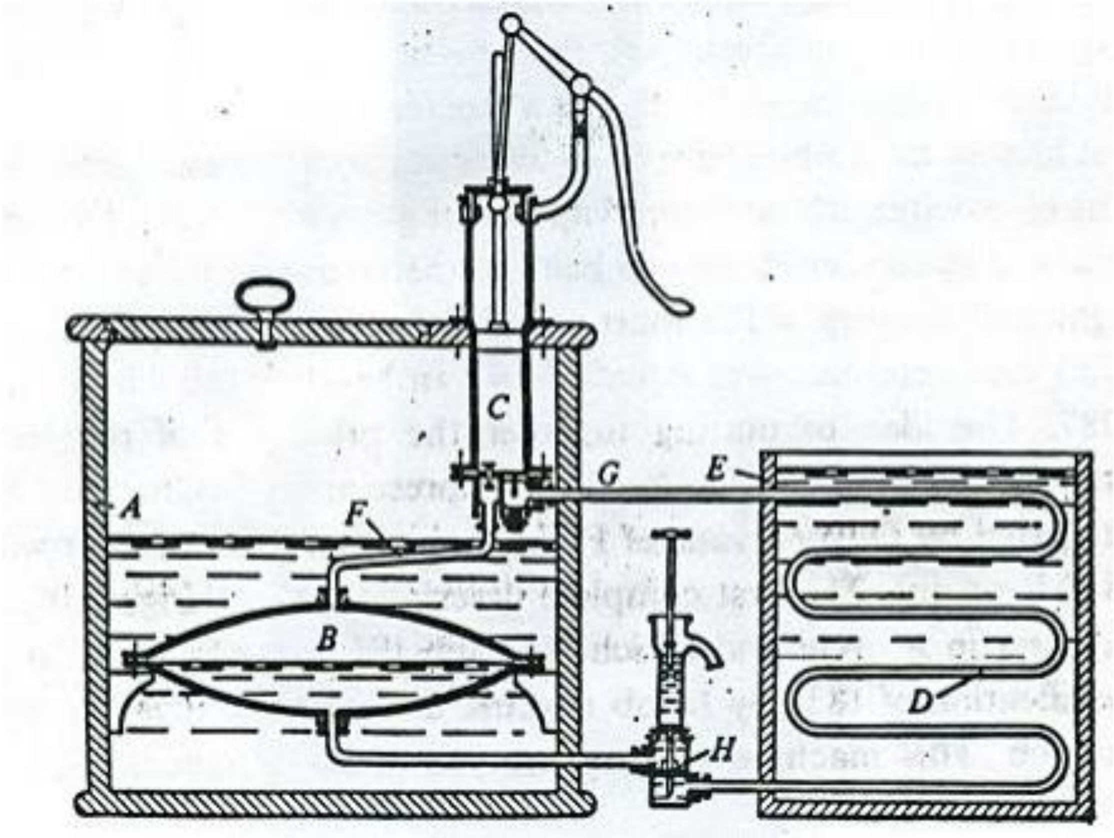
1. **Transported from colder regions,**
2. **Harvested in winter and stored in ice houses for summer use or,**
3. **Made during night by cooling of water by radiation to stratosphere.**

Artificial Refrigeration

- Refrigeration as it is known these days is produced by artificial means. Though it is very difficult to make a clear demarcation between natural and artificial refrigeration, it is generally agreed that the history of artificial refrigeration began in the year 1755, when the Scottish professor William Cullen made the first refrigerating machine, which could produce a small quantity of ice in the laboratory.

- Based on the working principle, refrigeration systems can be classified as vapour compression systems, vapour absorption systems, gas cycle systems etc.

Apparatus described by Jacob Perkins in his patent specification of 1834.



Reversed Carnot cycle employing a gas

- **Reversed Carnot cycle is an ideal refrigeration cycle for constant temperature external heat source and heat sinks.**

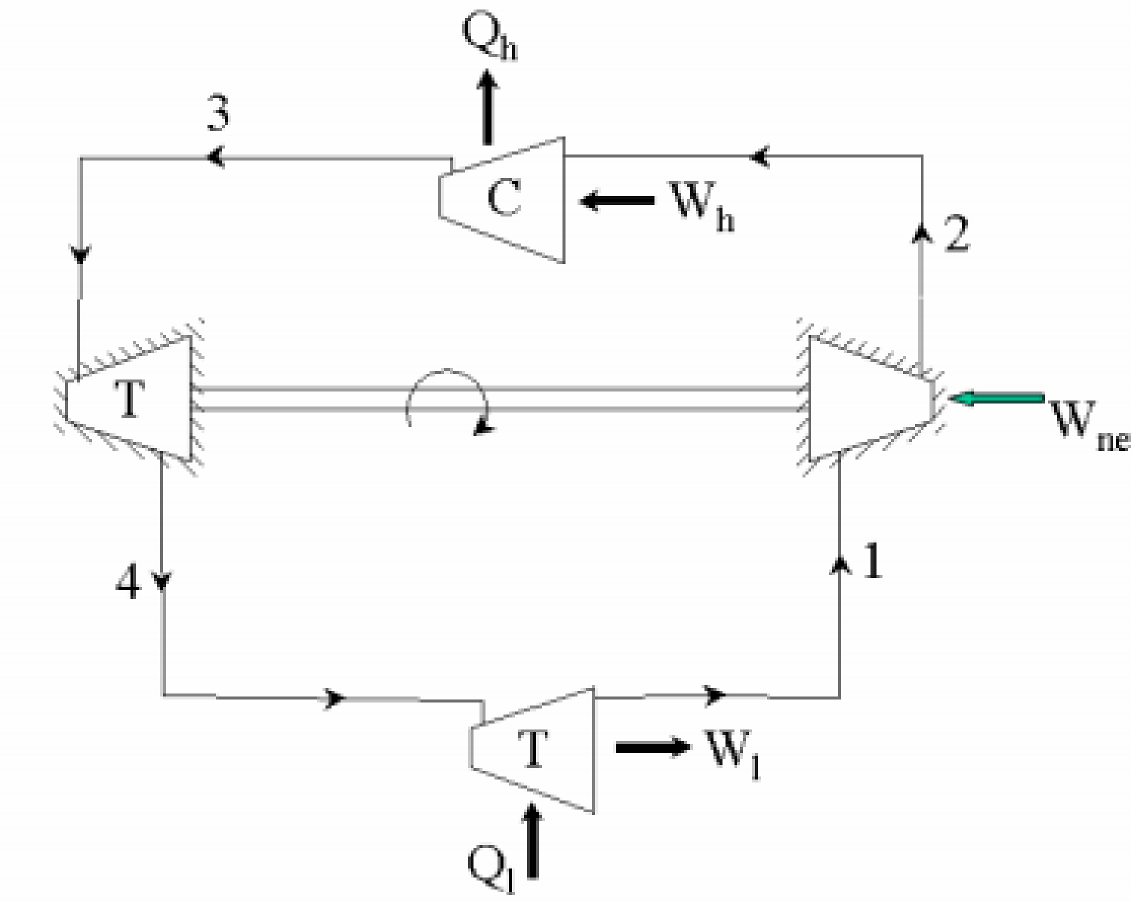
Process 1-2: **Reversible, adiabatic compression in a compressor**

Process 2-3: **Reversible, isothermal heat rejection in a compressor**

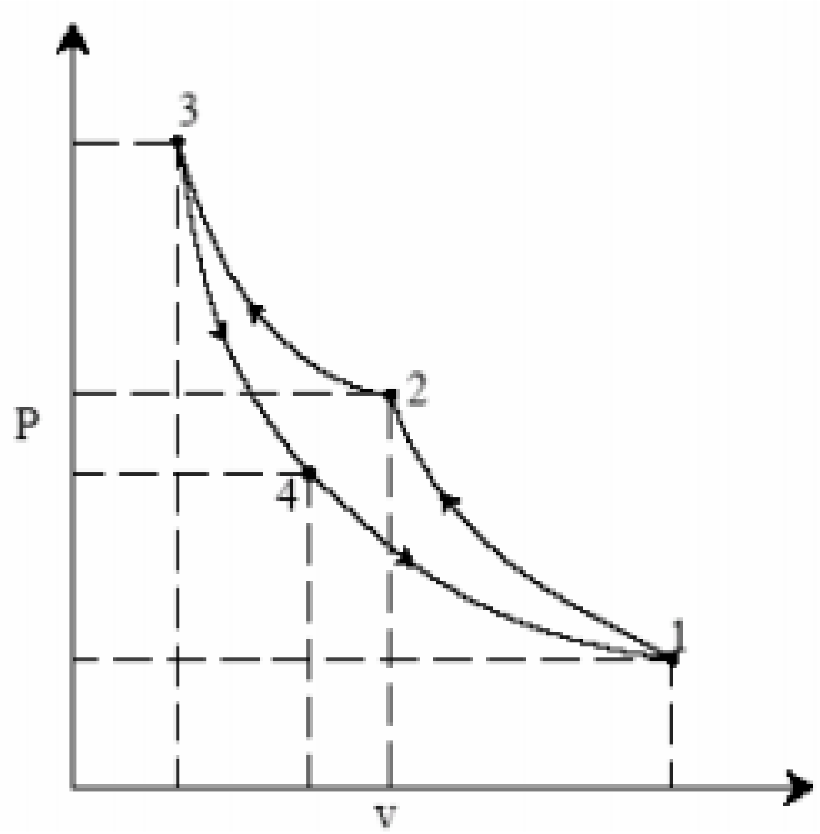
Process 3-4: **Reversible, adiabatic expansion in a turbine**

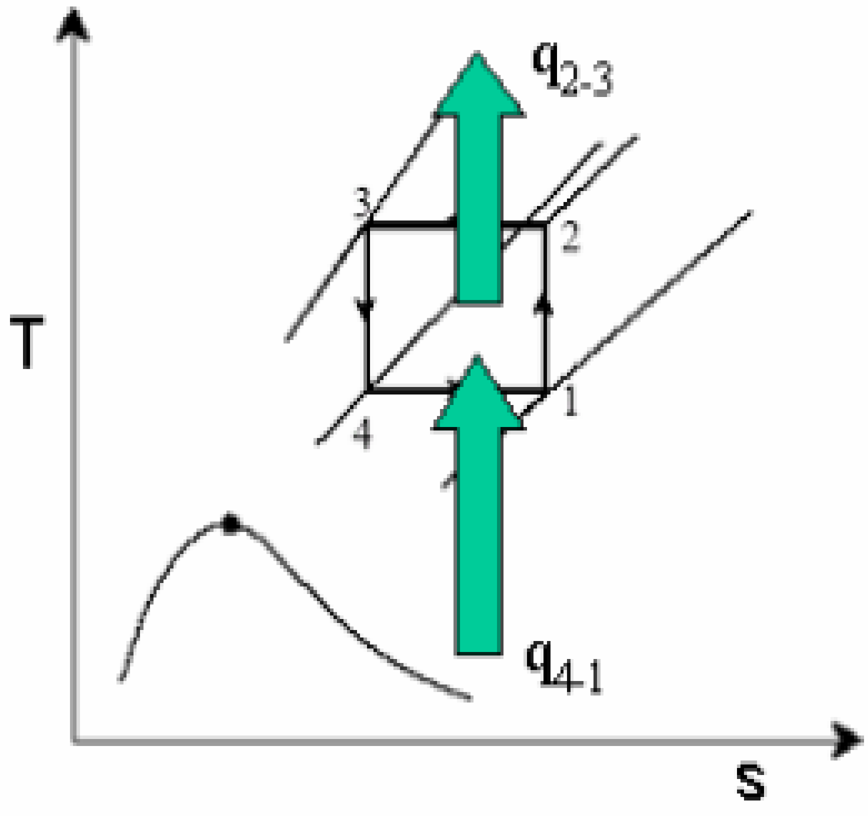
Process 4-1: **Reversible, isothermal heat absorption in a turbine**

Schematic of a reverse Carnot refrigeration system



Reverse Carnot refrigeration system in P-v and T-s coordinates



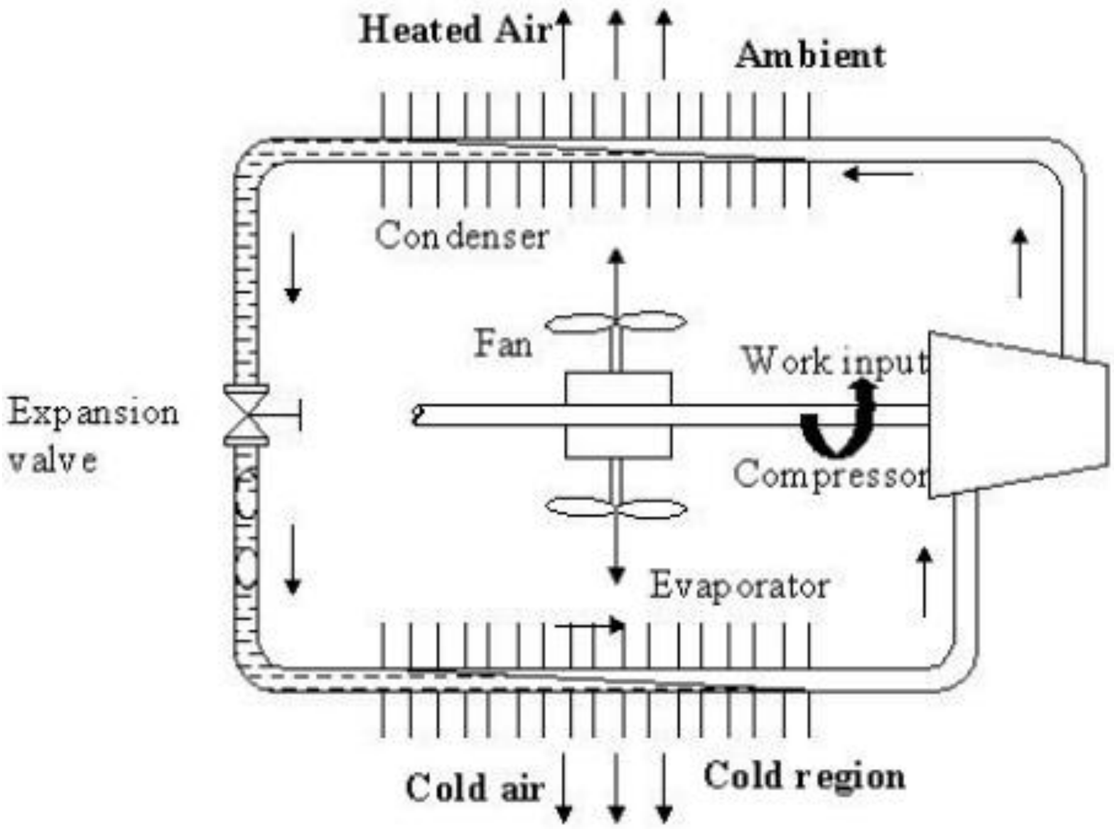


$$COP_{Carnot} = \left|\frac{q_{4-1}}{w_{net}}\right| = \left(\frac{T_l}{T_h - T_l}\right)$$

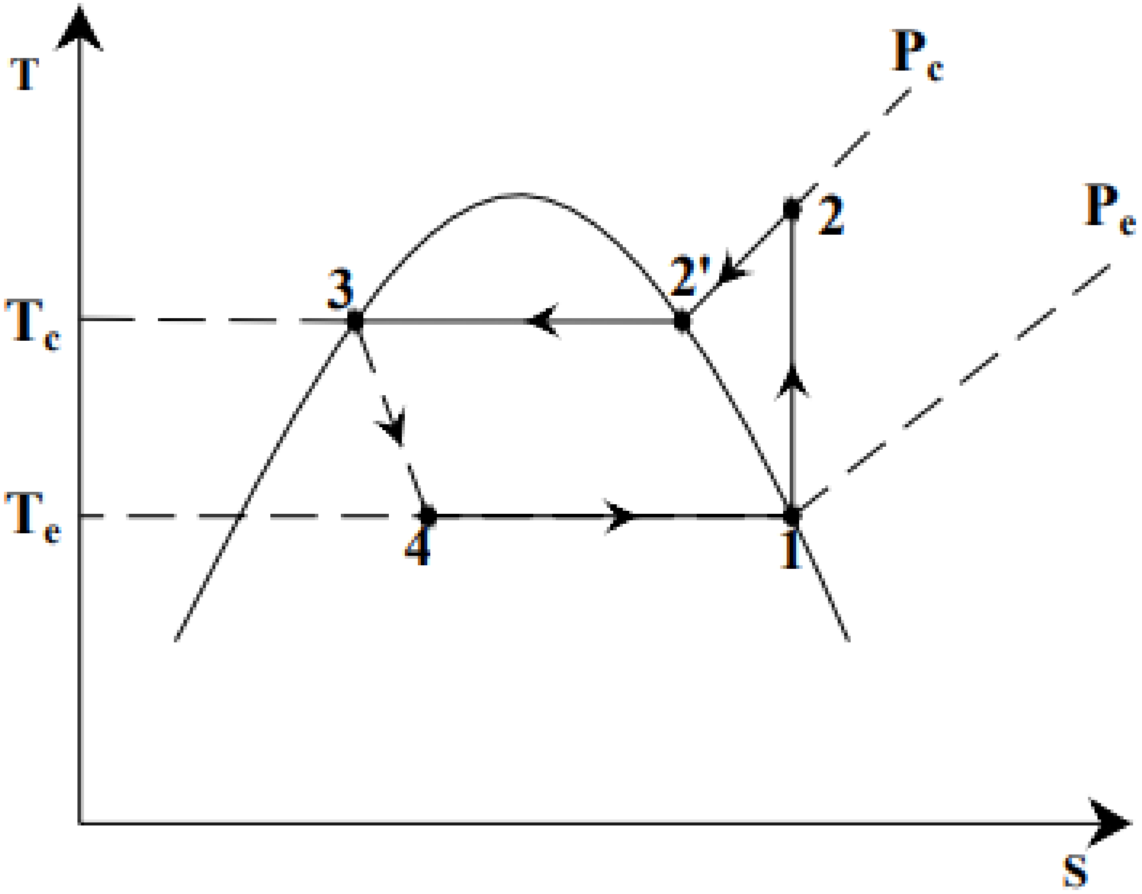
Vapour Compression Refrigeration Systems:

- The basis of modern refrigeration is the ability of liquids to absorb enormous quantities of heat as they boil and evaporate.
- Professor William Cullen of the University of Edinburgh demonstrated this in 1755 by placing some water in thermal contact with ether under a receiver of a vacuum pump.
- The evaporation rate of ether increased due to the vacuum pump and water could be frozen.
- This process involves two thermodynamic concepts, the vapour pressure and the latent heat. A liquid is in thermal equilibrium with its own vapor at a pressure called the saturation pressure, which depends on the temperature alone.

Schematic of a basic vapour compression refrigeration system



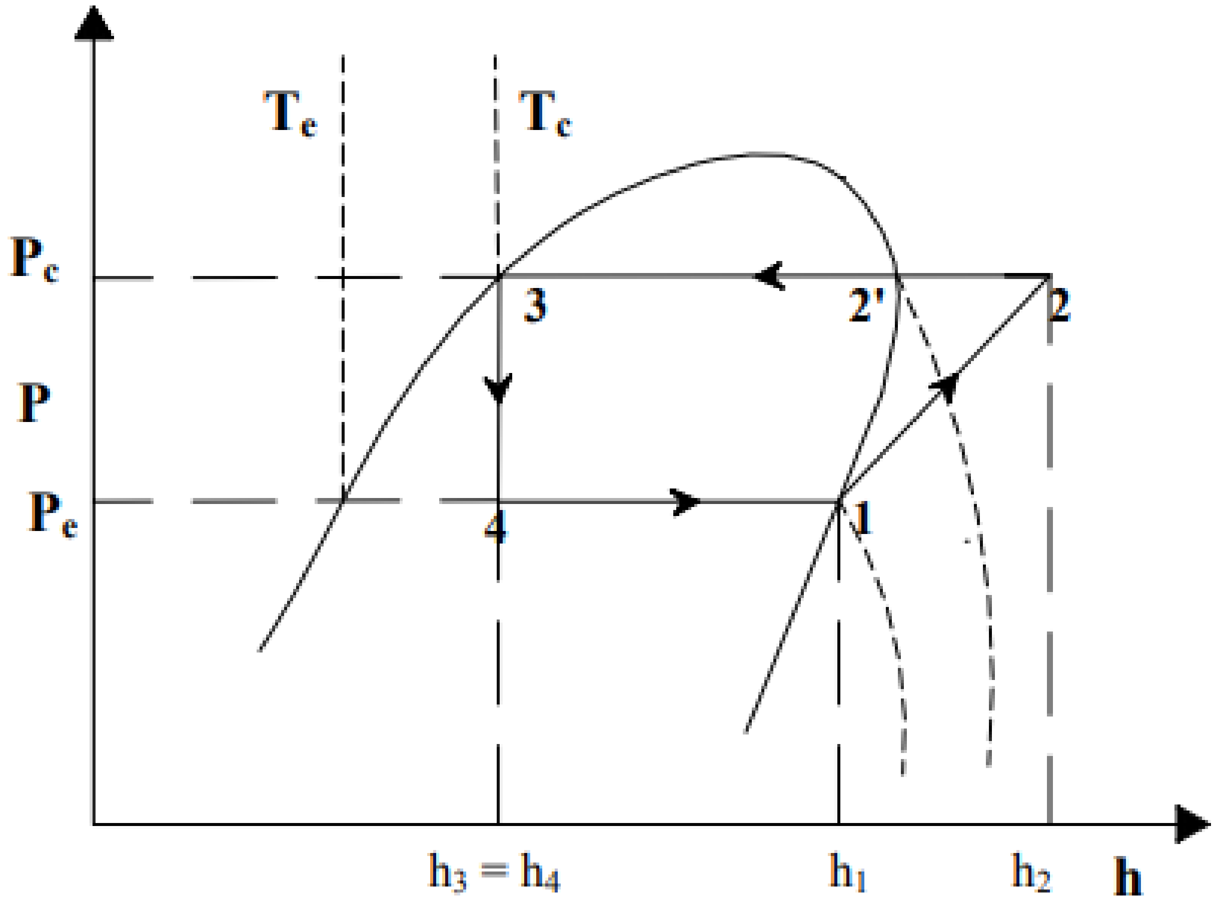
Vapour Compression Refrigeration Systems:



Standard Vapour Compression Refrigeration System (VCRS)

- **Process 1-2:** Isentropic compression of saturated vapour in compressor
- **Process 2-3:** Isobaric heat rejection in condenser
- **Process 3-4:** Isenthalpic expansion of saturated liquid in expansion device
- **Process 4-1:** Isobaric heat extraction in the evaporator

Standard vapour compression refrigeration cycle on a P-h chart



Analysis Standard Vapour Compression Refrigeration System (VCRS)

Evaporator:

- **Heat transfer rate at evaporator or refrigeration capacity, is given by:**

$$\dot{Q}_e = \dot{m}_r (h_1 - h_4)$$

- **Where m_r is the refrigerant mass flow rate in kg/s, h1 and h4 are the specific enthalpies (kJ/kg) at the exit and inlet to the evaporator, respectively. (h1-h4) is known as specific refrigeration effect or simply refrigeration effect, which is equal to the heat transferred at the evaporator per kilogram of refrigerant. The evaporator pressure Pe is the saturation pressure corresponding to evaporator temperature Te.**

Analysis Standard Vapour Compression Refrigeration System (VCRS)

Compressor:

- Power input to the compressor, is given by:

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

- here h2 and h1 are the specific enthalpies (kJ/kg) at the exit and inlet to the compressor respectively. (h1-h2) is known as specific work of compression or simply work of compression, which is equal to the work input to the compressor per kilogram of refrigerant.

Analysis Standard Vapour Compression Refrigeration System (VCRS)

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Condensor:

- Heat transfer rate at condenser, is given by

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

- where h3 and h2 are the specific enthalpies (kJ/kg) at the e respectively.

Analysis Standard Vapour Compression Refrigeration System (VCRS)

Expansion Device:

- **Expansion device: For the isenthalpic expansion process the kinetic energy change acrsoss the expansion device could be considerable, however, if we take the control volume, well downstream of the expansion device, then the kinetic energy gets dissipated due to viscous effects, and**

$$h_3 = h_4$$

Aircraft Refrigeration:

In an aircraft, cooling systems are required to keep the cabin temperatures at a comfortable level. Even though the outside temperatures are very low at high altitudes, still cooling of cabin is required due to:

- **Large internal heat generation due to occupants, equipment etc.**
- **Heat generation due to skin friction caused by the fast moving aircraft.**

- **At high altitudes, the outside pressure will be sub-atmospheric. When air at this low pressure is compressed and supplied to the cabin at pressures close to atmospheric, the temperature increases significantly.**
- **Solar radiation**

For low speed aircraft flying at low altitudes, cooling system may not be required, however, for high speed aircraft flying at high altitudes, a cooling system is a must.

Aircraft Refrigeration:

Even though the COP of air cycle refrigeration is very low compared to vapour compression refrigeration systems, it is still found to be most suitable for aircraft refrigeration systems as:

- **Air is cheap, safe, non-toxic and non-flammable. Leakage of air is not a problem.**
- **Cold air can directly be used for cooling thus eliminating the low temperature heat exchanger (open systems) leading to lower weight.**

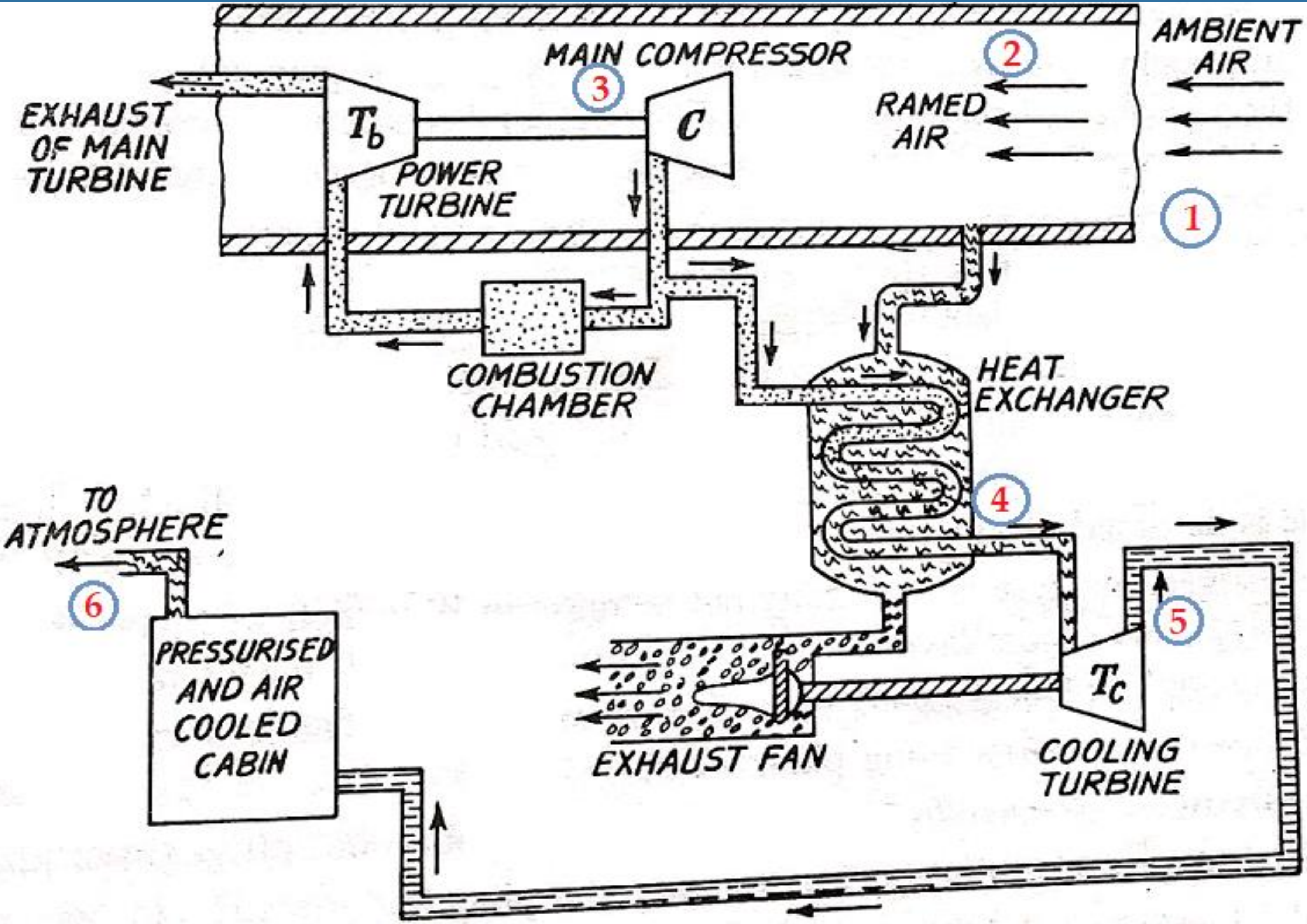
Aircraft Refrigeration:

- The aircraft engine already consists of a high speed turbo-compressor, hence separate compressor for cooling system is not required. This reduces the weight per kW cooling considerably.
- Design of the complete system is much simpler due to low pressures.
- Maintenance required is also less.

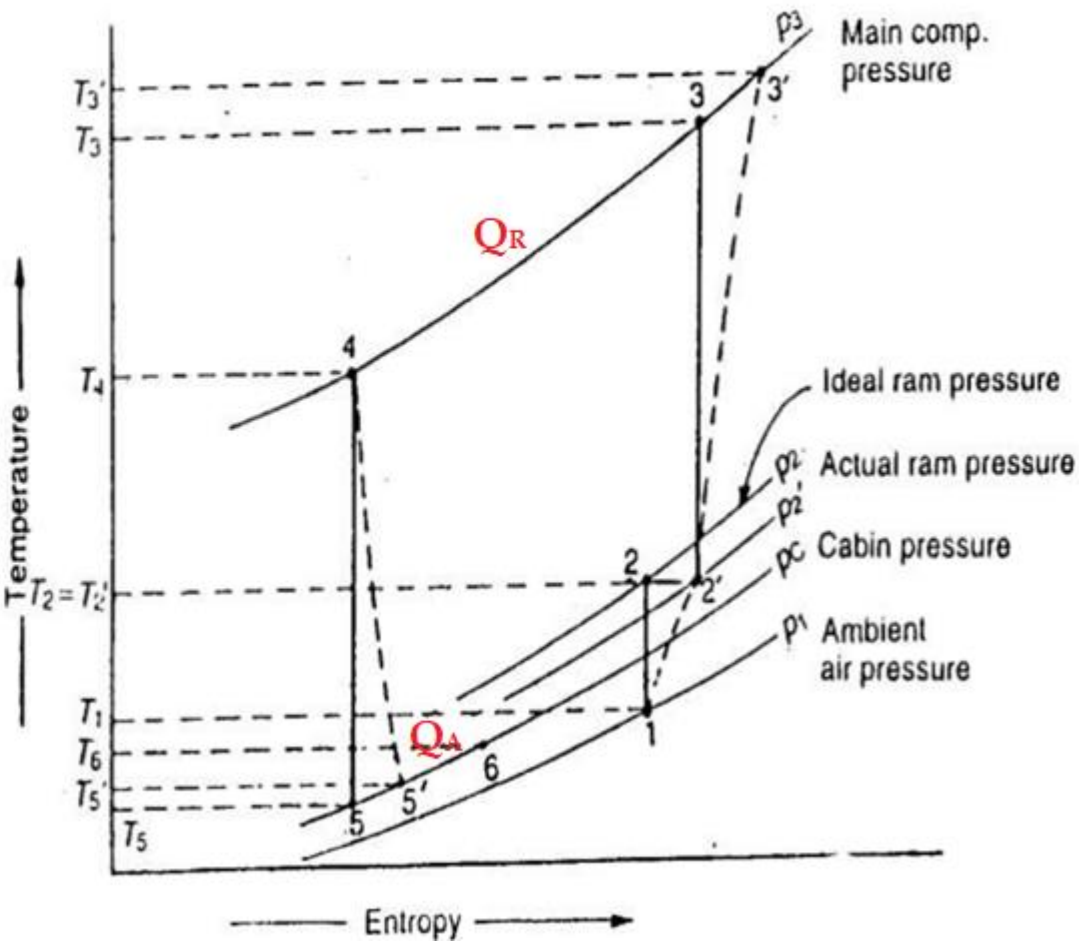
Various types of aircraft air refrigeration systems

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.

Simple air cooling system



Simple air cooling system: T-S Diagram



Process 1-2 = Isentropic ramming of air

Process 1-2' = Actual ramming of air

Process 2'-3 = Isentropic compression in main compressor

Process 2'-3' = Actual compression in main compressor

Process 3-4 = Constant pressure heat rejection in heat exchanger

Process 4-5 = Isentropic expansion in cooling turbine

Process 4-5' = Actual expansion in cooling turbine

Process 5-6 = Constant pressure heat addition in cabin

Simple air cooling system: T-S Diagram

- **Workdone during compression (2-3)**

  $W_C = m_a.C_p.(T_3-T_2)$ KJ --------(i)

- **Heat removed in heat exchanger (3-4)**

  $Q_R = m_a.C_p.(T_3-T_4)$ KJ --------(ii)

- **Workdone by the cooling turbine (4-5)**

  $W_T = m_a.C_p.(T_4-T_5)$ KJ --------(iii)

- **Refrigeration process in cabin (5-6)**

  $Q_A = m_a.C_p.(T_6-T_5)$ KJ --------(iv)

Various types of aircraft air refrigeration systems

$$COP = \frac{\text{Refrigeration effect}}{\text{Workdone}}$$

$$COP = \frac{m_a . C_p .(T_6 - T_5)}{m_{a.} C_p .(T_3 - T_2)}$$

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

(OR)

$$\text{Power required for the refrigeration system} = \frac{m_a .C_p .(T_3 - T_2)}{60} \, KW$$

$$\text{COP of the refrigeration system} = \frac{210.Q}{m_a .C_p .(T_3 - T_2)} = \frac{210.Q}{P \times 60}$$

Problem 1.0:

- A simple air cooled system is used for an aeroplane having a load of 10 tones. 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. C.O.P. of the system.

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

Problem 1.0:

Solution

Given :

$Q = 10$ TR;

$P_1 = 0.9$ bar;

$T_1 = 10°C = 10+273 = 283$ K;

$P_2 = 1.013$ bar;

$P_5 = P_6 = 1.01$bar;

$T_6 = 25°C=25+273=298$ K;

$P_3 = 3.5$ bar;

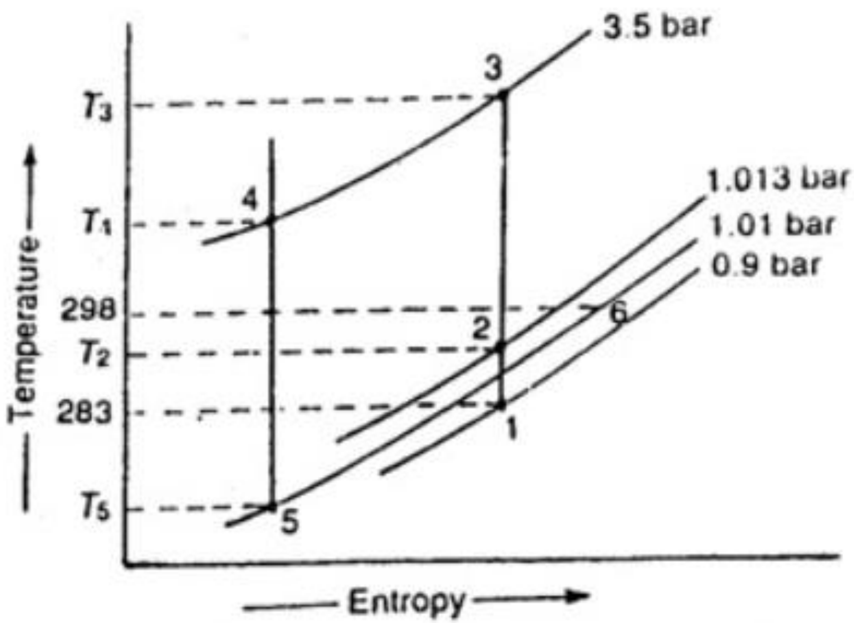
$T_6 = 25°C = 25+273 = 298$K;

$T_4 = T_3 – 50^0C$;

Solution:

1. Power required taking the load of cooling in the cabin:

First of all, let us find the mass of air (m_a) required for the refrigeration purpose. Since the compressions and expansions are isentropic, therefore the various processes on the T-s diagram are as shown in diagram below:



Solution:

We know that;

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.013}{0.9}\right)^{\frac{1.4-1}{1.4}} = (1.125)^{0.286} = 1.1034$$

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

Similarly $\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3.5}{1.013}\right)^{\frac{1.4-1}{1.4}} = (3.45)^{0.286} = 1.425$

Therefore $T_3 = T_2 \times 1.425 = 283 \times 1.425 = 417K = 144^\circ C$

Since the temperature of air is reduced by 50°C, in the heat exchanger, therefore temperature of air leaving the heat exchanger,

T_4 = 144–50 = 94°C = 367K

Solution:

Similarly;

$$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.01}{3.5}\right)^{\frac{1.4-1}{1.4}} = (0.288)^{0.286} = 0.7$$

$$T_5 = T_4 \times 0.7 = 367 \times 0.7 = 257K$$

We know that mass of air required for the refrigeration purpose,

$$m_a = \frac{210Q}{c_p(T_6 - T_5)} = \frac{210 \times 10}{1(298-257)} = 512 \text{kg/min}$$

Solution:

Therefore Power required to take the load of cooling in the cabin;

$$p = \frac{m_a c_p (T_3 - T_2)}{60} = \frac{51.2 \times 1 (417 - 292.6)}{60} = 106 kW \text{ (Ans)}$$

2. C.O.P. of the system

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

$$COP = \frac{(298 - 257)}{(417 - 292.6)}$$

$$COP = 0.329 (ANS)$$

Solution:

Therefore Power required to take the load of cooling in the cabin;

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2. C.O.P. of the system

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

$$COP = \frac{(298 - 257)}{(417 - 292.6)}$$

$$COP = 0.329 \, (ANS)$$

Problem 2.0:

An aircraft refrigeration plant has to handle a cabin load of 30 tons. 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 I 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;

$T_1 = 17°C = 17+237 = 290$ K;

$P_2 = 0.95$ bar;

$T_2 = 30°C = 30+273 = 303$ K;

$P_3 = P_3' = 4.75$ bar

$T_4 = 67°C = 67+273 = 340$ K;

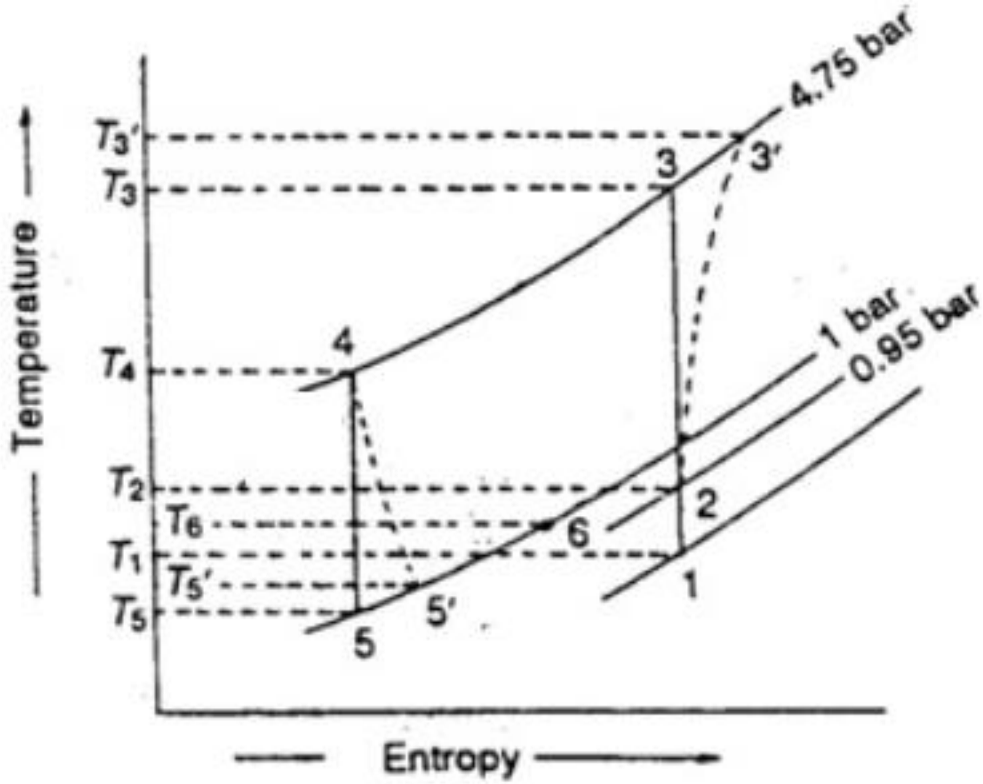
$P_5 = P_5' = 1$ bar;

$T_6 = 27°C = 27+273 = 300$ K;

$\eta_c = \eta_T = 0.9$;

$C_p = 1.004$ kJ/kgK;

$c_p/c_v = \gamma = 1.4$



Solution:

We know that for isentropic compression process 2-3,

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

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

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

$$0.9 = \frac{480 - 303}{T_3' - 303} = \frac{177}{T_3' - 303}$$

$$T_3' - 303 = \frac{177}{0.9} = 16.7 (or) T_3' = 303 + 16.7 = 499.7K$$

Solution:

Now for isentropic expansion process 4-5,

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

$$T_5 = \frac{T_4}{1.561} = \frac{340}{1.561} = 217.8\,\text{K}$$

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

$$0.9 = \frac{340 - T_5'}{340 - 217.8} = \frac{340 - T_5'}{122.2}$$

$$T_5' = 340 - 0.9 \times 122.2 = 230\,\text{K}$$

Solution:

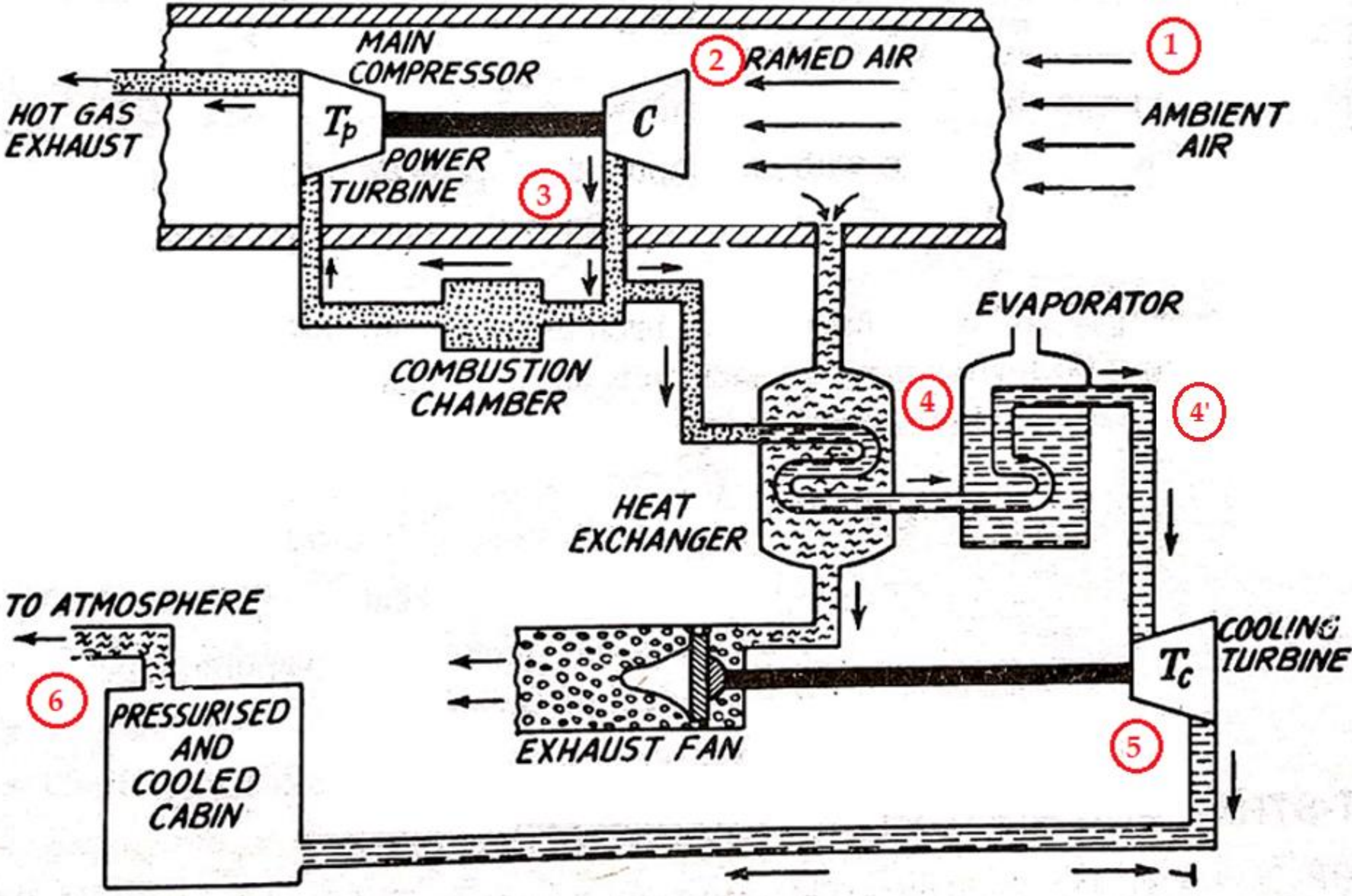
Mass of air circulated per minute:

$$m_a = \frac{210Q}{c_p(T_6 - T_5')} = \frac{210 \times 10}{1.004(300 - 230)} = 89.64\text{kg/min } \textbf{(Ans)}$$

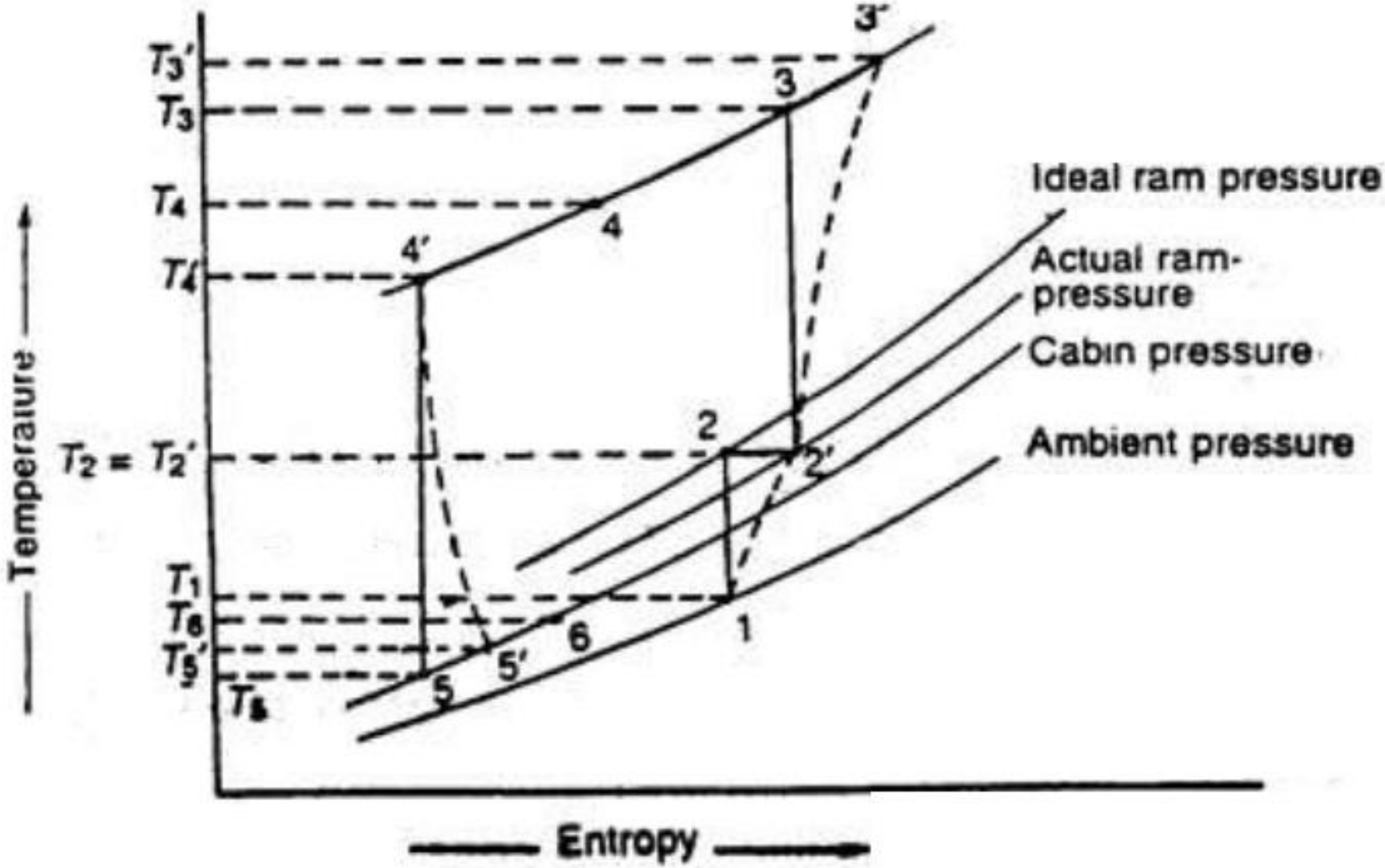
COP =

$$= \frac{210Q}{m_a c_p(T_3' - T_2)} = \frac{210 \times 30}{89.64 \times 1.004(499.7 - 303)} = 0.356 \textbf{(Ans)}$$

Simple Air Evaporative Cooling System



Simple Air Evaporative Cooling System



Simple Air Evaporative Cooling System

$$\text{Power required for the refrigeration system} = \frac{m_a . C_p .(T_3 - T_2)}{60} KW$$

$$\text{COP of the refrigeration system} = \frac{210.Q}{m_a . C_p .(T_3 - T_2)} = \frac{210.Q}{P \times 60}$$

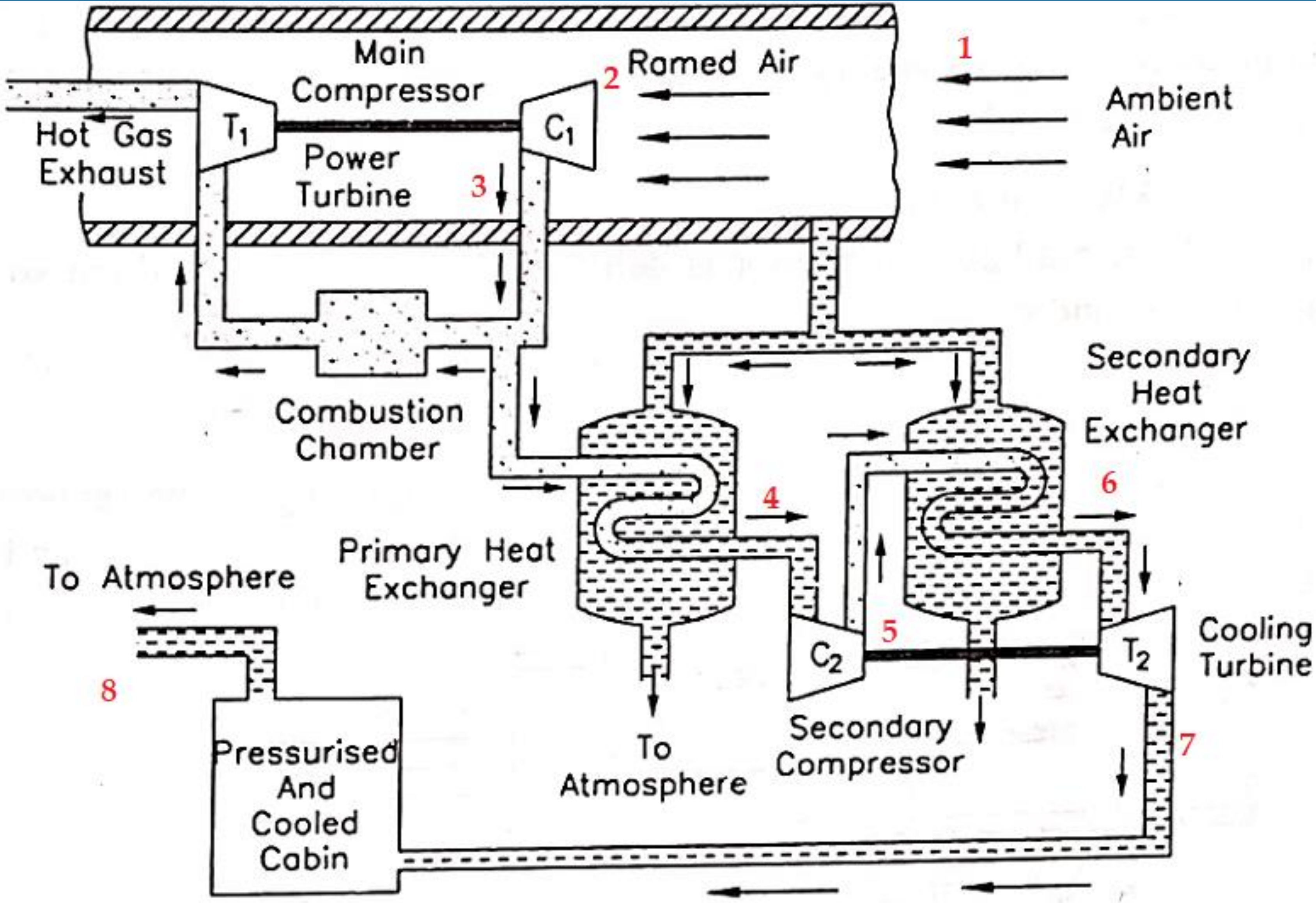
(OR)

$$COP = \frac{\text{Refr. effect}}{\text{Workdone}}$$

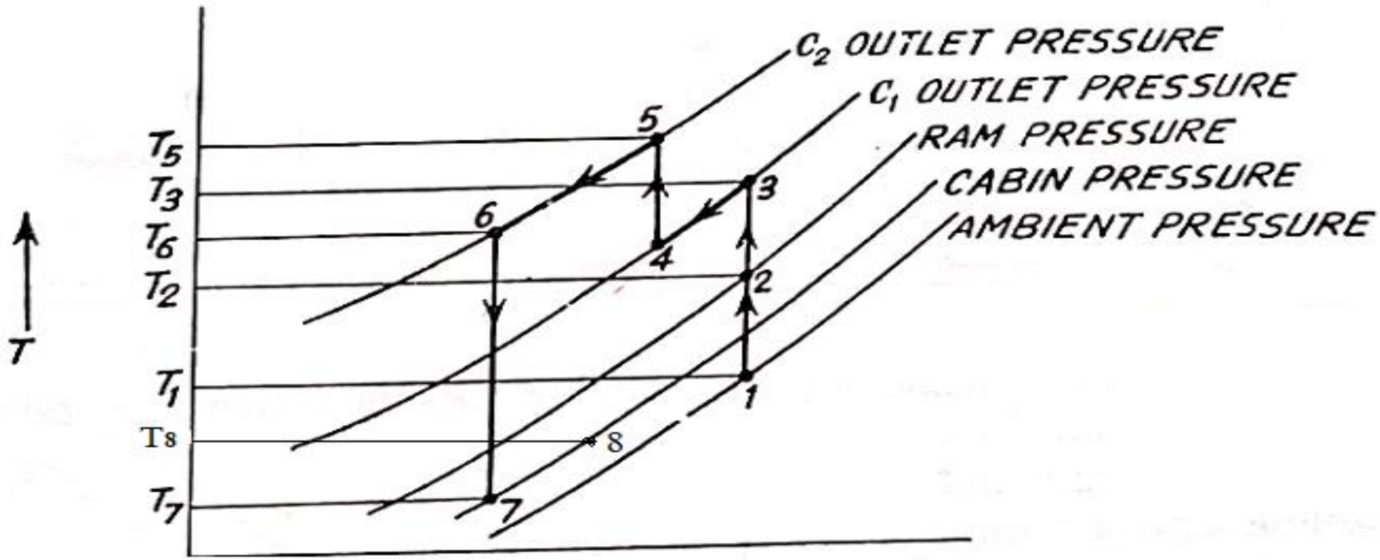
$$COP = \frac{m_a . C_p .(T_6 - T_5)}{m_{a.} C_p .(T_3 - T_2)}$$

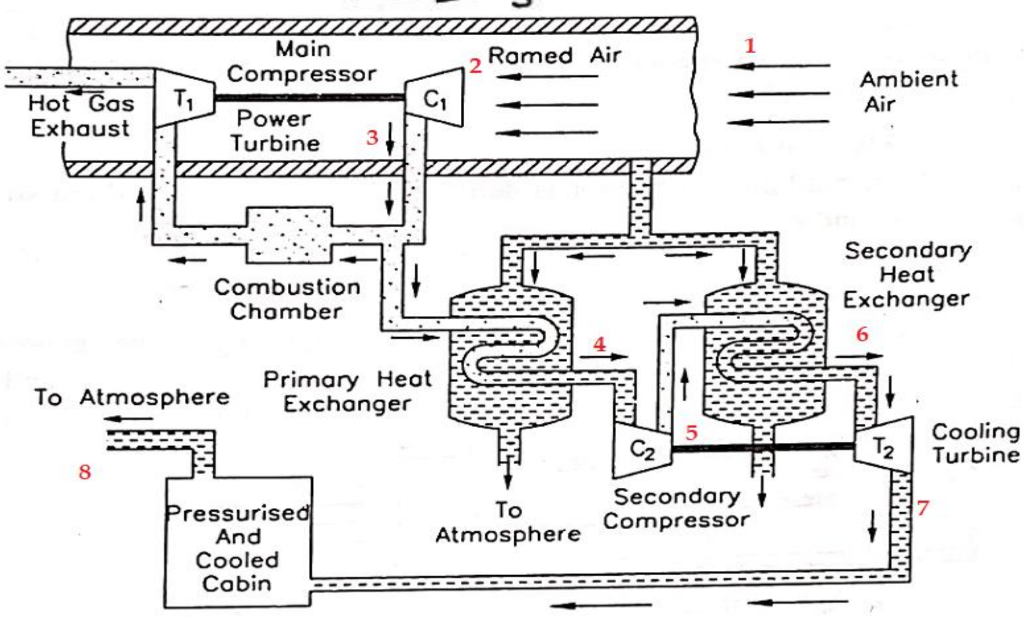
$$COP = \frac{(T_6 - T_5)}{(T_3 - T_2)}$$

Boot-Strap Air Cooling System

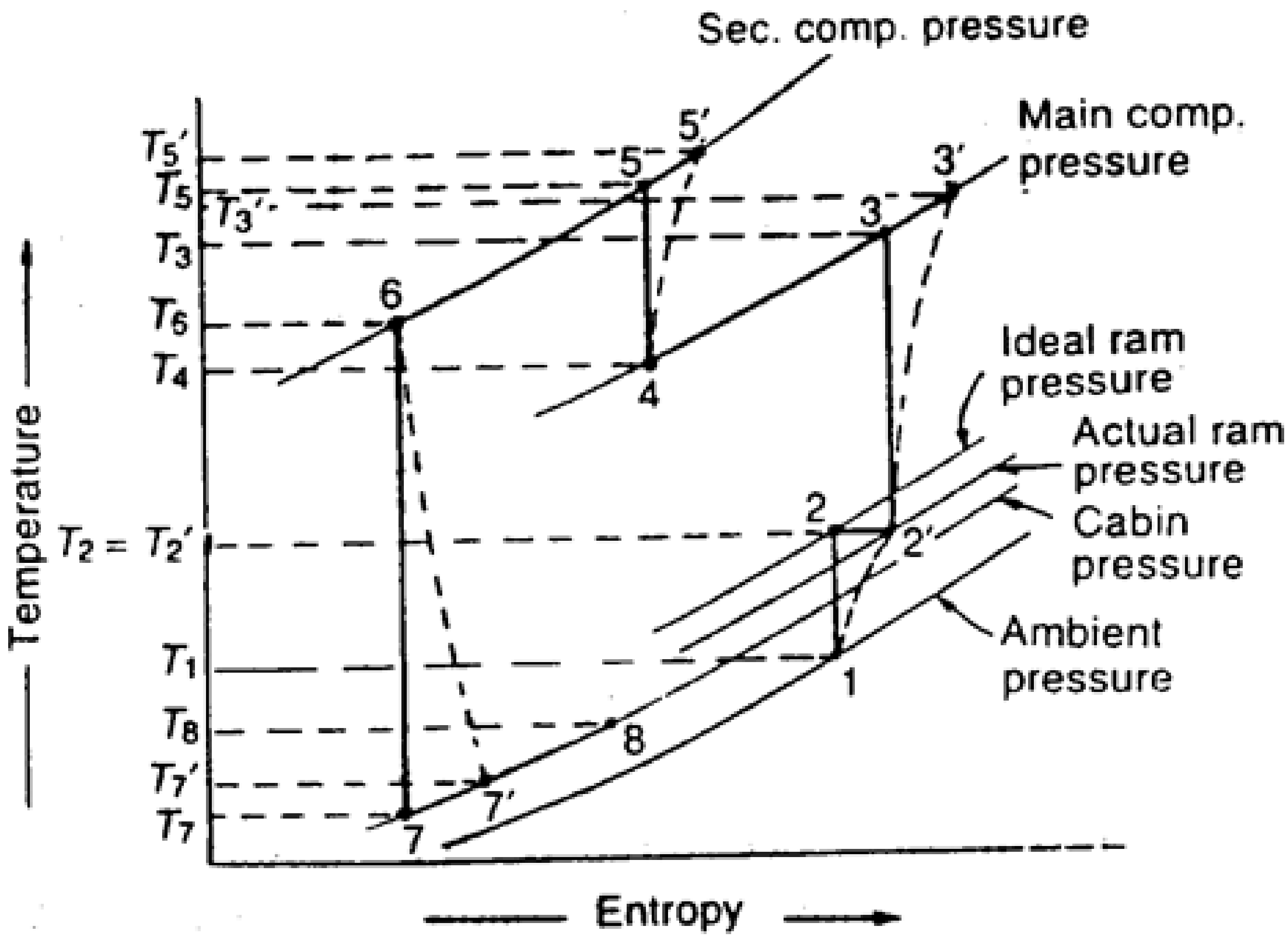


Boot-Strap Air Cooling System: T-S Diagram





Boot-Strap Air Cooling System: T-S Diagram (actual and ideal)



Boot-Strap Air Cooling System

- The term Bootstrap as used in air cycle refrigeration systems, indicates a system in which the pressure of the working fluid is raised to a higher level than the main compressor by a separate compressor, before expanding in the cooling turbine.
- The power required for the secondary compressor is taken from the cooling turbine.

The main components of this system are:

- Two heat exchangers (air cooler and after cooler)
- Two compressors (main and secondary compressors).

Boot-Strap Air Cooling System

- **Assuming cooling load in the cabin is Q tons then the quantity of air circulated in refrigeration system;**

$$m_a = \frac{210.Q}{C_p.(T_8 - T_7)}$$

$$\text{Power required for the refrigeration system} = \frac{m_a.C_p.(T_3 - T_2)}{60} KW$$

$$\text{COP of the refrigeration system} = \frac{210.Q}{m_a.C_p.(T_3 - T_2)} = \frac{210.Q}{P \times 60}$$

Problem 3.0:

- A boot-strap cooling system of 10 TR 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 first heat exchanger and 30% of the enthalpy of air discharged from the auxiliary compressor is removed in the second heat exchanger using rammed air.

Problem 3.0:

Assuming ramming action to be isentropic, the required cabin pressure of 0.9 bar and temperature of the air leaving the cabin not more than 20° C, find : 1. the power required to operate the system, and 2. the C.O.P. of the system. Draw the schematic and temperature -entropy diagram of the system. Take γ = 1.4 and C_p= 1 kJ/kg K.

Solution:

Given :

Q = 10 TR;

T_1 = 20° C = 20 + 273 = 293 K ;

p_1 = 0.85 bar ; p_2 = 1 bar ;

$P_3 = P_3' = P_4 = 3$ bar ;

$p_5 = p_5' = p_6 = 4$ bar ;

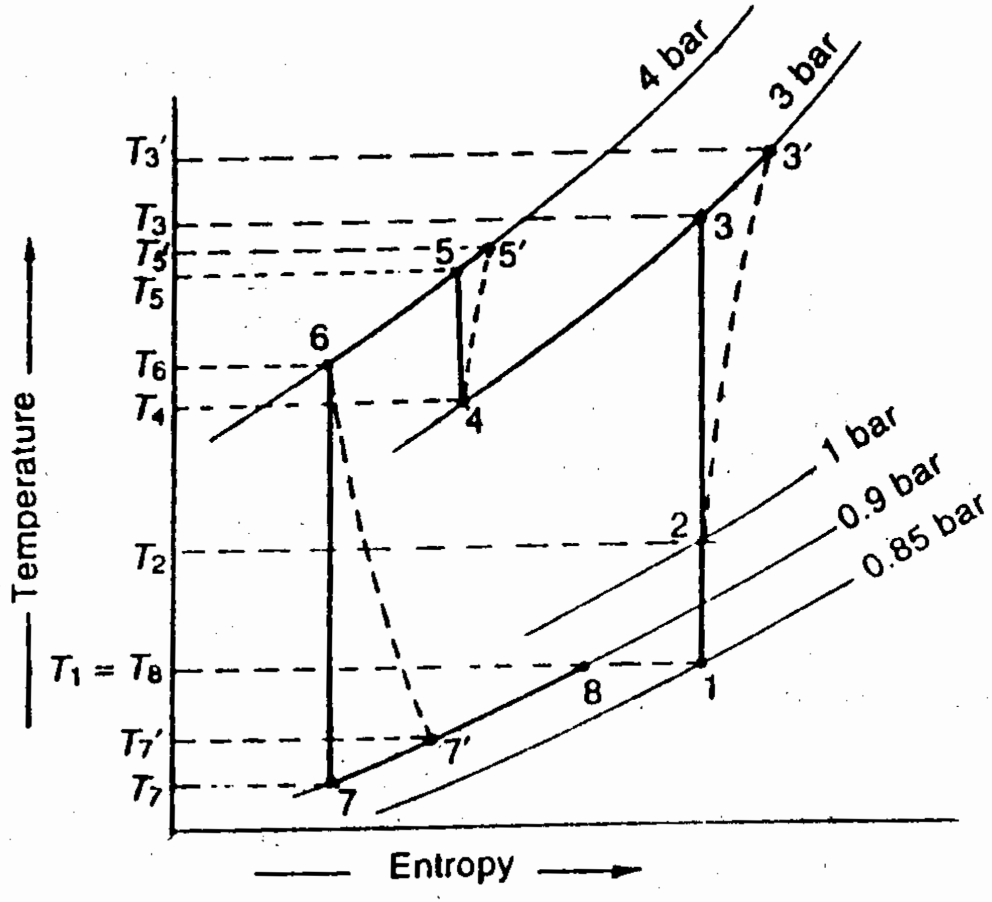
$\eta_{C1} = \eta_{C2} =$ 80% = 0.8 ;

η_T = 85% = 0.85 ;

$p_7 = p_7' = p_8 =$ 0.9 bar ;

$T_8 = 20^0C = 20 + 273 = 293$ K ; y= 1.4; Cp = 1 kJ/kg K

Solution:



4 bar
3 bar
1 bar
0.9 bar
0.85 bar
T3′
T3
T5′
T5
T6
T4
T2
T1 = T8
T7′
T7
3′
3
5
5′
6
4
2
8
1
7′
7
Temperature
Entropy

Solution:

We know that for isentropic ramming process. 1-2

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1}{0.85}\right)^{\frac{1.4-1}{1.4}} = (1.176)^{0.286} = 1.047$$

$$\therefore\ T_2 = T_1 \times 1.047 = 293 \times 1.047 = 306.8\ K = 33.8^\circ C$$

Now for isentropic process in compressor1: 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{3}{1}\right)^{\frac{1.4-1}{1.4}} = (3)^{0.286} = 1.37$$

$$\therefore\ T_3 = T_2 \times 1.37 = 306.8 \times 1.37 = 420.3\ K = 147.3^\circ C$$

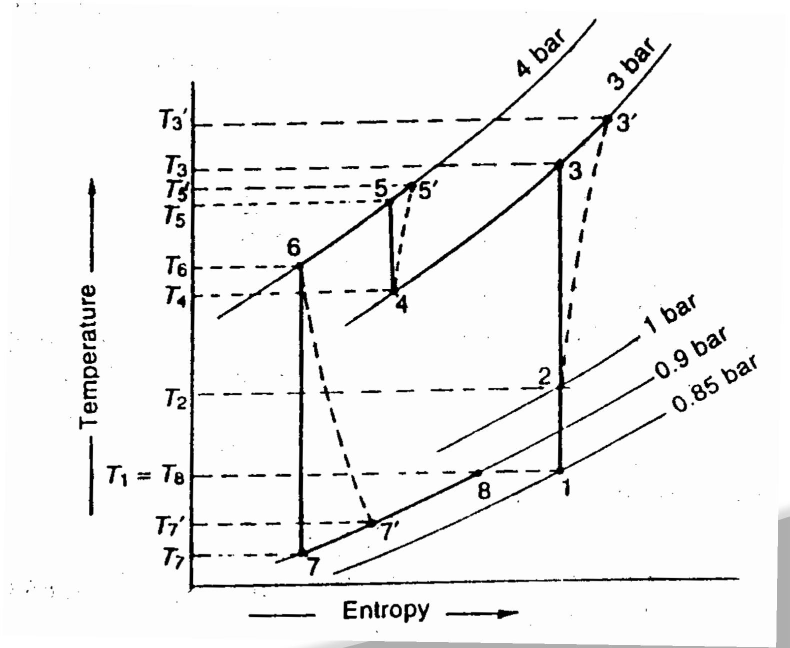
Solution:

We know that isentropic efficiency of the compressor,

$$\eta_{C1} = \frac{Isentropic\ increase\ in\ temperature}{Actual\ increase\ in\ temperature} = \frac{T_3 - T_2}{T_3' - T_2}$$

$$08 = \frac{420.3 - 306.8}{T_3' - 306.8} = \frac{113.5}{T_3' - 306.8}$$

$$\therefore \quad T_3' = 448.7\ K = 175.7°\ C$$



Solution:

- **Since 50% of the enthalpy of air discharged from the main compressor is removed in the first heat exchanger (i.e. during the process 3'-4); Therefore temperature of air leaving the-first heat exchanger,**

$$T_4 = 0.5 \times T_3'$$

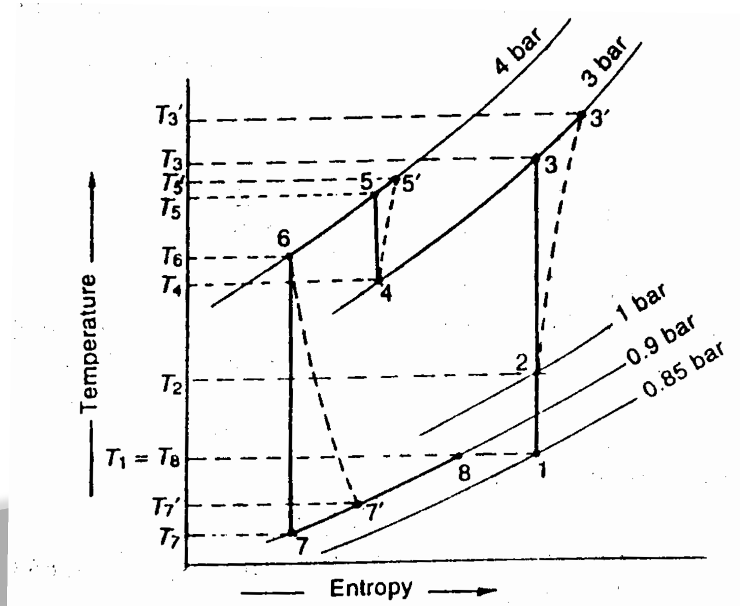
$$\therefore \quad T_4 = 0.5 \times 175.7 = 87.85^\circ C = 360.85\ K$$

Solution:

- **Now for the isentropic process 4-5,**

$$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{3}\right)^{\frac{1.4-1}{1.4}} = (1.33)^{0.286} = 1.085$$

$$\therefore \quad T_5 = T_4 \times 1.085 = 360.85 \times 1.085 = 391.5\ K = 118.5^{\circ}\ C$$



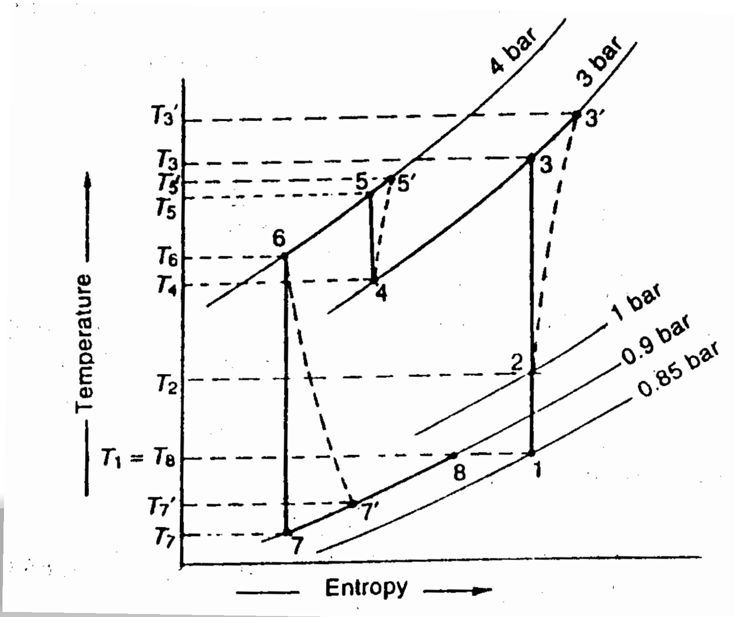
Solution:

- **We know that isentropic efficiency of the auxiliary compressor,**

$$\eta_{c2} = \frac{T_5 - T_4}{T_5' - T_4}$$

$$0.8 = \frac{391.5 - 360.85}{T_5' - 360.85} = \frac{30.65}{T_5' - 360.85}$$

$$\therefore \quad T_5' = 399.16\ K = 126.16°\ C$$



Solution:

- **Since 30% of the enthalpy of air discharged from the auxiliary compressor is removed in the second heat exchanger (i.e. during the process 5'-6); Therefore temperature of air leaving the second heat exchanger,**

$$T_6 = 0.7 \times T_5'$$

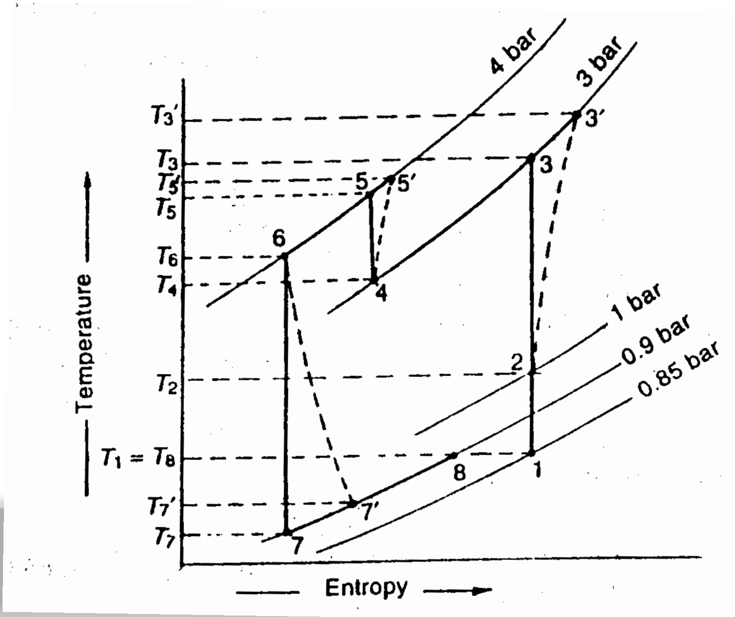
$$\therefore \quad T_6 = 0.7 \times 126.16 = 88.3^\circ C = 361.3\,K$$

Solution:

- **For the isentropic process 6-7,**

$$\frac{T_7}{T_6} = \left(\frac{p_7}{p_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{0.9}{4}\right)^{\frac{1.4-1}{1.4}} = (0.225)^{0.286} = 0.653$$

$$\therefore\ T_7 = T_6 \times 0.653 = 361.3 \times 0.653 = 236\ K = -37^\circ\ C$$



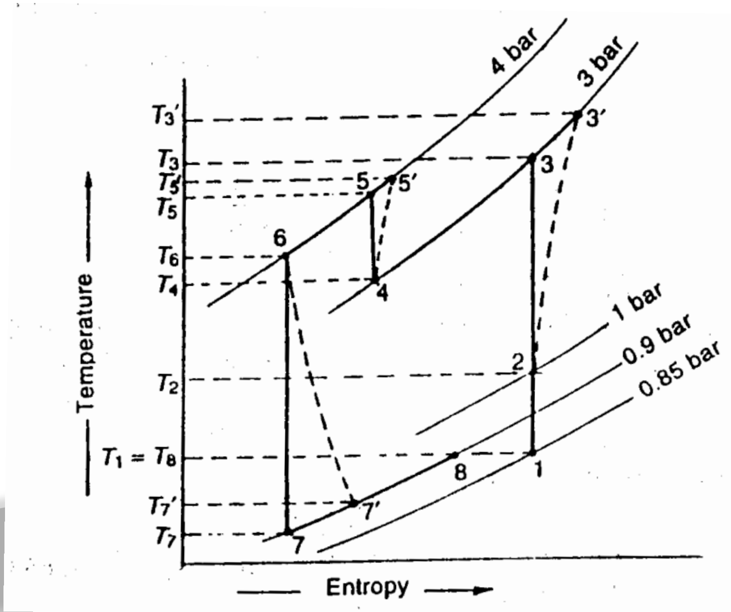
Solution:

- We know that turbine efficiency

$$\eta_T = \frac{Actual\ increase\ in\ temperature}{Isentropic\ increase\ in\ temperature} = \frac{T_6 - T_7'}{T_6 - T_7}$$

$$0.85 = \frac{361.3 - T_7'}{361.3 - 236} = \frac{361.3 - T_7'}{125.3}$$

$$\therefore \quad T_7' = 254.8\ K = -18.2^\circ C$$



Solution:

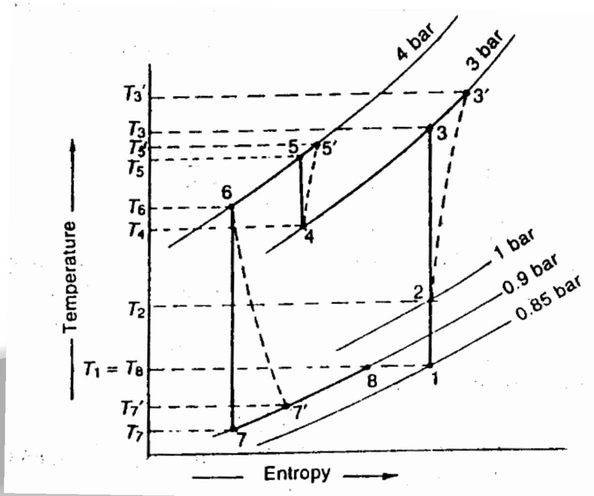
1. Power required to operate the system

We know that amount of air required for cooling the cabin,

$$m_a = \frac{210\,Q}{c_p(T_8 - T_7')} = \frac{210 \times 10}{1(293 - 254.8)} = 55\ kg/min$$

and power required to operate the system,

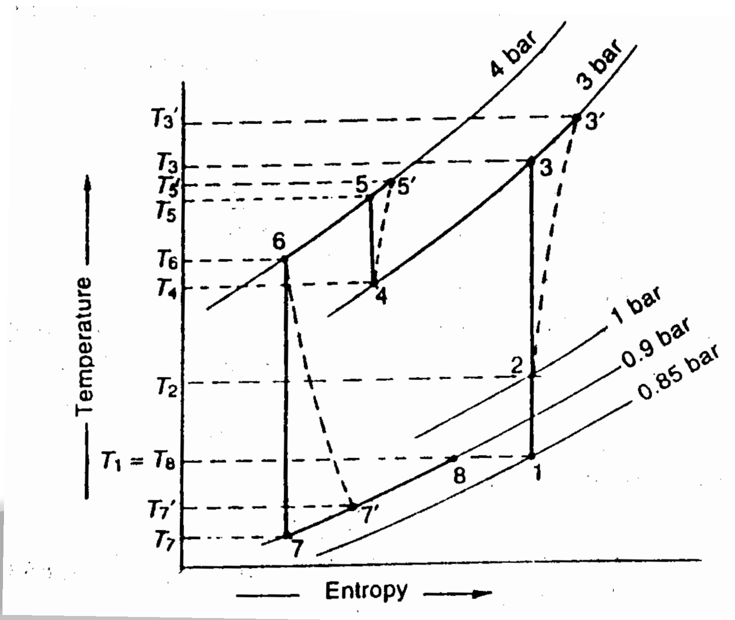
$$\therefore P = \frac{m_a\, c_p(T_3' - T_2)}{60} = \frac{55 \times 1(448.7 - 306.8)}{60} = 130\ kW \quad Ans.$$



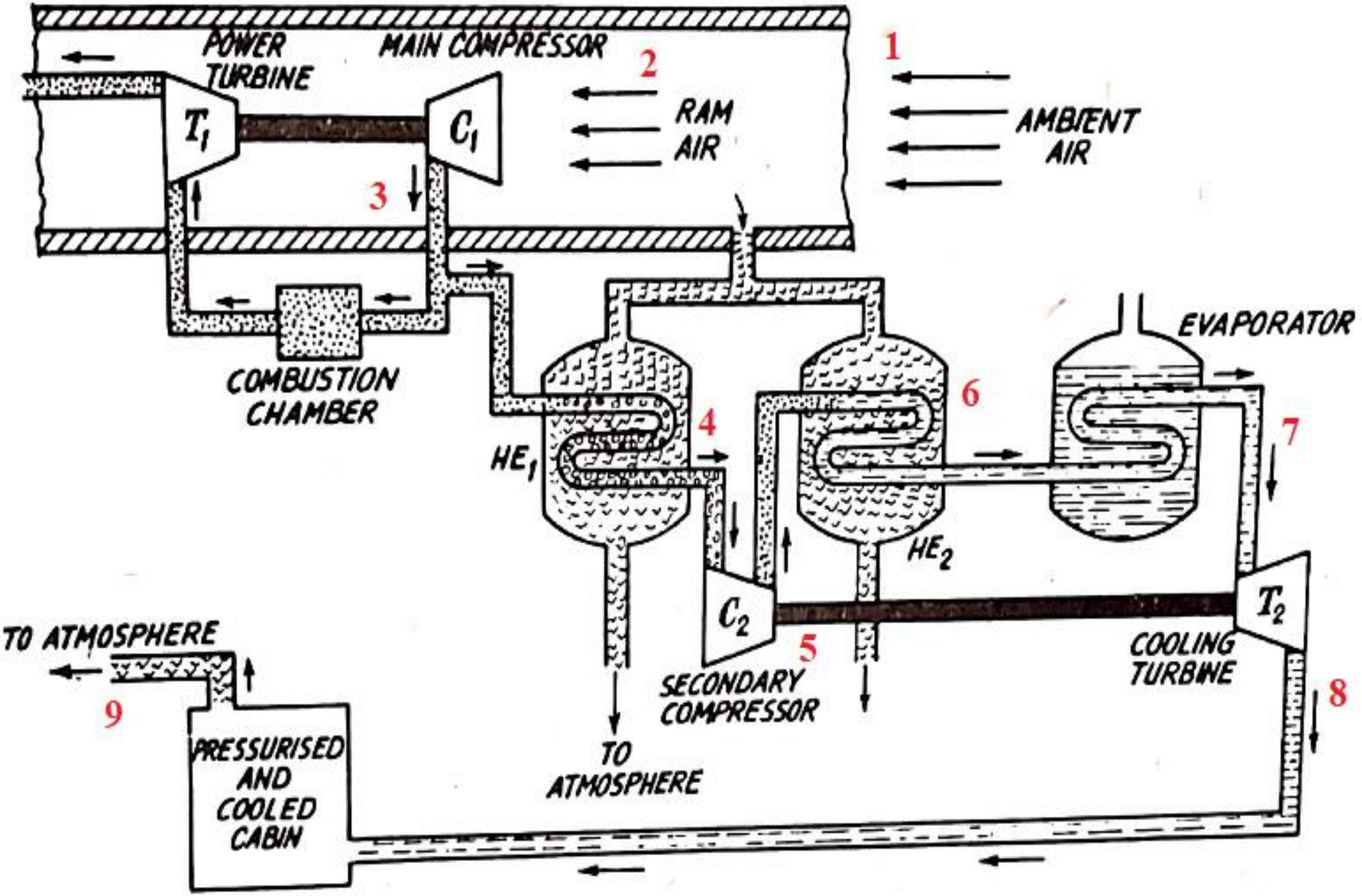
Solution:

2. C.O. P. of the system

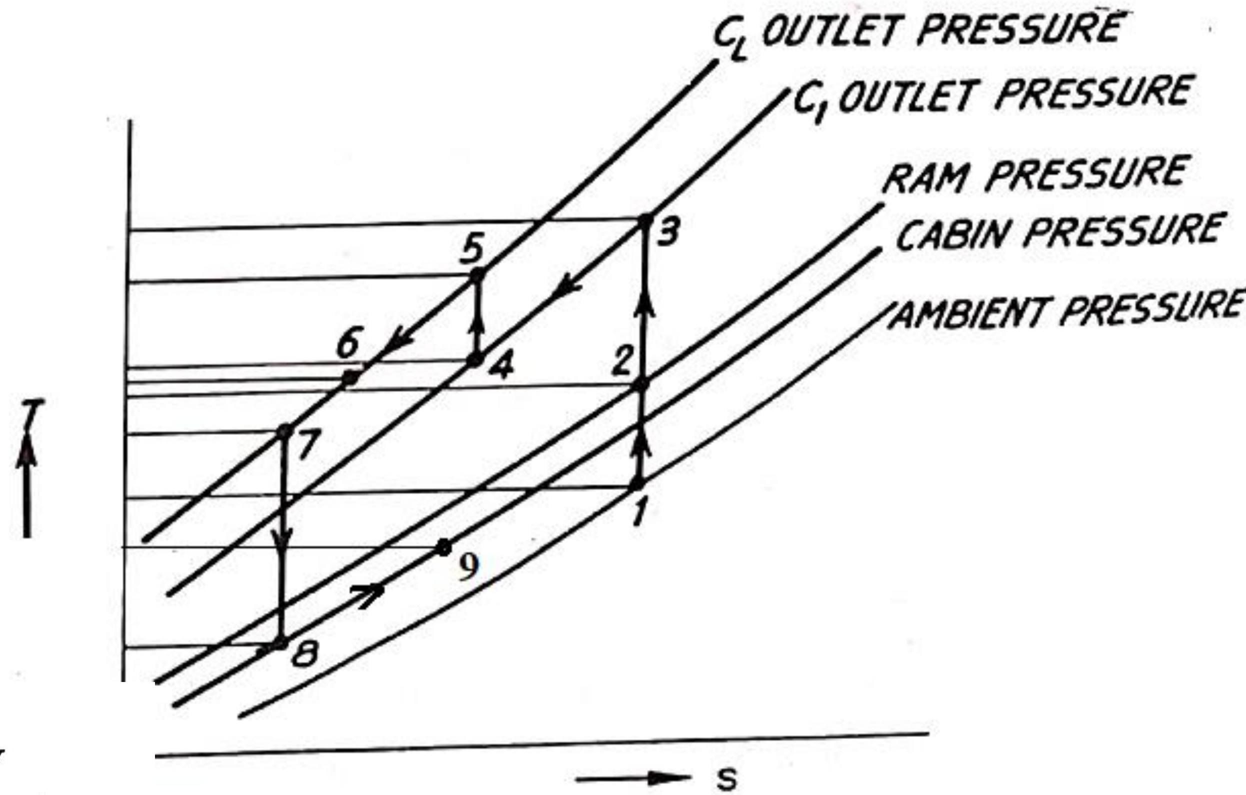
$$= \frac{210\,Q}{m_a\,c_p(T_3' - T_2)} = \frac{210 \times 10}{55 \times 1(448.7 - 306.8)}$$

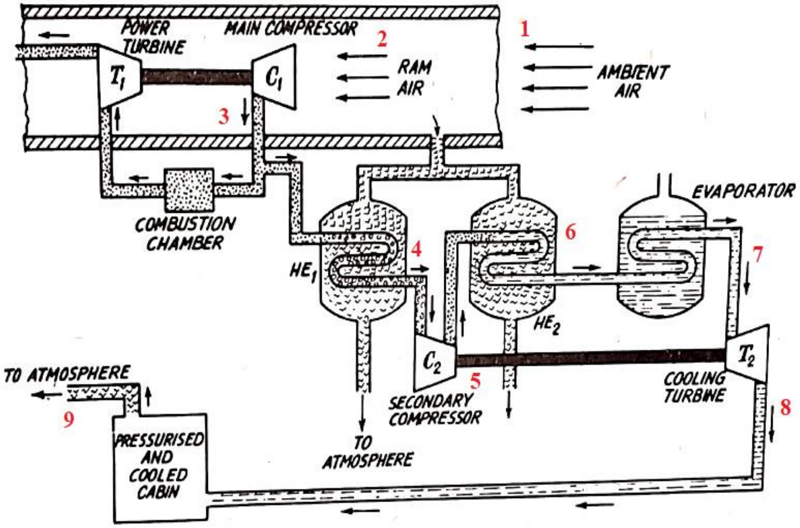


4. Boot-Strap Air Evaporative Cooling System



4. Boot-Strap Air Evaporative Cooling System





4. Boot-Strap Air Evaporative Cooling System

- It 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.
- Since the temperature of air leaving the cooling turbine in boot-strap evaporative system is lower than the simple boot-strap system, therefore mass of air (m_a) per ton of refrigeration will be less in boot- strap evaporative system.
- If Q tonnes of refrigeration is the cooling load in the cabin, then the quantity of air required for the refrigeration purpose will be;

$$m_a = \frac{210\,Q}{c_p(T_9 - T_8)} \quad kg/\min$$

4. Boot-Strap Air Evaporative Cooling System

$$\text{Power required for the refrigeration system} = \frac{m_a.C_p.(T_3 - T_2)}{60} KW$$

$$\text{COP of the refrigeration system} = \frac{210.Q}{m_a.C_p.(T_3 - T_2)} = \frac{210.Q}{P \times 60}$$

(OR)

$$COP = \frac{\text{Refr. effect}}{\text{Workdone}}$$

$$COP = \frac{m_a.C_p.(T_9 - T_8)}{m_{a.} C_p.(T_3 - T_2)}$$

$$COP = \frac{(T_9 - T_8)}{(T_3 - T_2)}$$

Problem 4.0:

- The following data refer to a boot strap air cycle evaporative refrigeration system used for an aeroplane to take 20 tonnes of refrigeration load:

Ambient air temperature	= 15^0C
Ambient air pressure	= 0.8 bar
Mach number of the flight	= 1.2
Ram efficiency	= 90%
Pressure of air bled off the main compressor	= 4 bar
Pressure of air in the secondary compressor	= 5 bar
Isentropic efficiency of the main compressor	= 90%
Isentropic efficiency of the secondary compressor	= 80%

Problem 4.0:

Isentropic efficiency of the cooling turbine	= 80%
Temperature of air leaving the first heat exchanger	= 170^0C
Temperature of air leaving the second heat exchange	= 155^0C
Temperature of air leaving the evaporator	= 100^0C
Cabin temperature	= 25^0C
Cabin pressure	= 1 bar

Find:

1. Mass of air required to take the cabin load,
2. Power required for the refrigeration system, and
3. C.O.P. of the system.

Solution:

Given: Q = 20 TR ; T_1=15°C= 15+237=288 K ;

p_1 = 0.8 bar ; M=1.2 ;

η_R = 90% = 0.9;

$p_3 = p_3' = p_4$ = 4 bar; $p_5 = p_5' = p_5'' = p_6$ = 5 bar ;

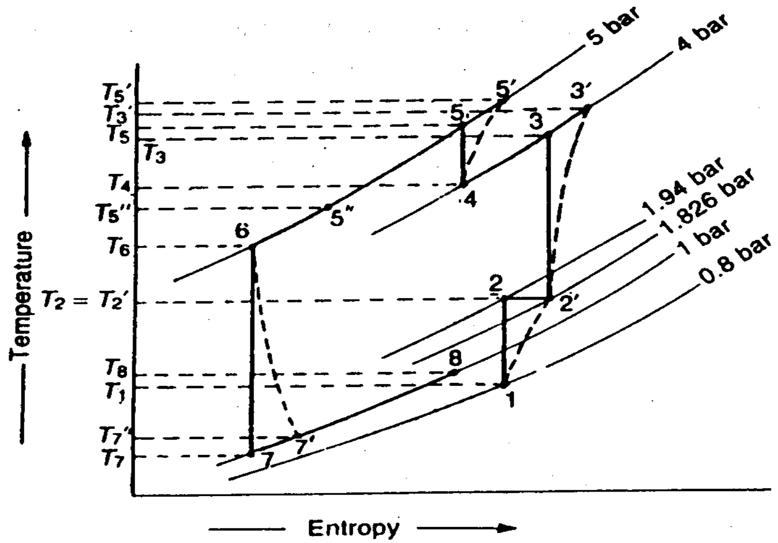
η_{c1} = 90% = 0.9; η_{c2} = 80% = 0.8;

T_4 = 170°C=170+273 = 443 K ; T_5''=155°C = 155+273 = 428 K;

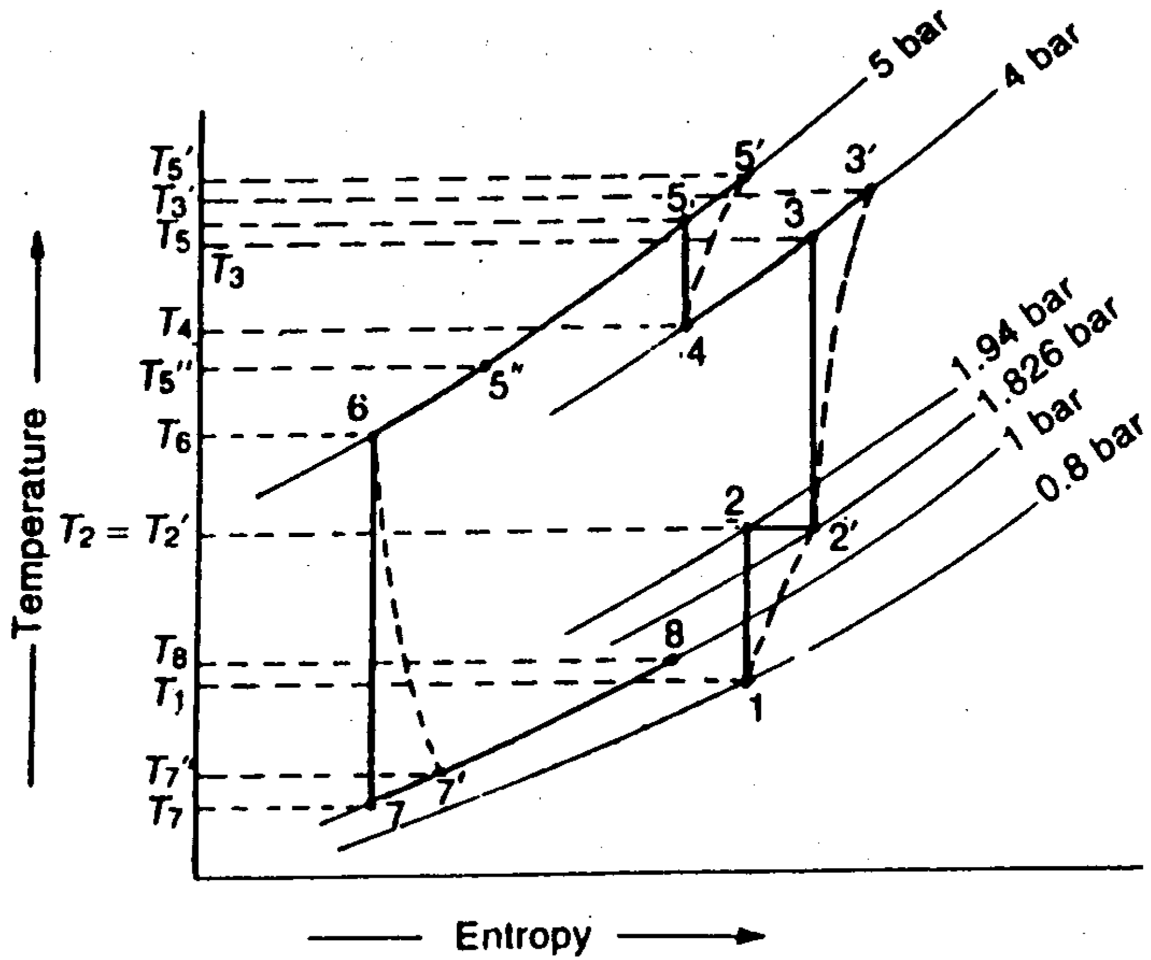
T_6 = 100°C = 100+273 = 373 K ;

T_8 = 25°C = 25+273 = 298 K;

$p_8 = p_7 = p_7''$ = 1 bar



Solution:


5 bar
4 bar
1.94 bar
1.826 bar
1 bar
0.8 bar
T5′
T3′
T5
T3
T4
T5″
T6
T2 = T2′
T8
T1
T7′
T7
5′
3′
5
3
4
5″
6
2
2′
8
1
7′
7
Temperature
Entropy

Solution:

We know that

$$\frac{T_2'}{T_1} = 1 + \frac{\gamma - 1}{2} M^2 = 1 + \frac{1.4 - 1}{2}(1.2)^2 = 1.288$$

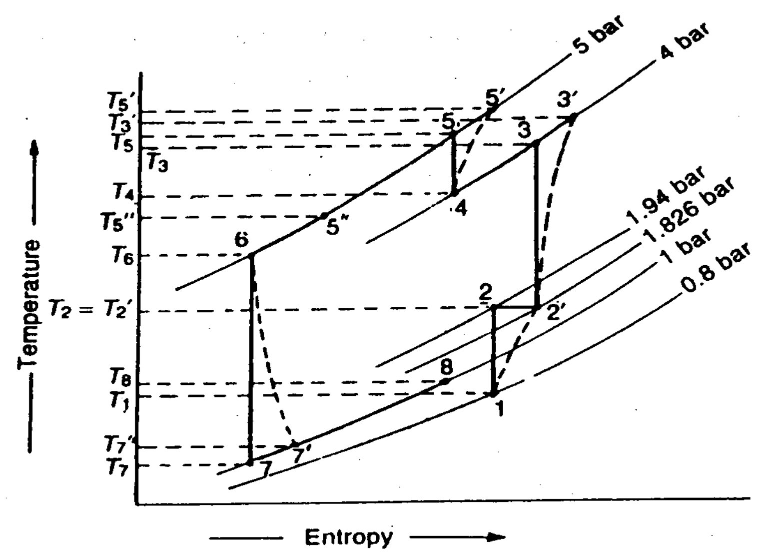
$$T_2' = T_1 \times 1.288 = 288 \times 1.288 = 371\,K$$

For isentropic process 1-2,

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{371}{288}\right)^{\frac{1.4}{1.4-1}} = (1.288)^{3.5} = 2.425$$

$\therefore$

$$p_2 = p_1 \times 2.425 = 0.8 \times 2.428 = 1.94\,bar$$



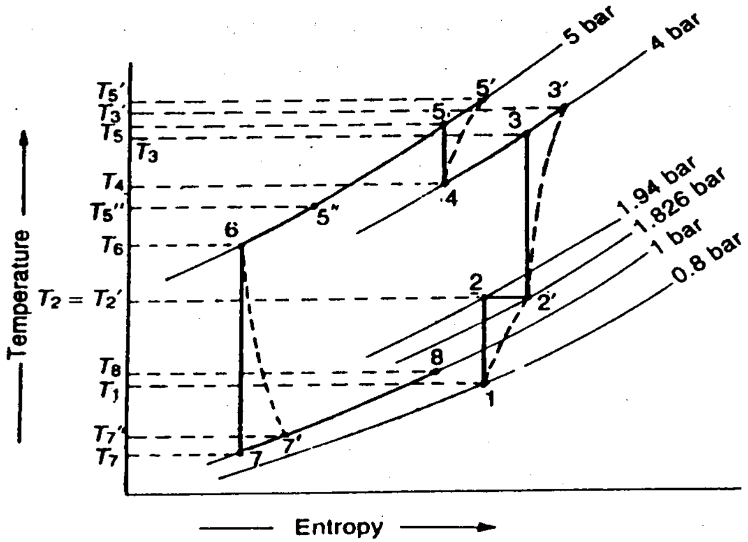
Solution:

We know that ram efficiency,

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

$$0.9 = \frac{p_2' - 0.8}{1.94 - 0.8} = \frac{p_2' - 0.8}{1.14}$$

$$\therefore \quad p_2' = 0.9 \times 1.14 + 0.8 = 1.826\ bar$$



Now for the isentropic process 2'-3,

$$\frac{T_3}{T_2'} = \left(\frac{p_3}{p_2'}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4}{1.826}\right)^{\frac{1.4-1}{1.4}} = (2.19)^{0.286} = 1.25$$

$$\therefore \quad T_3 = T_2' \times 1.25 = 371 \times 1.25 = 463.8\ K$$

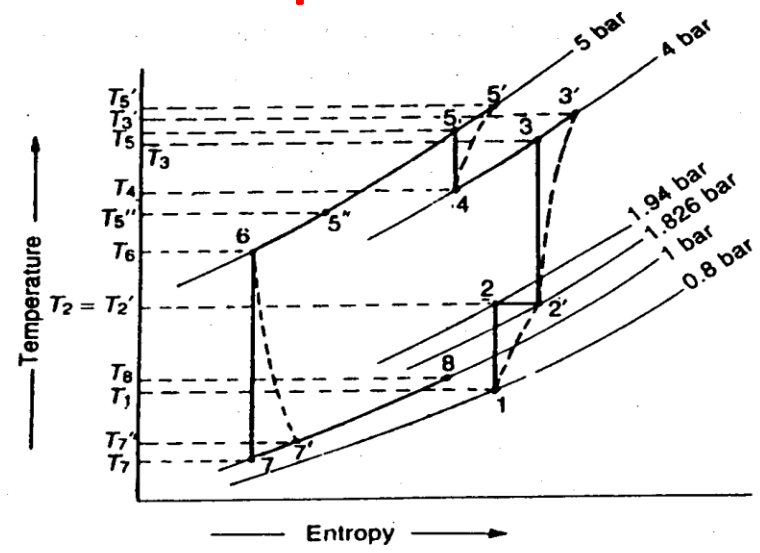
Solution:

We know that isentropic efficiency of the main compressor

$$\eta_{C1} = \frac{\text{Isentropic increase in temp.}}{\text{Actual increase in temp.}} = \frac{T_3 - T_2'}{T_3' - T_2'}$$

$$0.9 = \frac{463.8 - 371}{T_3' - 371} = \frac{92.8}{T_3' - 371}$$

$$\therefore \quad T_3' = 474\ K$$



Temperature of air leaving the first heat exchanger,

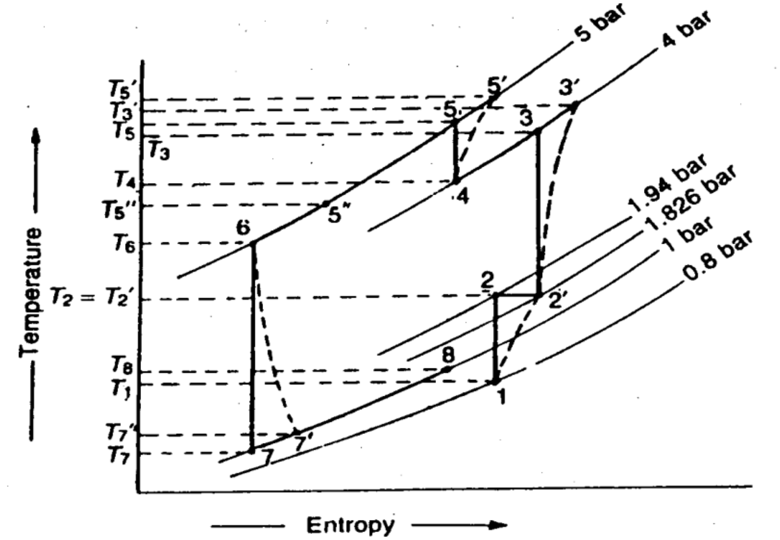
$$\therefore \quad T_4 = 443\ K$$

Solution:

For the isentropic process 4-5,

$$\frac{T_5}{T_4} = \left(\frac{p_5}{p_4}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{4}\right)^{\frac{1.4-1}{1.4}} = (1.25)^{0.286} = 1.066$$

$$\therefore\ T_5 = T_4 \times 1.066 = 443 \times 1.066 = 472\ K$$



Isentropic efficiency of the secondary compressor,

$$\eta_{C2} = \frac{T_5 - T_4}{T_5' - T_4}$$

$$0.8 = \frac{472 - 443}{T_5' - 443} = \frac{29}{T_5' - 443}$$

$$\therefore\quad T_5' = 479\ K$$

Solution:

Temperature of air leaving the second heat exchanger,

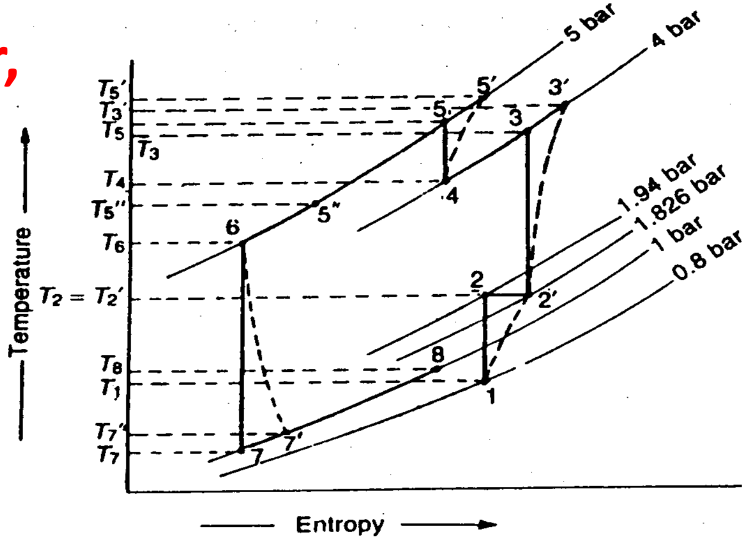
$$\therefore \quad T_5'' = 428\ K$$

Temperature of air leaving the evaporator,

$$\therefore \quad T_6 = 373\ K$$

Now for the isentropic process 6-7,

$$\frac{T_6}{T_7} = \left(\frac{p_6}{p_7}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = (5)^{0.286} = 1.584$$



$$\therefore \; T_7 = T_6 / 1.586 = 373 / 1.584 = 235.5\ K$$

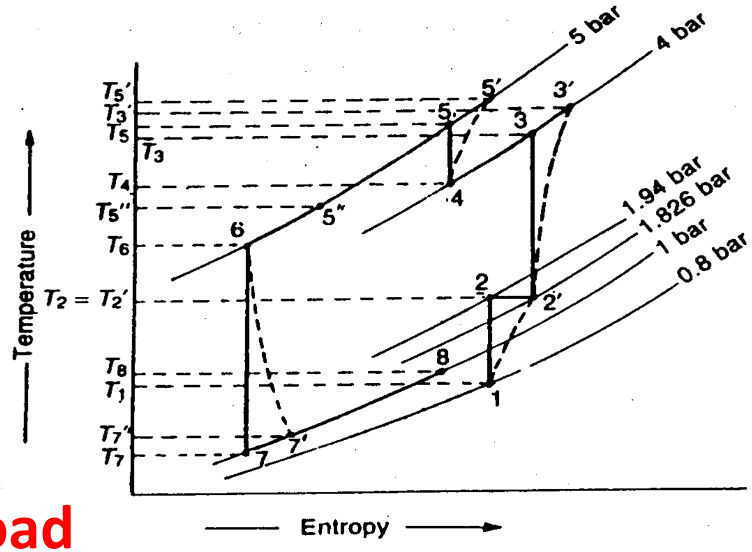
Solution:

We know that isentropic efficiency of the cooling turbine,

$$\eta_T = \frac{\text{Actual increase in temp.}}{\text{Isentropic increase in temp.}} = \frac{T_6 - T_7'}{T_6 - T_7}$$

$$0.8 = \frac{373 - T_7'}{373 - 235.5} = \frac{373 - T_7'}{137.5}$$

$$\therefore \quad T_7' = 263\ K$$



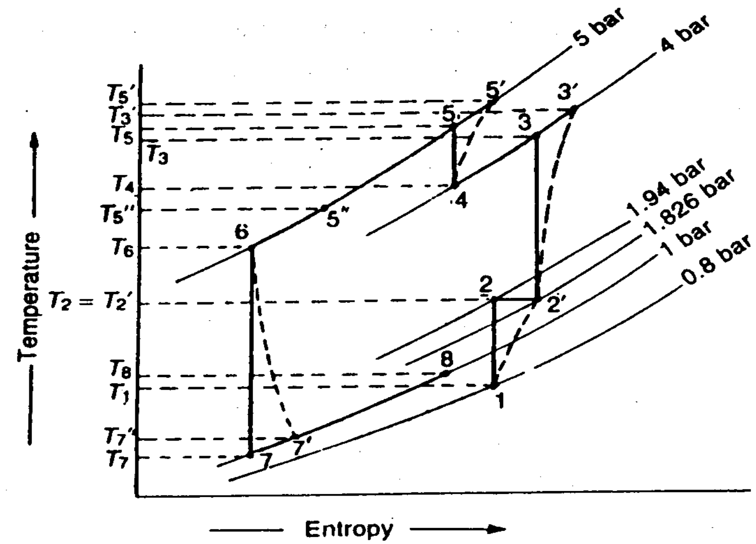
1. Mass of air required to take the cabin load

$$\therefore \quad m_a = \frac{210\ Q}{c_p(T_8 - T_7)} = \frac{210 \times 20}{1(298 - 263)} = 120\ kg/min\ \ Ans.$$

Solution:

2. Power required for the refrigeration system

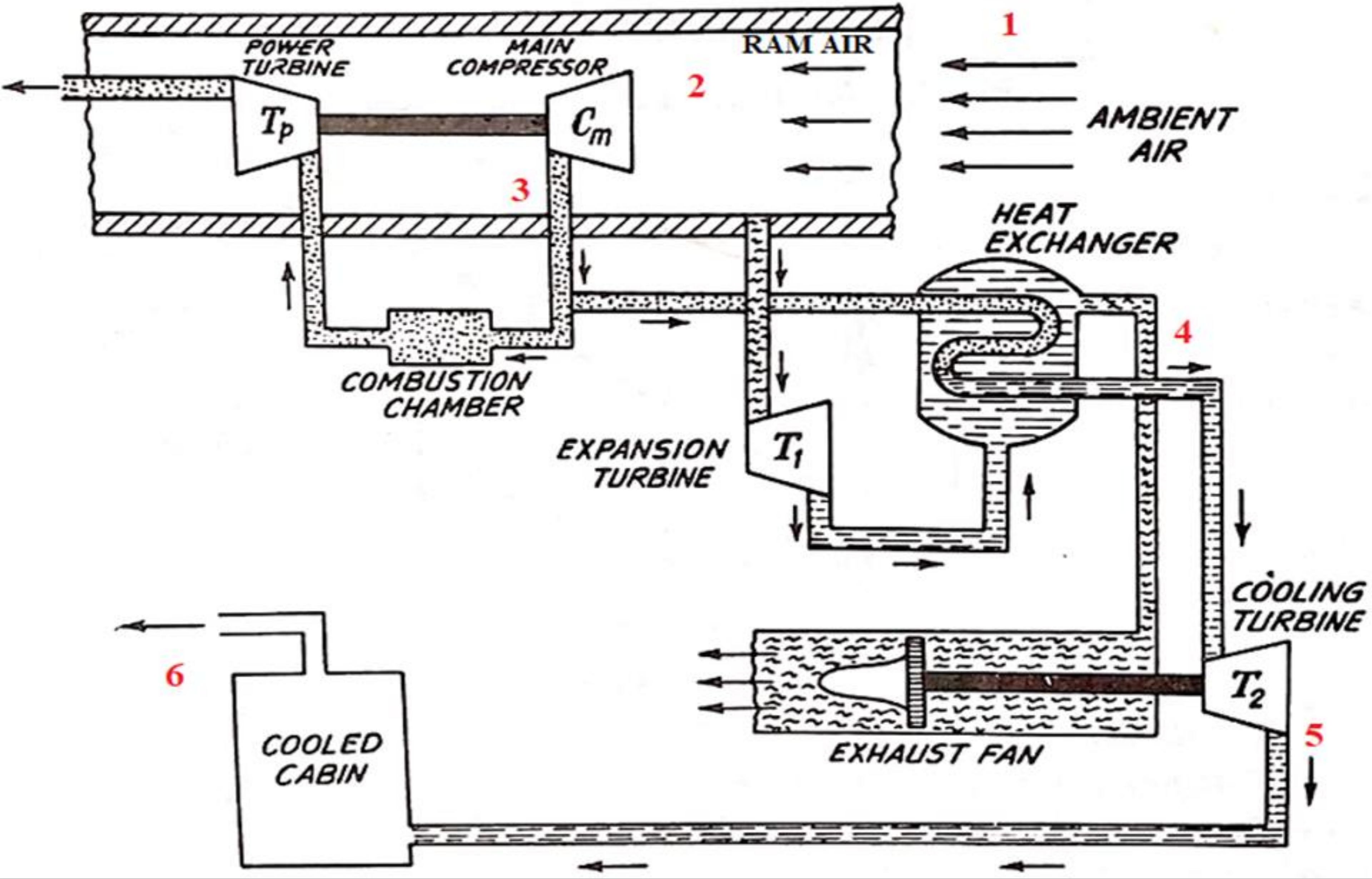
$$\therefore\ P = \frac{m_a\ c_p(T_3' - T_2')}{60} = \frac{120 \times 1(474 - 371)}{60} = 206\ kW\ \ Ans.$$



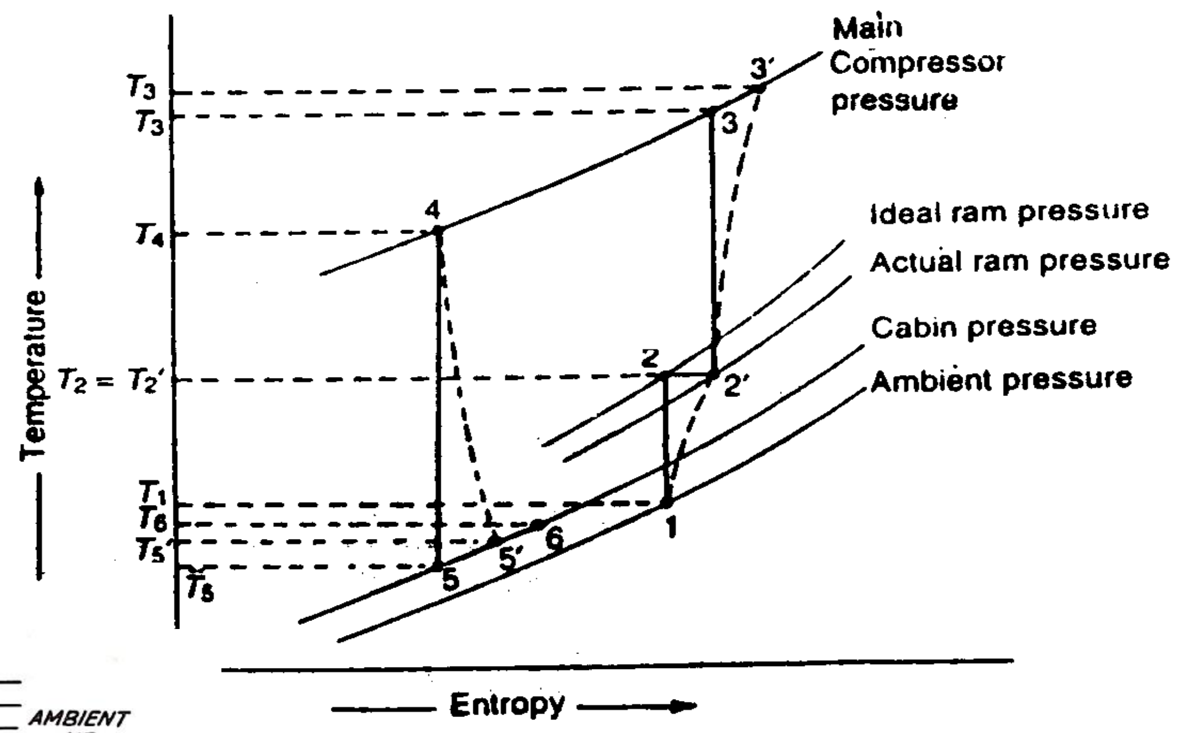
3. C.O.P. of the system

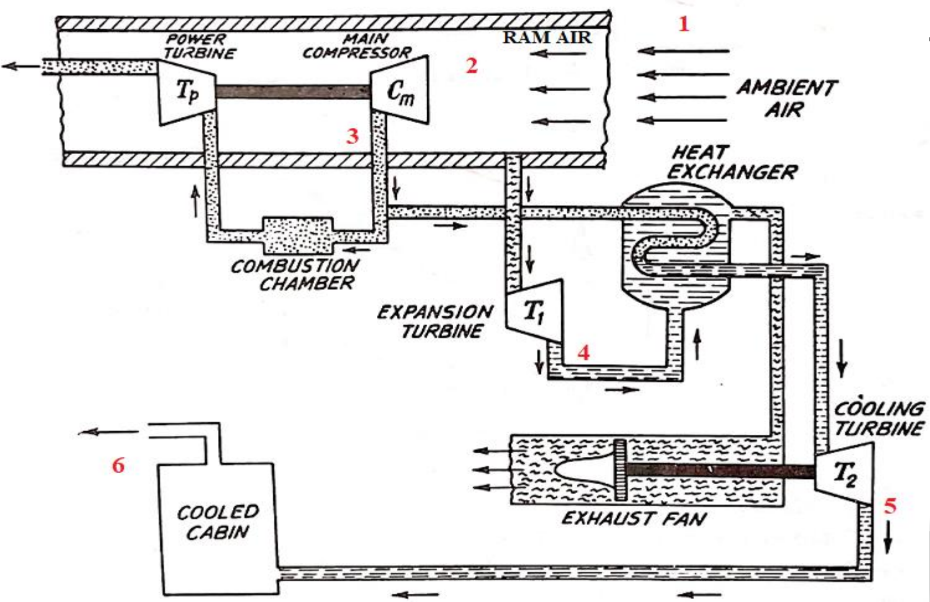
$$\therefore\ = \frac{210\,Q}{m_a\ c_p(T_3' - T_2')} = \frac{210 \times 20}{120 \times 1(474 - 371)} = 0.34\ \ Ans.$$

5. Reduced Ambient Air Cooling System:



5. Reduced Ambient Air Cooling System:





5. Reduced Ambient Air Cooling System:

- **It is composed of an air-to-air heat exchanger and two expansion turbines supplying power through appropriate gearing to a single fan.**
- **High pressure high temperature air is cooled first as it passes through the heat exchanger.**
- **The air required for cooling is taken from the turbine T_1 which lowers the temperature of rammed air which is quite high due to ramming action.**
- **Then the high pressure air is passed through the cooling turbine T_2 for further cooling by expansion.**

5. Reduced Ambient Air Cooling System:

- The process 1-2 represents isentropic ramming of air and the process 1-2' represents actual ramming of air because of internal friction due to irreversibilities.
- The process 2'-3 represents isentropic compression in the main compressor and the process 2'-3' represents actual compression of air, because of internal friction due to irreversibilities.
- The process 3'-4 represents cooling of compressed air by ram air which after passing through the first cooling turbine is led to the heat exchanger. The pressure drop in the heat exchanger is neglected.

5. Reduced Ambient Air Cooling System:

- **The process 4-5 represents isentropic expansion of air in the second cooling turbine upto the cabin pressure. The actual expansion of air in the second cooling turbine is represented by the curve 4-5'.**
- **The process 5'-6 represents the heating of air upto the cabin temperature T6.**

5. Reduced Ambient Air Cooling System:

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

$$\therefore \quad m_a = \frac{210\,Q}{c_p(T_6 - T_5')} \, kg/min$$

- **Power required for the refrigeration system is given by**

$$\therefore \quad P = \frac{m_a\, c_p(T_3' - T_2')}{60} \, kW$$

- **C.O.P. of the system:**

$$\therefore \quad = \frac{210\,Q}{m_a\, c_p(T_3' - T_2')} = \frac{210\,Q}{P \times 60}$$

Problem 5.0:

- **The reduced ambient air refrigeration system used for an aircraft consists of two cooling turbines, one heat exchanger and one air cooling fan. The speed of aircraft is 1500 Km/h. The ambient air conditions are 0.8 bar and 10°C. The ram efficiency may be taken as 90%. The rammed air used for cooling is expanded in the first cooling turbine and leaves it at a pressure of 0.8 bar.**

  The air bled from the main compressor at 6 bar is cooled in the heat exchanger and leaves it at 100°C: The cabin is to be maintained at 20°C and 1 bar. The pressure loss between the second cooling turbine and cabin is 0.1 bar.

Problem 5.0:

If the isentropic efficiency for the main compressor and both of the cooling turbines are 85% and 80% respectively. find:

1. **mass flow rate of air supplied to cabin to take a cabin load of 10 tonnes of refrigeration ;**
2. **Quantity of air passing through the heat exchanger if the temperature rise of ram air is limited to 80 K ;**
3. **Power used to drive the cooling fan; and**
4. **C.O.P. of the system.**

Solution:

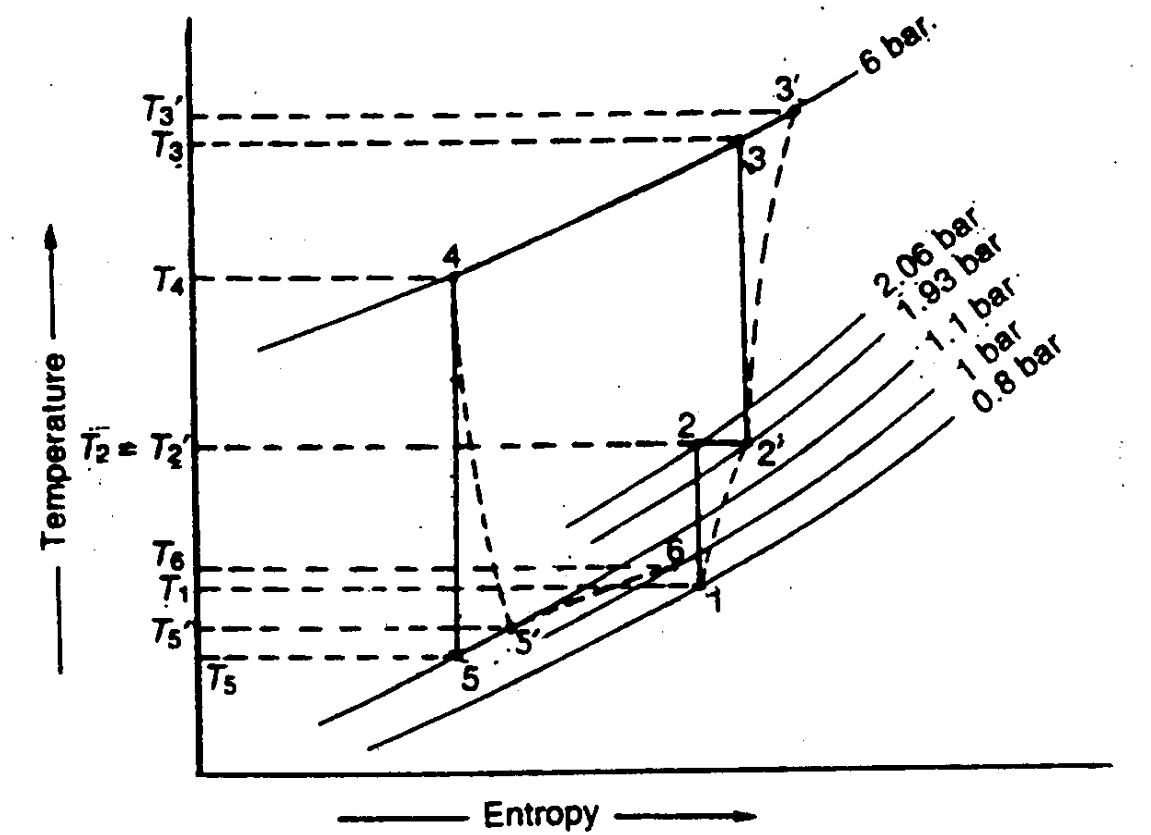
Given : ***V=1500 km/h=417 m/s ; p_1=0.6 bar ; T_1=10° C=10+273=283 K;***

$\eta_R =$ ***90%=0.9 ; p_3=p_4=6 bar ; T_4=100° C=100+273=373 K;***
T_6=20° C=20+273=293 K ; p_6= 1 bar ;

$\eta_C =$ ***85%=0.85 ;***

$\eta_{T1} = \eta_{T2} =$ ***80%=0.8 ; Q=10 TR***

Solution:



6 bar
2.06 bar
1.93 bar
1.1 bar
1 bar
0.8 bar
T3'
T3
T4
T2 = T2'
T6
T1
T5'
T5
3'
3
4
2
2'
6
1
5'
5
Temperature
Entropy

Solution:

We know that

$$T_2' = T_1 + \frac{V^2}{2000\,c_p} = 283 + \frac{(417)^2}{2000 \times 1} = 370\ K$$

For the isentropic ramming process 1-2,

$$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left(\frac{370}{283}\right)^{\frac{1.4}{1.4-1}} = (1.31)^{3.5} = 2.57$$

$$\therefore\ p_2 = p_1 \times 2.57 = 0.8 \times 2.57 = 2.06\ bar$$

Solution:

We know that ram efficiency,

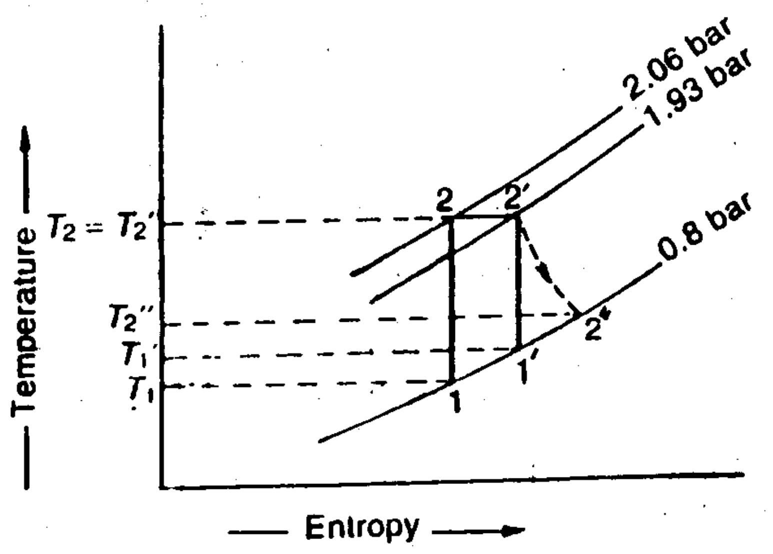
$$\eta_R = \frac{Actual\ rise\ in\ pressure}{Insentropic\ rise\ in\ pressure} = \frac{p_2' - p_1}{p_2 - p_1}$$

$$0.9 = \frac{p_2' - 0.8}{2.06 - 0.8} = \frac{p_2' - 0.8}{1.26}$$

$$\therefore \quad p_2' = 1.93\ bar$$

- **The T-s diagram for the expansion of ram air in the first cooling turbine is shown in Fig. The vertical line 2'-1' represents the isentropic cooling process and the curve 2'-2'' represents the actual cooling process.**

Solution:



T-S diagram for the first cooling turbine.

- **We know that isentropic efficiency of the compressor,**

$$\eta_C = \frac{Isentropic\ increase\ in\ temp.}{Actual\ increase\ in\ temp.} = \frac{T_3 - T_2'}{T_3' - T_2'}$$

Solution:

- We know that isentropic efficiency of the compressor,

$$0.85 = \frac{511 - 370}{T_3' - 370} = \frac{141}{T_3' - 370}$$

$$\therefore \quad T_3' = 536\ K$$

- Since there is a pressure drop of 0.1 bar between the second cooling turbine and the cabin,

$$p_5 = p_5' = p_6 + 0.1 = 1 + 0.1 = 1.1\ \ bar$$

- Now for the isentropic expansion of air in the second cooling turbine (process 4-5),

Solution:

$$\frac{T_4}{T_5} = \left(\frac{p_4}{p_5}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{6}{1.1}\right)^{\frac{1.4-1}{1.4}} = (5.45)^{0.286} = 1.62$$

$$\therefore\ T_5 = T_4 / 1.62 = 373/1.62 = 230\ K$$

- **We know that the isentropic efficiency of the second cooling turbine,**

$$\eta_{T2} = \frac{\text{Actual increase in temp.}}{\text{Isentropic increase in temp.}} = \frac{T_4 - T_5'}{T_4 - T_5}$$

$$0.8 = \frac{373 - T_5'}{373 - 230} = \frac{373 - T_5'}{143}$$

$$\therefore\ T_5' = 258.6\ K$$

Solution:

1. Mass flow rate of air supplied to cabin;

$$\therefore \quad m_a = \frac{210\ Q}{c_p(T_6 - T_5')} = \frac{20 \times 10}{1(293 - 258.6)} = 61\ kg/min \quad Ans.$$

2. Quantity of ram air passing through the heat exchanger

Let, m_R = Quantity of ram air passing through the heat exchanger.

The compressed air bled off at temperature T_3'= 536 K is cooled in the heat exchanger to a temperature T_4 = 373 K K by the ram air from the first cooling turbine at a temperature T_2"= 304 K. The temperature rise of ram air in the heat exchanger is limited to 80 K. Considering perfect heat transfer in the heat exchanger,

Solution:

$$m_R \times c_p \times 80 = m_a \times c_p(T_3' - T_4)$$

$$m_R \times 1 \times 80 = 61 \times 1(536 - 373) = 9943$$

$$\therefore \quad m_R = 9943/80 = 124.3\, kg/min \quad Ans.$$

3. Power used to drive the cooling fan

Since the work output of both the cooling turbines is used to drive the cooling fan, therefore work output from the first cooling turbine,

$$W_{T1} = m_R \times c_p(T_2' - T_2'')$$

$$= 124.3 \times 1(370 - 304) = 8204\, kJ/min$$

Solution:

and work output from the second cooling turbine,

$$W_{T2} = m_a \times c_p (T_4 - T_5')$$

$$= 61 \times 1 (373 - 258.6) = 6978\ kJ/min$$

$\therefore$ Combined work output from both the cooling turbines,

$$W_T = W_{T1} + W_{T2} = 8204 + 6978 = 15182\ kJ/min$$

and power used to drive the cooling fan

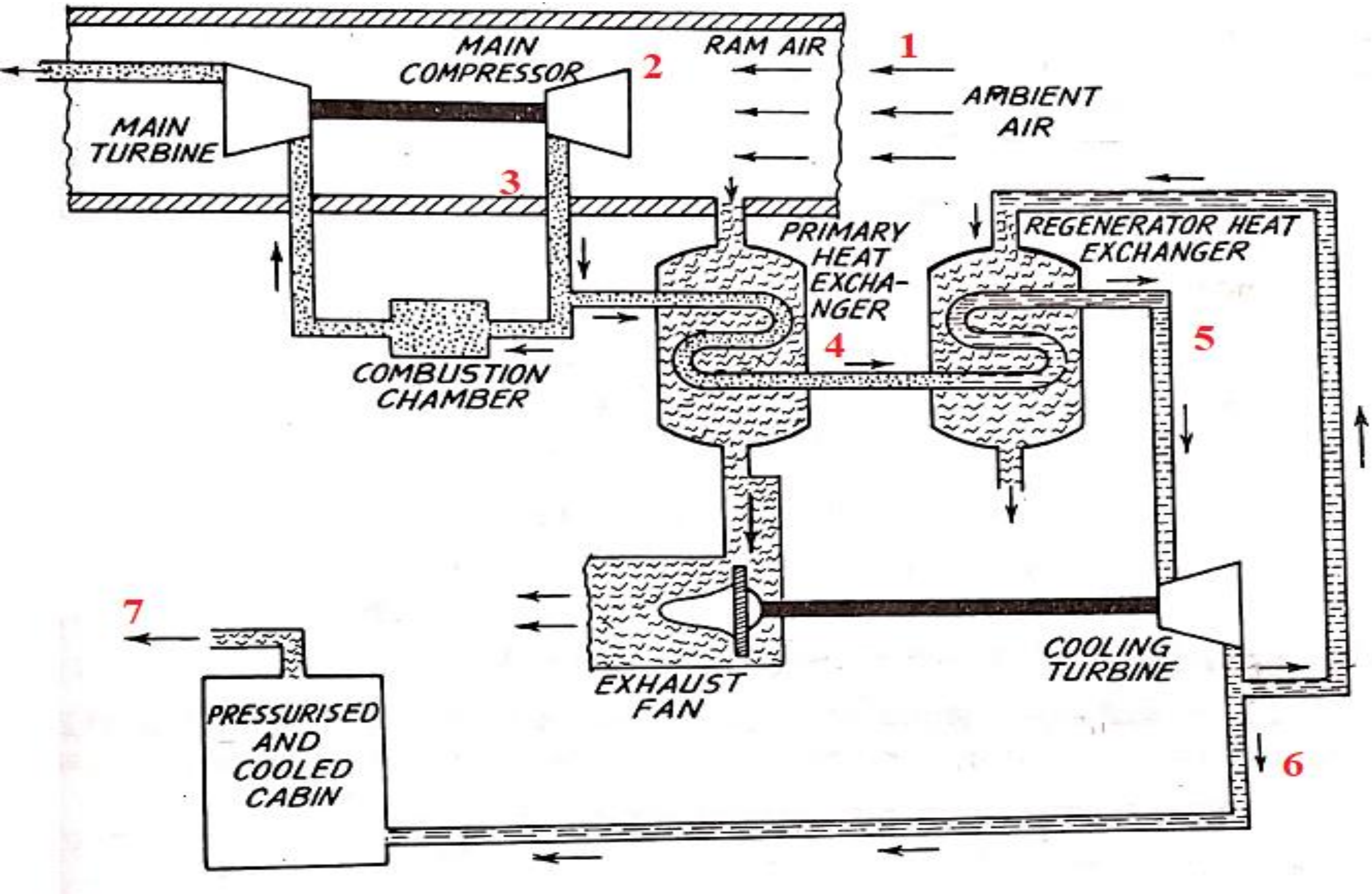
$$= 15182/60 = 253\ kW \ \textbf{Ans.}$$

Solution:

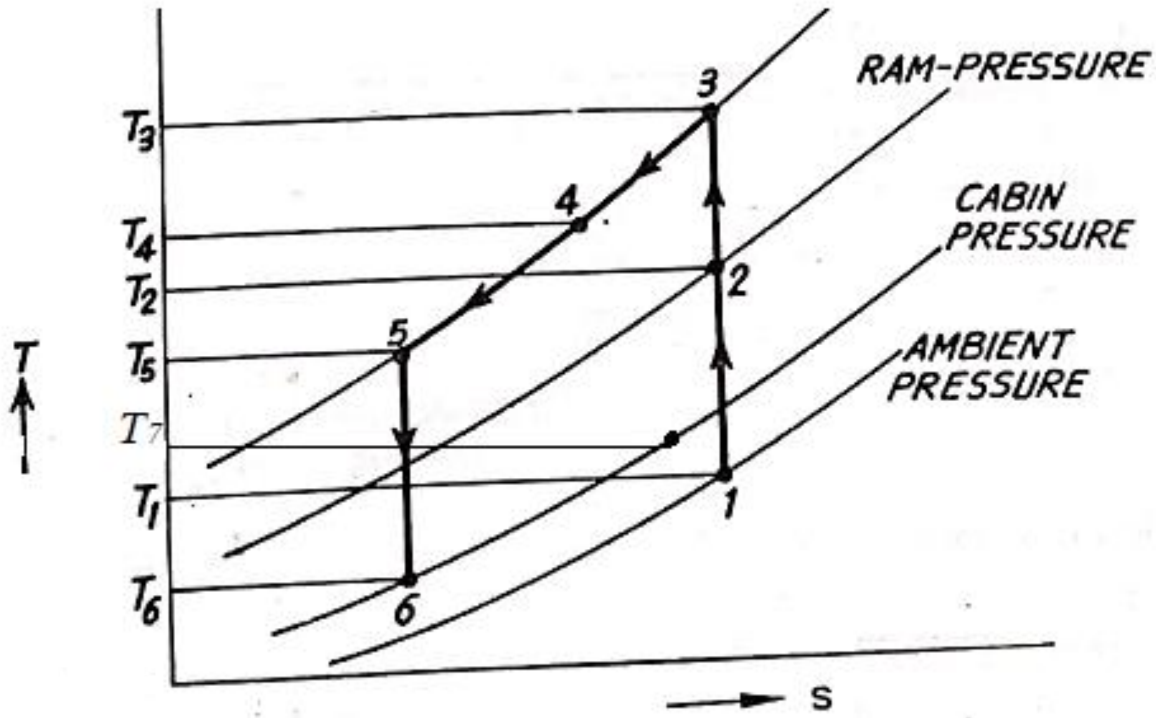
4. C.O.P. of the system

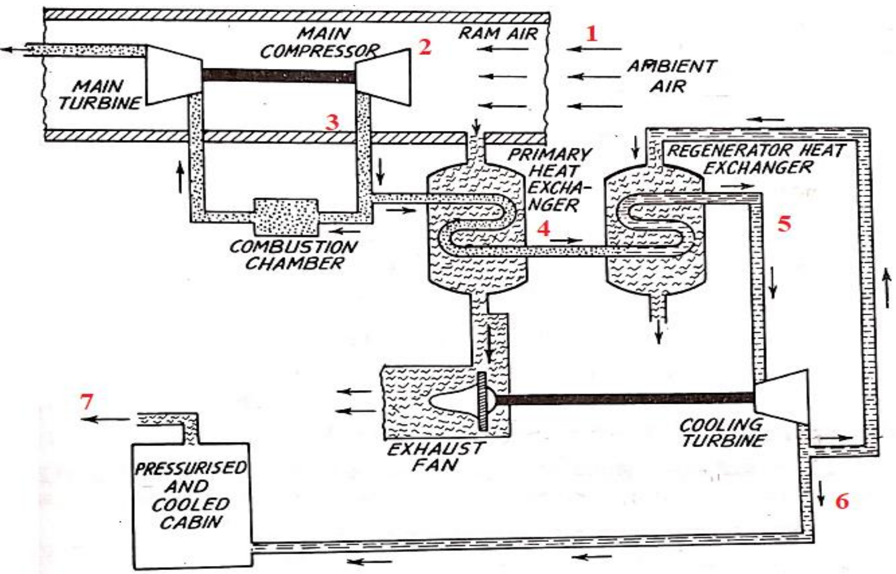
$$\therefore \quad = \frac{210\,Q}{m_a c_p (T_3' - T_2')} = \frac{210 \times 10}{61 \times 1(536 - 370)} = 0.21 \quad Ans.$$

Regenerative Air Cooling System

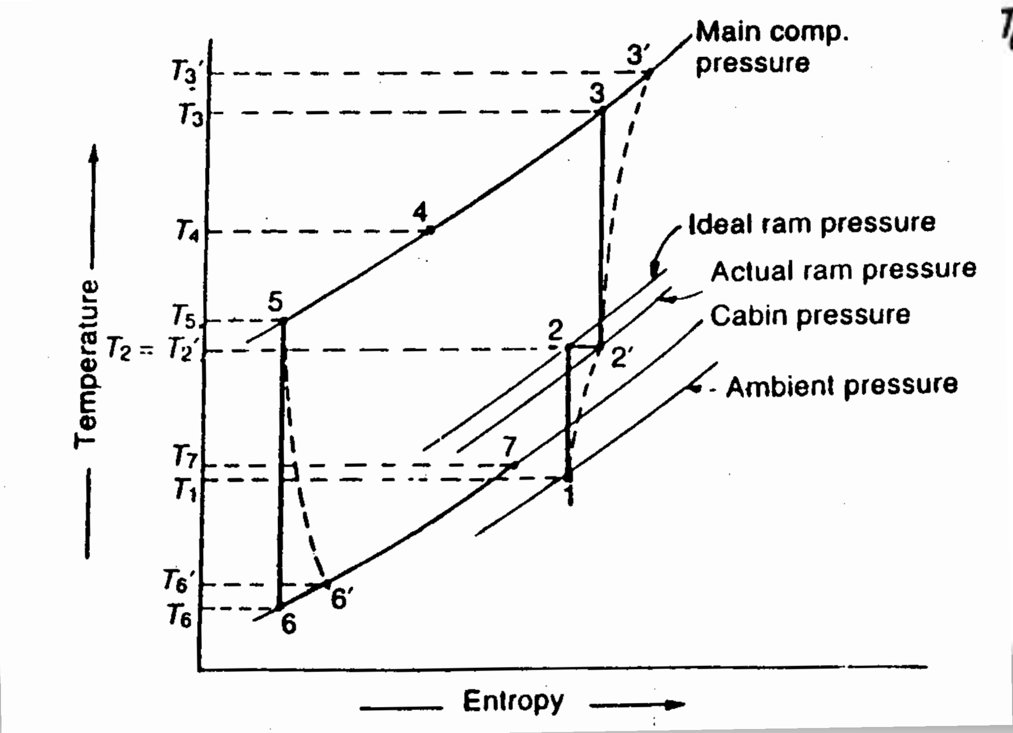


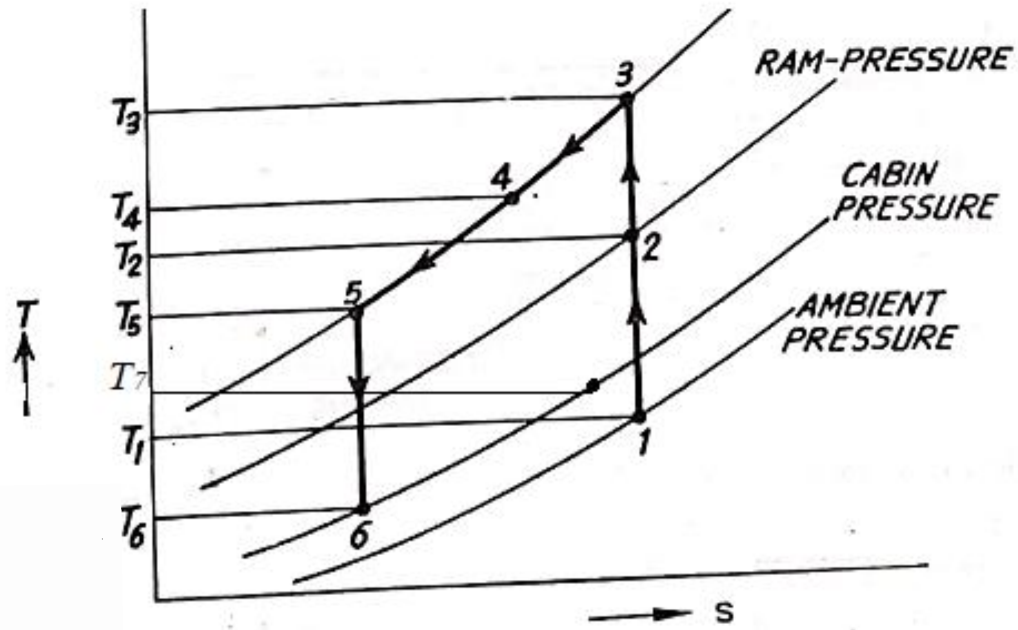
Regenerative Air Cooling System





Regenerative Air Cooling System





Regenerative Air Cooling System

- If the cooling turbine discharge temperature of a simple system is too high, then the regenerative system is used.
- The regenerative air cycle system consists of a primary air-to-air heat exchanger, a regenerative heat exchanger, and a cooling turbine.
- High pressure, high temperature air coming from compressor is cooled first in primary heat exchanger, then the regenerative heat exchanger and finally in the cooling turbine.
- Ram air is used as heat sink in the primary heat exchanger and part of the cold air from the turbine discharge is used as the heat sink regenerative heat exchanger.
- This type of cooling system preferred for super sonic airplanes.

Regenerative Air Cooling System

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

$$\therefore \qquad m_a = \frac{210\,\mathrm{Q}}{\mathrm{c_p}(T_7 - T_6)} kg/\min$$

- **Power required for the refrigeration system is given by**

$$\therefore \qquad P = \frac{m_a\, c_p (T_3 - T_2)}{60} kW$$

- **C.O.P. of the system:**

$$\therefore \qquad = \frac{210\,\mathrm{Q}}{m_a\, c_p (T_3 - T_2)} = \frac{210\, Q}{P \times 60}$$

Problem 6.0:

- A regenerative air cooling system is used for an airplane to take 20 tonnes of refrigeration load. The ambient air at pressure -0.8 bar and temperature 10°C is rammed isentropically till the pressure rises to 1.2 bar. The air bled off the main compressor at 4.5 bar is,. cooled by the ram air in the heat exchanger whose effectiveness is 60%. The air from the heat exchanger is further cooled to 60°C in the regenerative heat exchanger with a portion of the air bled after expansion in the cooling turbine . The cabin is to be maintained at a temperature of 25°C and a pressure of I bar. If the isentropic efficiencies of the compressor and turbine are 90% and 80% respectively, find:

Problem 6.0:

1. Mass of the air bled from cooling turbine to be used for regenerative cooling ;
2. Power required for maintaining the cabin at the required condition and
3. C. O. P. of the system.

Assume the temperature of air leaving to atmosphere from the regenerative heat exchanger as 1 00° C.

Solution:

Given : ***Q = 20 TR ; p_1 =0.8 bar ; T_1 =10° C =10 + 273 = 283 K ; p_2 = 1.2 ba***

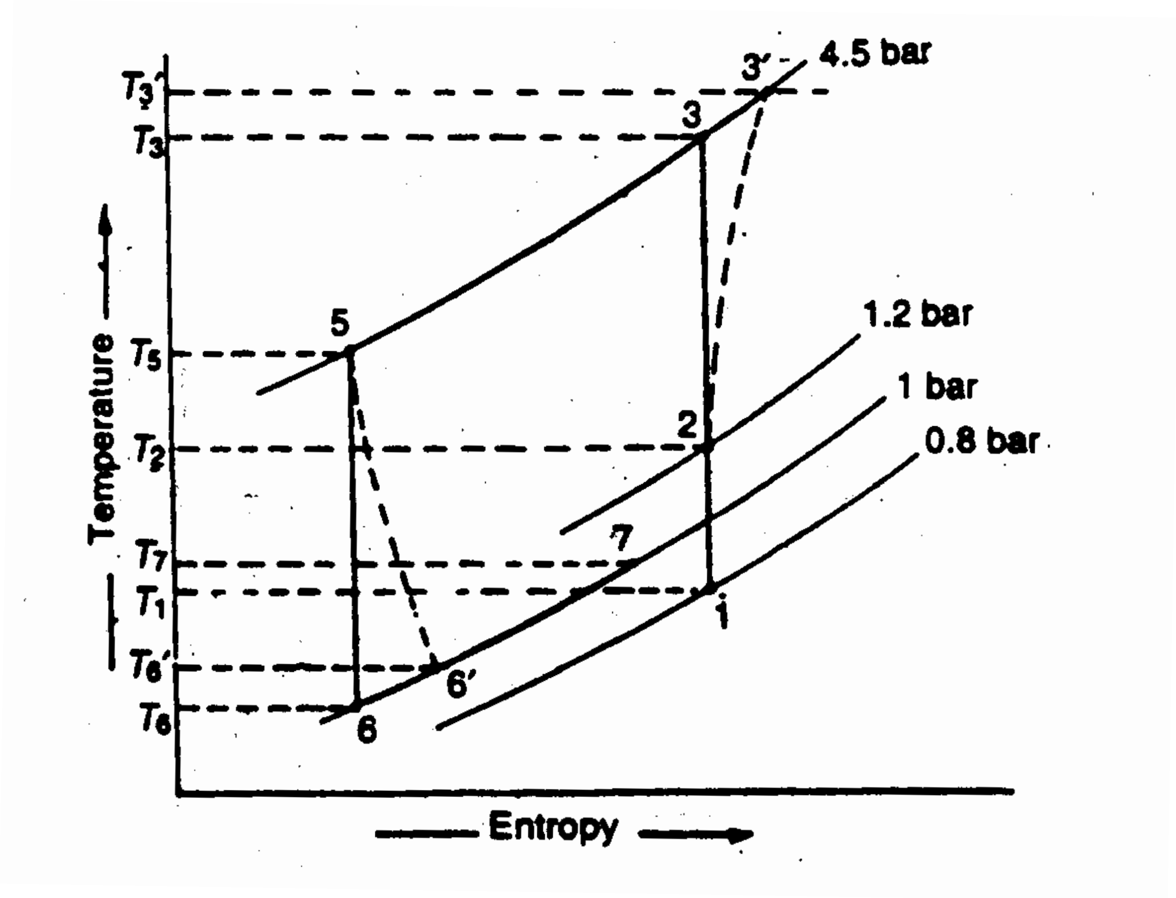
η_H = ***60%=0.6 ; T_5 = 60° C = 60+273 = 333 K;***
T_7=25°C=25+273= 298 K ;
p_7= p_6 = p_6' =1 bar ;

η_C = ***90% = 0.9 ;***

η_T ***= 80% = 0.8 ; T_8 =100° C =100 + 273 = 373 K***

$$p_3 = p_4 = p_5 = 4.5\,bar$$

Solution:



4.5 bar
3′
3
T_3'
T_3
5
T_5
1.2 bar
1 bar
0.8 bar
2
T_2
7
T_7
T_1
1
T_6'
6′
T_6
6
Temperature
Entropy

Solution:

We know that for the isentropic ramming of air (process 1-2),

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{1.2}{0.8}\right)^{\frac{1.4-1}{1.4}} = (1.5)^{0.286} = 1.123$$

$$\therefore \quad T_2 = T_1 \times 1.123 = 283 \times 1.123 = 317.8\ K$$

and for the isentropic compression process 2-3,

$$\frac{T_3}{T_2} = \left(\frac{p_3}{p_2}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.5}{1.2}\right)^{\frac{1.4-1}{1.4}} = (3.7)^{0.286} = 1.46$$

$$\therefore \quad T_3 = T_2 \times 1.46 = 317.8 \times 1.46 = 464\ K$$

Solution:

Isentropic efficiency of the compressor,

$$\eta_C = \frac{Isentropic\ increase\ in\ temp.}{Actual\ increase\ in\ temp.} = \frac{T_3 - T_2}{T_3' - T_2}$$

$$0.9 = \frac{464 - 317.8}{T_3' - 317.8} = \frac{146.2}{T_3' - 317.8}$$

$$\therefore\ T_3' = 480\ K$$

We know that effectiveness of the heat exchanger

$$0.6 = \frac{T_3' - T_4}{T_3' - T_2} = \frac{480 - T_4}{480 - 317.8} = \frac{480 - T_4}{162.2}$$

$$\therefore\quad T_4 = 382.7\ K$$

Solution:

Now for the isentropic cooling in the cooling turbine (process 5-6),

$$\frac{T_5}{T_6} = \left(\frac{p_5}{p_6}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{4.5}{1}\right)^{\frac{1.4-1}{1.4}} = (4.5)^{0.286} = 1.54$$

$$\therefore \; T_6 = T_5 / 1.54 = 333 / 1.54 = 216 \; K$$

and isentropic efficiency of the cooling turbine,

$$\eta_T = \frac{\text{Actual increase in temp.}}{\text{Isentropic increase in temp.}} = \frac{T_5 - T_6'}{T_5 - T_6}$$

$$0.8 = \frac{333 - T_6'}{333 - 216} = \frac{333 - T_6'}{117}$$

$$\therefore \quad T_6' = 239.4 \; K$$

Solution:

1. **Mass of air bled from the cooling turbine to be used for regenerative cooling**

Let,

m_a = Mass of air bled from the cooling turbine to be used for regenerative cooling,

m_1 = Total mass of air bled from the main compressor, and

m_2 = Mass of cold air bled from the cooling turbine for regenerative heat exchanger.

We know that the mass of air supplied to the cabin,

$$m_a = m_1 - m_2$$

Solution:

$$= \frac{210\,Q}{c_p(T_7 - T_6')} = \frac{210 \times 20}{1(298 - 239.4)} = 71.7\ kg/min$$

$$m_2 = \frac{m_1(T_4 - T_5)}{(T_8 - T_6')} = \frac{m_1(282.7 - 333)}{(373 - 239.4)} = 0.327\ m_1$$

$$m_1 - m_2 = 71.7 \quad or \quad m_1 - 0.372\,m_1 = 71.7$$

$$m_1 = \frac{71.7}{1 - 0.372} = 113.4\ kg/min$$

$$m_2 = 0.372\,m_1 - 0.372 \times 13.4 = 42.2\ kg/min \quad Ans.$$

Solution:

2. Power required for maintaining the cabin at the required condition

$$P = \frac{m_1\, c_p(T_3' - T_2)}{60} = \frac{113.4 \times 1(480 - 317.8)}{60} = 307\ kW \quad Ans.$$

3. C.O.P. of the system

$$= \frac{210\, Q}{m_1\, c_p(T_3' - T_2)} = \frac{210 \times 20}{113.4 \times 1(480 - 317.8)} = 0.23 \quad Ans.$$

UNIT – II

VAPOR ABSORPTION AND AIR REFRIGERATION

At the end of the unit students are able to:		
	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	**Identify** the modifications required in an impossible reversed Carnot cycle to convert it into practical cycle for refrigeration applications.	Remember
CO2	**Illustrate** the working principles, limitations of practical aqua ammonia, LiBr-Water and Electrolux vapour absorption refrigeration systems.	Understand
CO3	**Analyze** theoritical, practical steam jet refrigeration cycles with T-S diagrams, by stating merits, limitations, etc.	Understand
CO4	**Discuss** the measures to protect the ozone layer through global control, eventually elimination of production and utilization of ozone depleting substances.	Analyze

Basic principle

- When a solute such as lithium bromide salt is dissolved in a solvent such as water, the boiling point of the solvent (water) is elevated. On the other hand, if the temperature of the solution (solvent + solute) is held constant, then the effect of dissolving the solute is to reduce the vapour pressure of the solvent below that of the saturation pressure of pure solvent at that temperature.

- If the solute itself has some vapour pressure (i.e., volatile solute) then the total pressure exerted over the solution is the sum total of the partial pressures of solute and solvent.

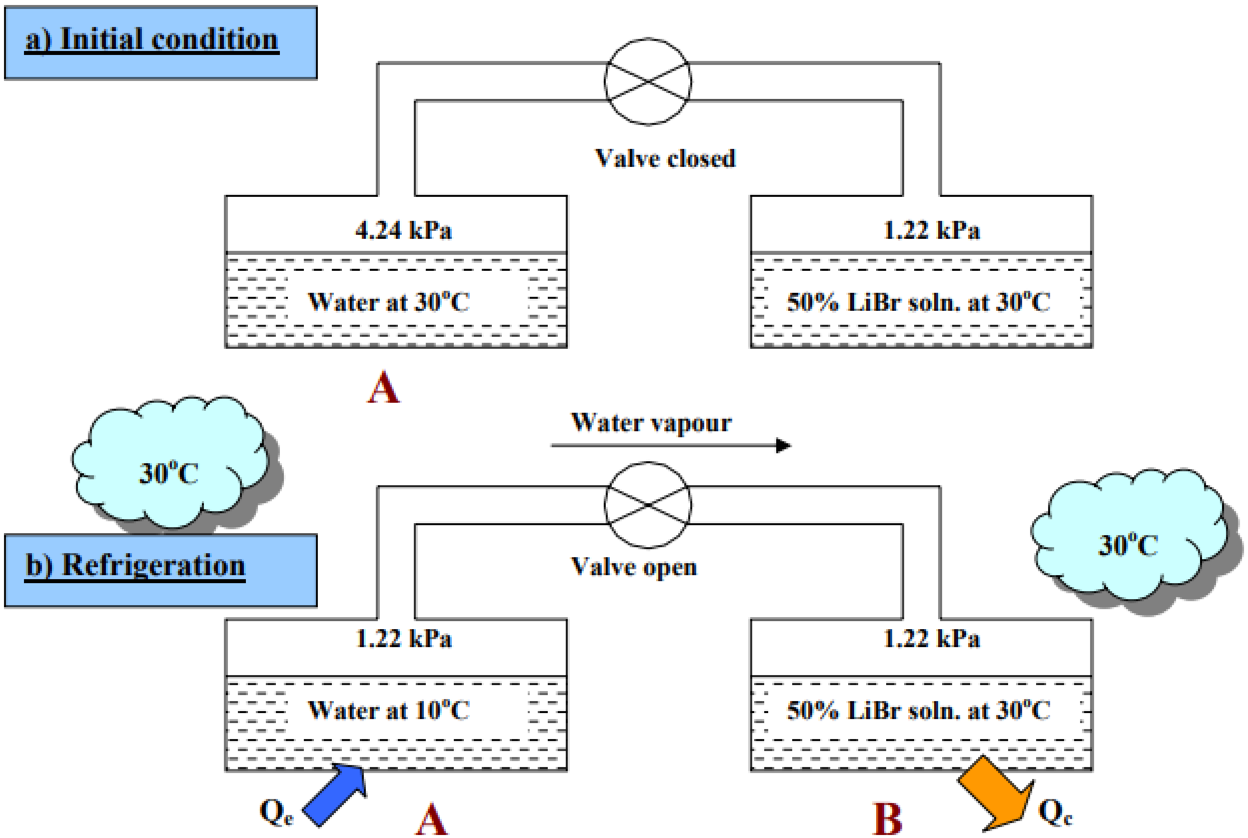
- In the simplest absorption refrigeration system, refrigeration is obtained by connecting two vessels, with one vessel containing pure solvent and the other containing a solution.

Basic principle

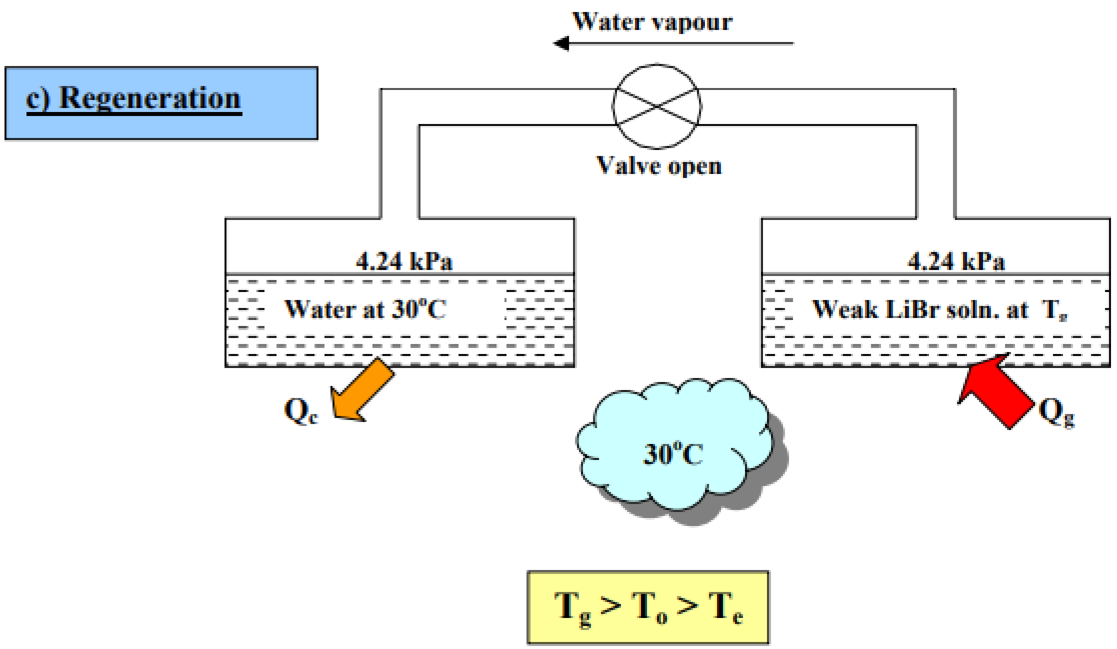
- Since the pressure is almost equal in both the vessels at equilibrium, the temperature of the solution will be higher than that of the pure solvent. This means that if the solution is at ambient temperature, then the pure solvent will be at a temperature lower than the ambient.

- Hence refrigeration effect is produced at the vessel containing pure solvent due to this temperature difference. The solvent evaporates due to heat transfer from the surroundings, flows to the vessel containing solution and is absorbed by the solution. This process is continued as long as the composition and temperature of the solution are maintained and liquid solvent is available in the container.

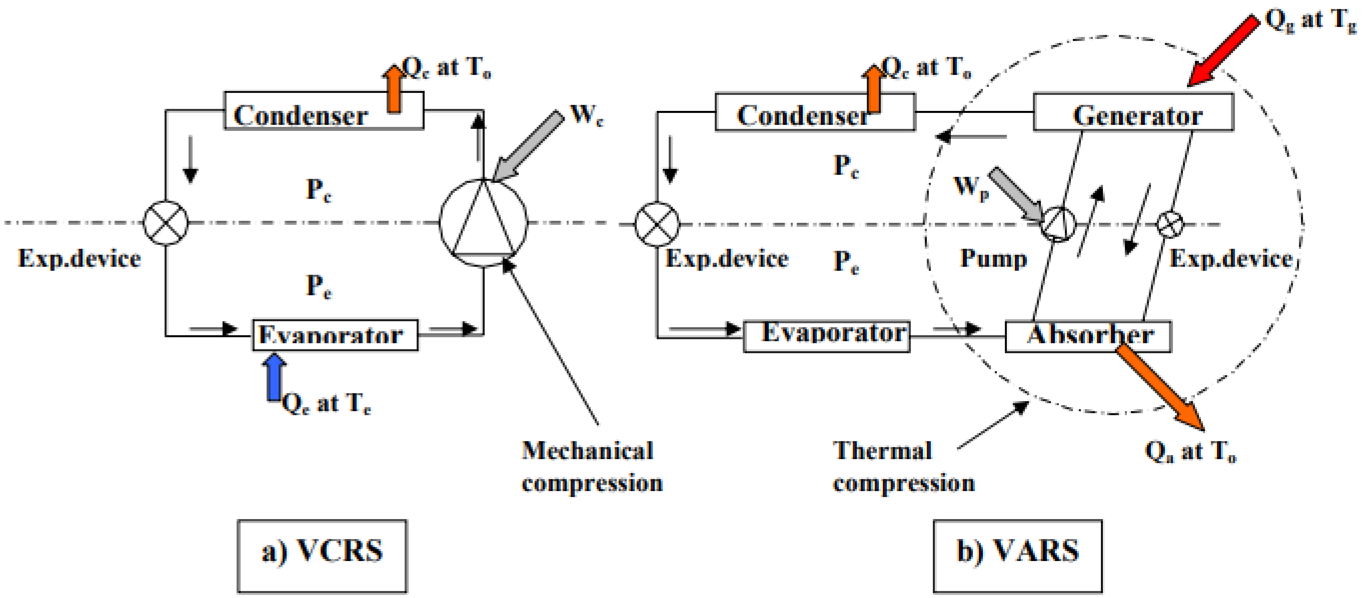
Basic principle



Basic principle



Difference between VCRS AND VARS



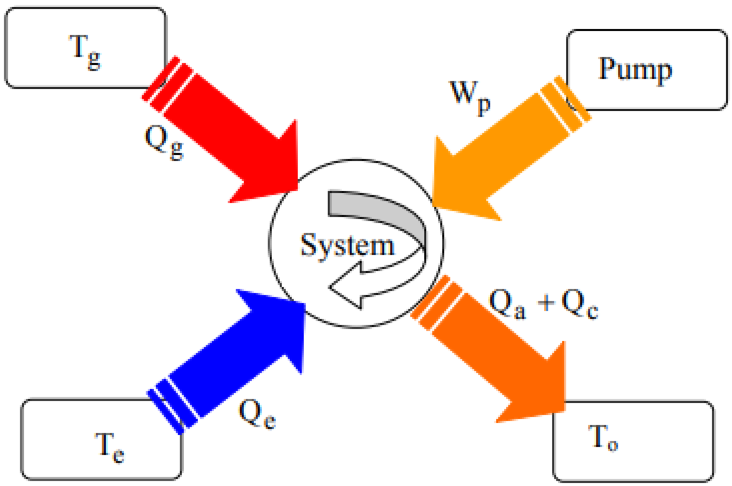
Maximum COP of ideal absorption refrigeration system

- In case of a single stage compression refrigeration system operating between constant evaporator and condenser temperatures, the maximum possible COP is given by Carnot COP:

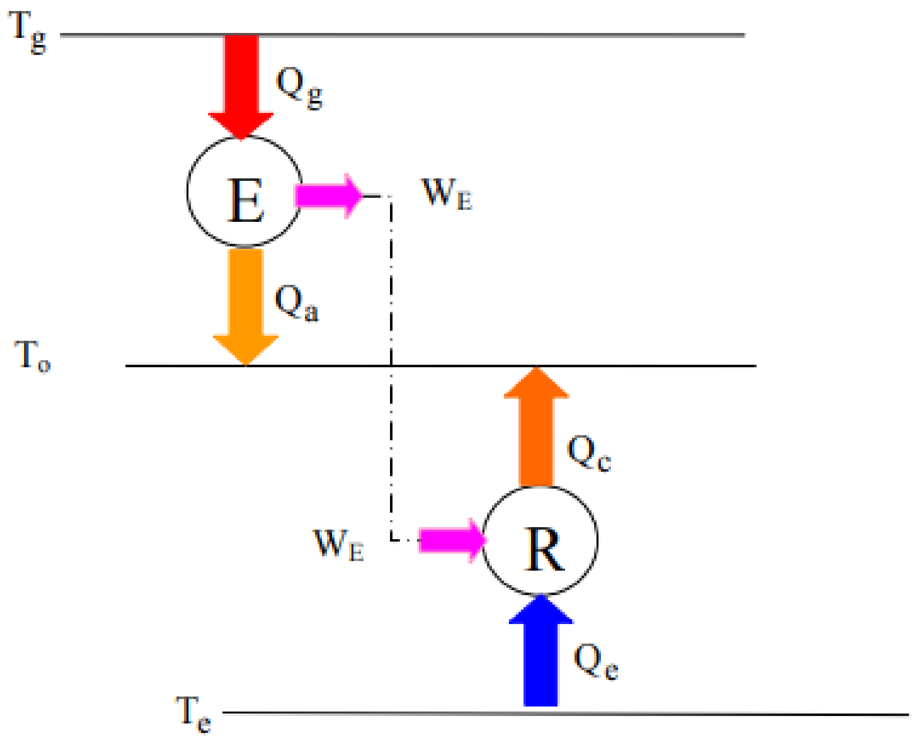
$$COP_{Carnot} = \frac{T_e}{T_c - T_e}$$

- If we assume that heat rejection at the absorber and condenser takes place at same external heat sink temperature To, then a vapour absorption refrigeration system operates between three temperature levels, Tg, To and Te. The maximum possible COP of a refrigeration system operating between three temperature levels can be obtained by applying first and second laws of thermodynamics to the system.

Various Energy Transfers



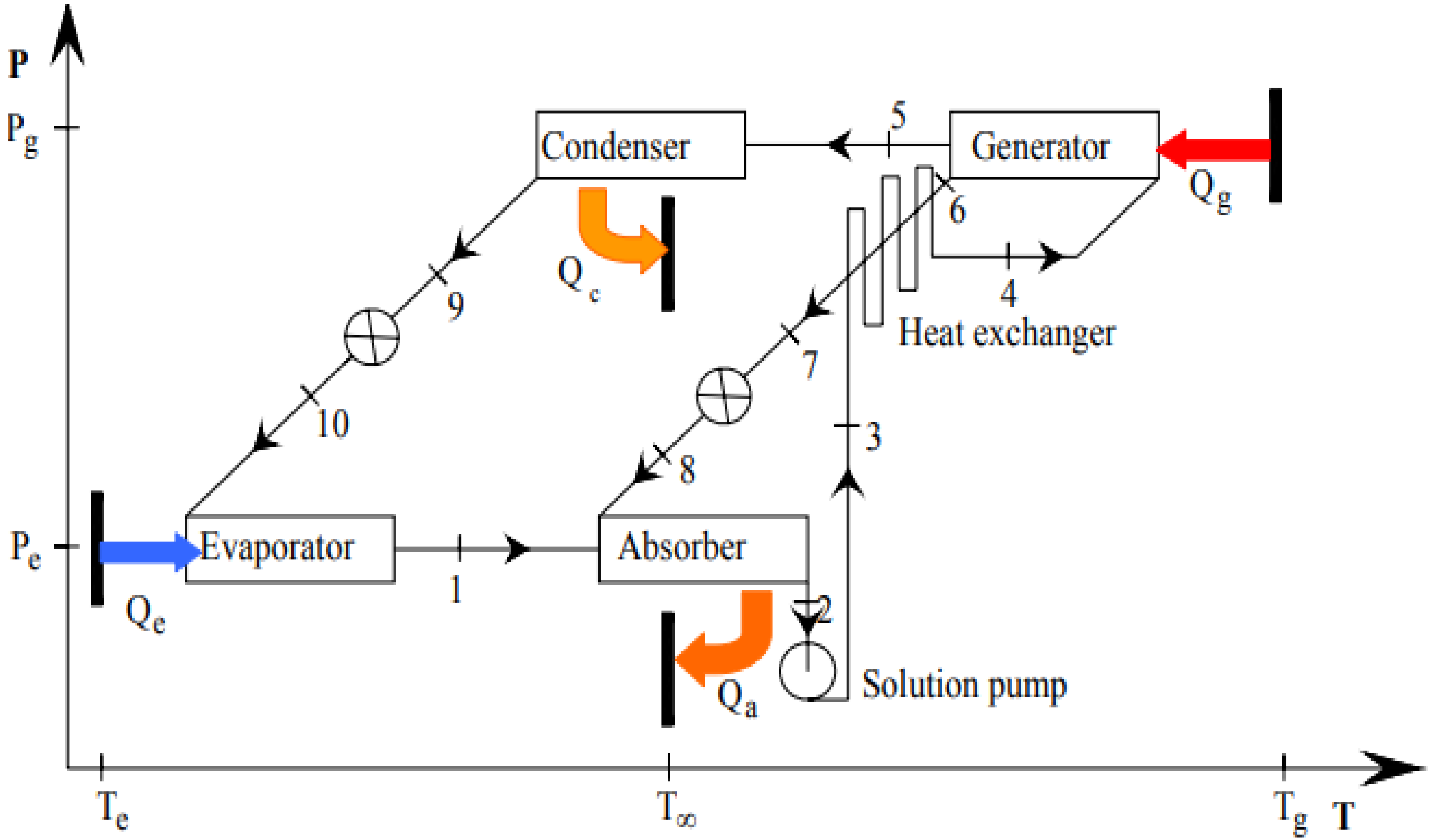
Vapour absorption refrigeration system as a combination of a heat engine and a refrigerator



Properties of refrigerant-absorbent mixtures

- **The solution used in absorption refrigeration systems may be considered as a homogeneous binary mixture of refrigerant and absorbent.**
- **Depending upon the boiling point difference between refrigerant and absorbent and the operating temperatures, one may encounter a pure refrigerant vapour or a mixture of refrigerant and absorbent vapour in generator of the absorption system.**
- **Unlike pure substances, the thermodynamic state of a binary mixture (in liquid or vapour phase) cannot be fixed by pressure and temperature alone.**
- **According to Gibbs' phase rule, one more parameter in addition to temperature and pressure is required to completely fix the thermodynamic state.**

Basic Vapour Absorption Refrigeration System



Basic Vapour Absorption Refrigeration System

- **The thermodynamic performance of the above system can be evaluated by applying mass and energy balance to each component assuming a steady flow process.**

- **In simple theoretical analyses, internal irreversibilities such as pressure drops between the components are generally neglected.**

- **To find the performance from the mass and energy balance equations one needs to know inputs such as the type of refrigerant-absorbent mixtures used in the system, operating temperatures, composition of solution at the entry and exit of absorber, effectiveness of solution heat exchanger etc.**

Refrigerant-absorbent combinations for VARS

- **The refrigerant should exhibit high solubility with solution in the absorber. This is to say that it should exhibit negative deviation from Raoult's law at absorber.**

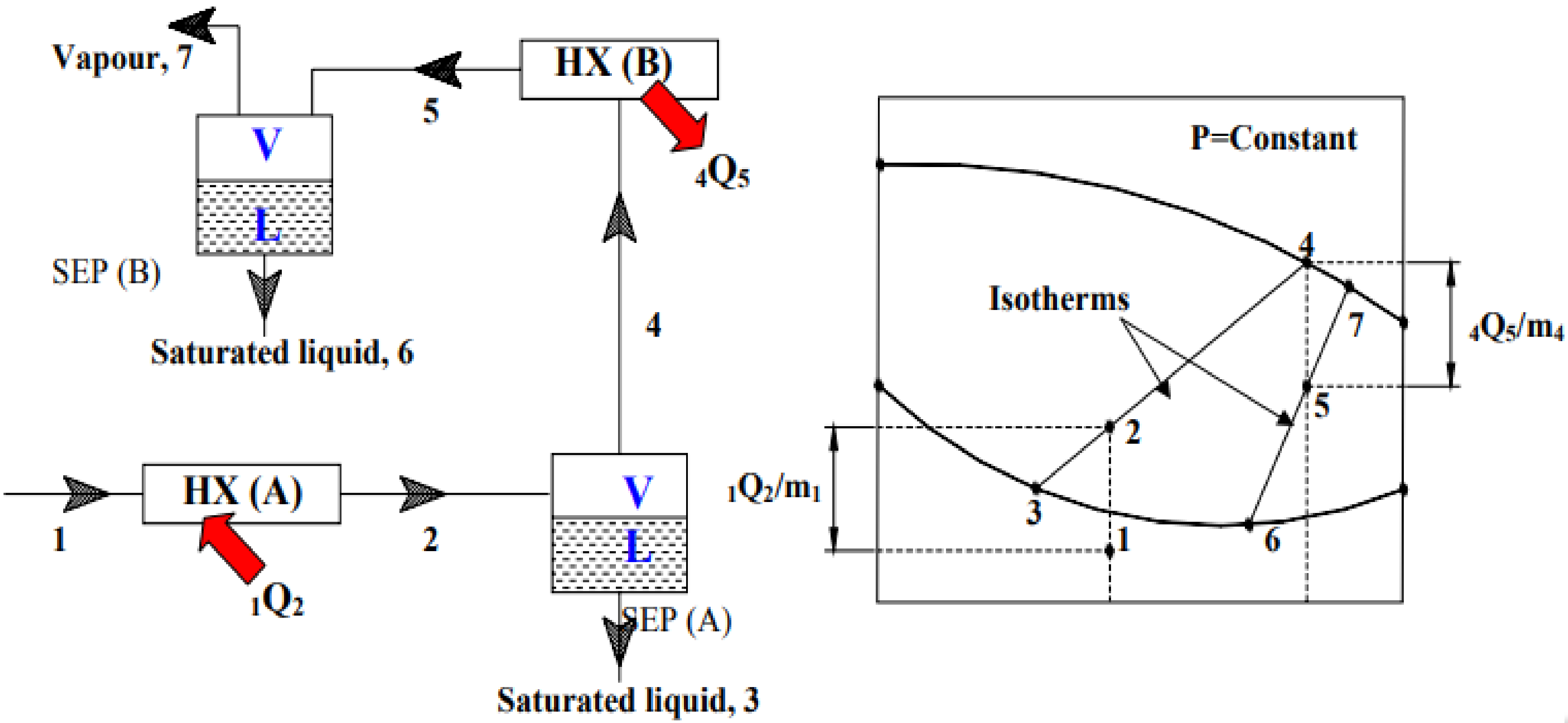
- **There should be large difference in the boiling points of refrigerant and absorbent (greater than 200^{o}C), so that only refrigerant is boiled-off in the generator. This ensures that only pure refrigerant circulates through refrigerant circuit (condenser-expansion valve-evaporator) leading to isothermal heat transfer in evaporator and condenser.**

- **It should exhibit small heat of mixing so that a high COP can be achieved. However, this requirement contradicts the first requirement. Hence, in practice a trade-off is required between solubility and heat of mixing.**

- **The refrigerant-absorbent mixture should have high thermal conductivity and low viscosity for high performance.**

- **It should not undergo crystallization or solidification inside the system. vi. The mixture should be safe, chemically stable, non-corrosive, inexpensive and should be available easily**

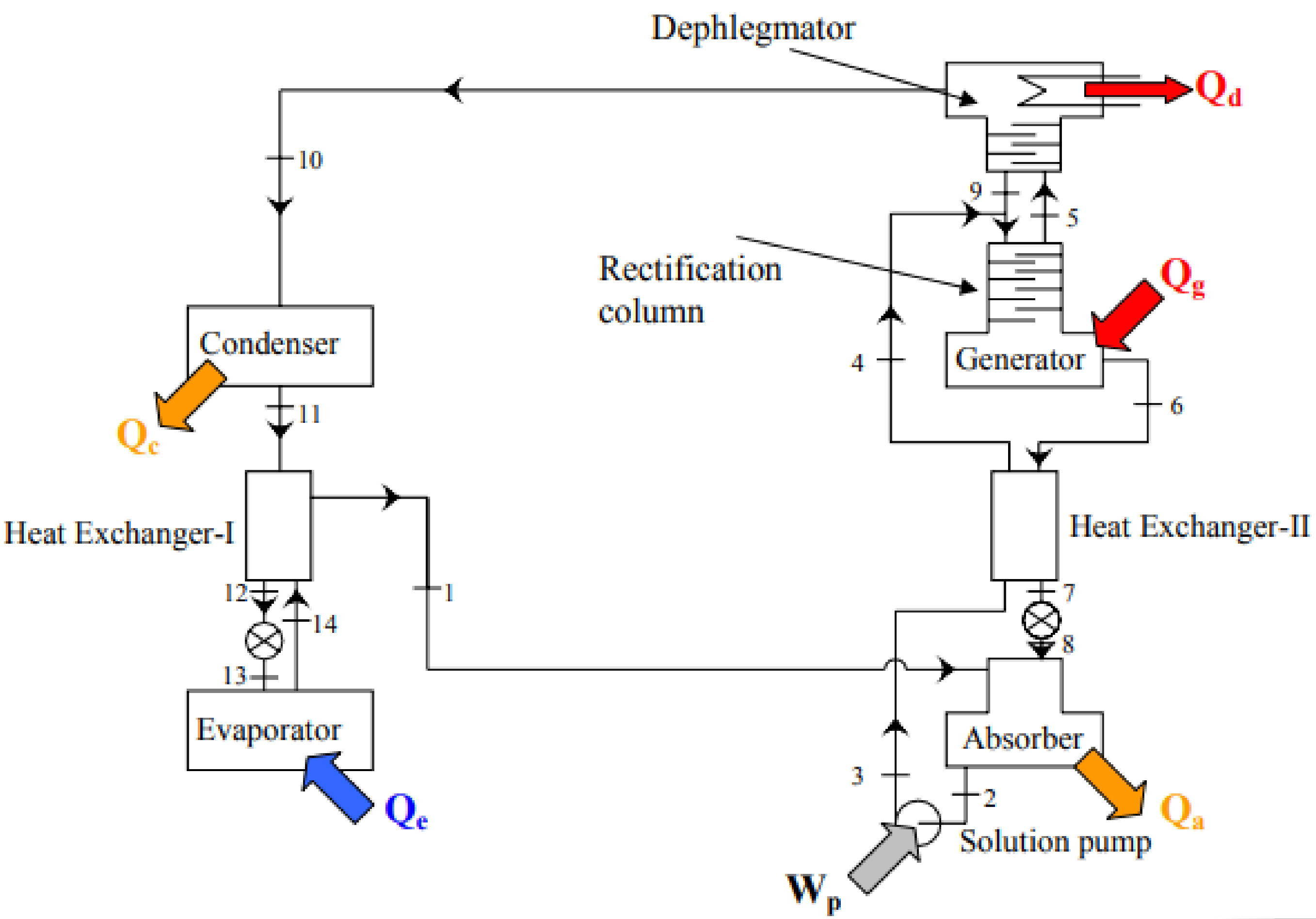
Heating and cooling of NH_3-H_2O solution – concept of rectification



Simple Ammonia-Water VARS

- It may be noted that from the above arrangement consisting of heating, cooling and separation, one finally obtains a vapour at state 7 that is rich in ammonia.
- That is the combination of heat exchangers with separators is equivalent to the process of rectification. Heat exchanger A plays the role of generator, while heat exchanger B plays the role of dephlegmator.
- To improve the process of rectification in actual vapour absorption refrigeration systems, a rectifying column is introduced between the generator and dephlegmator.
- In the rectifying column, the vapour from the separator A comes in contact with the saturated liquid coming from separator B. As a result, there will be heat and mass transfer between the vapour and liquid and finally the vapour comes out at a much higher concentration of ammonia.

Schematic of NH3-H2O based vapour absorption refrigeration system



Working principle

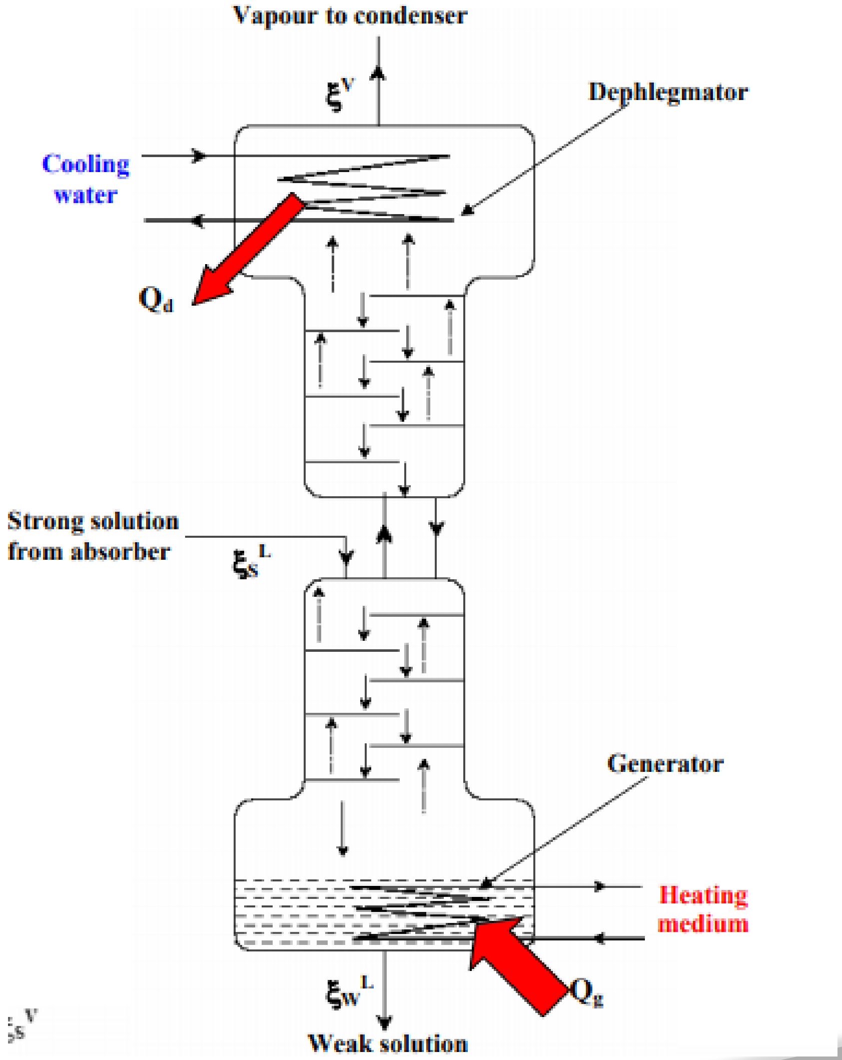
- Compared to water-lithium bromide systems, this system uses three additional components: a rectification column, a dephlegmator and a subcooling heat exchanger (Heat Exchanger-I).
- As mentioned before, the function of rectification column and dephlegmator is to reduce the concentration of water vapour at the exit of the generator. Without these the vapour leaving the generator may consist of five to ten percent of water.
- However, with rectification column and dephlegmator the concentration of water is reduced to less than one percent. The rectification column could be in the form of a packed bed or a spray column or a perforated plate column in which the vapour and solution exchange heat and mass.

Simple Ammonia-Water VARS

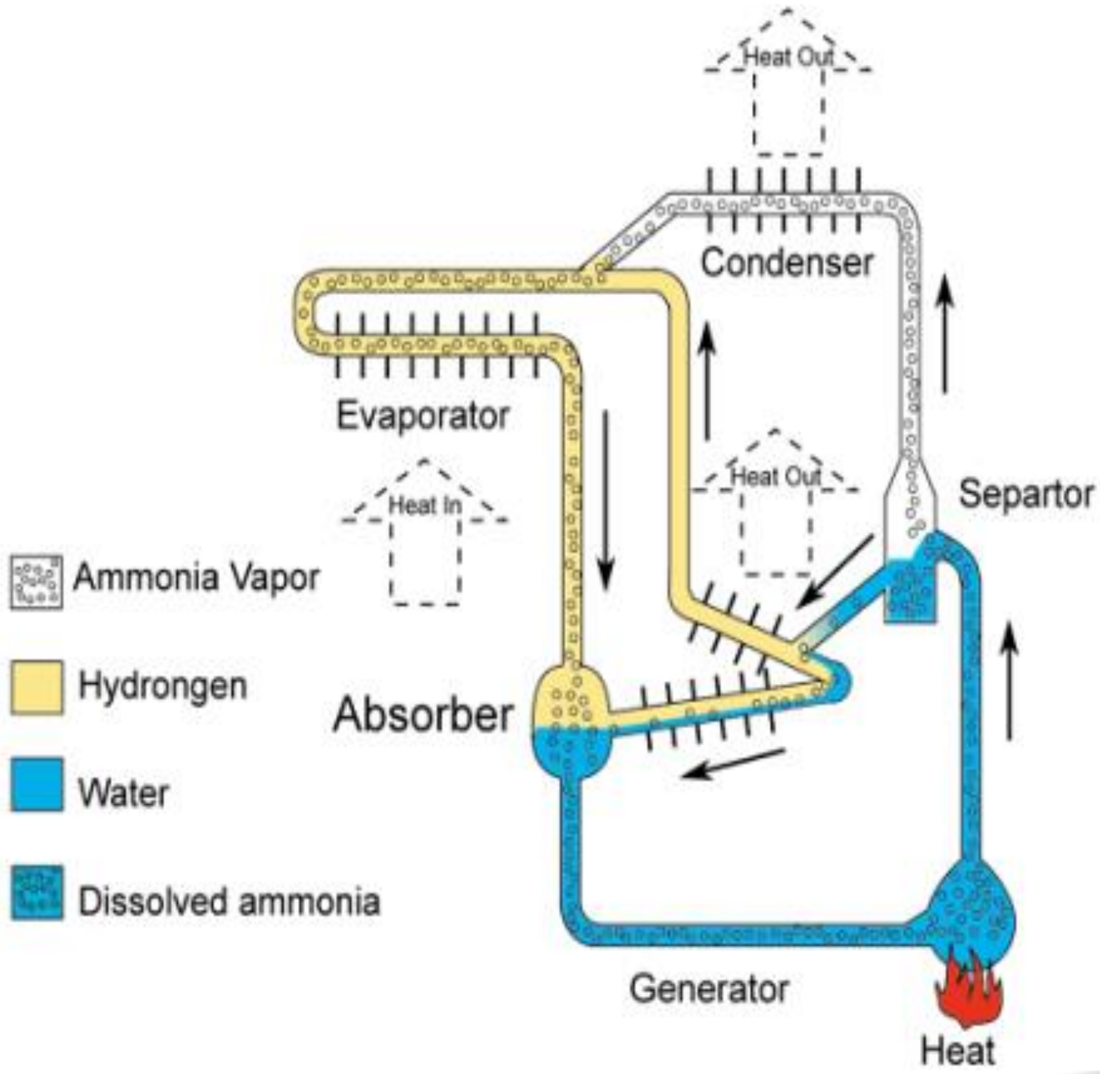
- **It is designed to provide a large residence time for the fluids so that high heat and mass transfer rates could be obtained.**

- **The subcooling heat exchanger, which is normally of counterflow type is used to increase the refrigeration effect and to ensure liquid entry into the refrigerant expansion valve.**

Rectification process in the generator



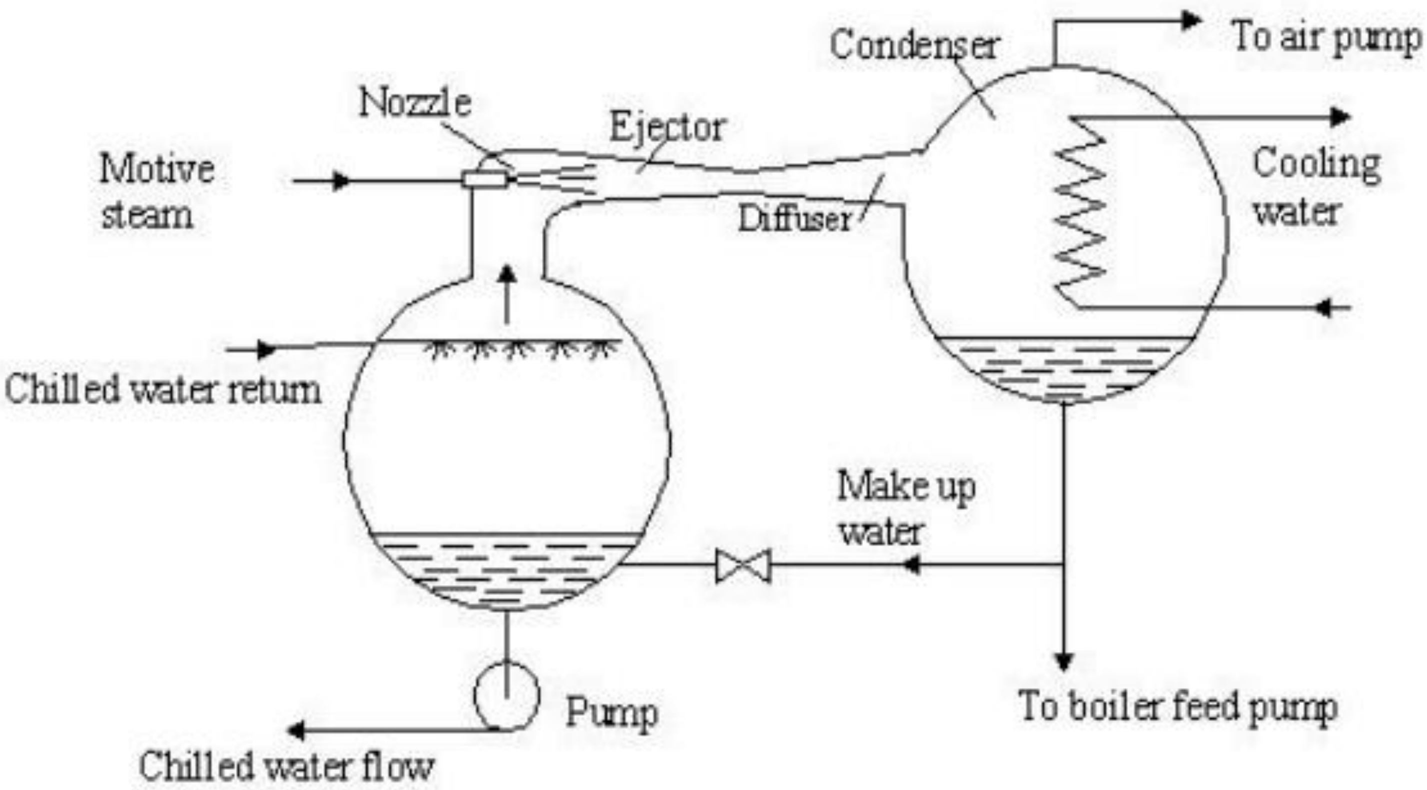
Schematic of a triple fluid vapour absorption refrigeration system



Steam Jet Refrigeration System:

- If water is sprayed into a chamber where a low pressure is maintained, a part of the water will evaporate. The enthalpy of evaporation will cool the remaining water to its saturation temperature at the pressure in the chamber.
- Obviously lower temperature will require lower pressure. Water freezes at 0^o C hence temperature lower than 4^o C cannot be obtained with water.
- In this system, high velocity steam is used to entrain the evaporating water vapour. High-pressure motive steam passes through either convergent or convergentdivergent nozzle where it acquires either sonic or supersonic velocity and low pressure of the order of 0.009 kPa corresponding to an evaporator temperature of 4^o C.

SJRS


Condenser
To air pump
Nozzle
Ejector
Motive steam
Cooling water
Diffuser
Chilled water return
Make up water
Pump
To boiler feed pump
Chilled water flow

UNIT – III

COMPONENTS OF REFRIGERATION

At the end of the unit students are able to:		
	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	**Identify** the modifications required in an impossible reversed Carnot cycle to convert it into practical cycle for refrigeration applications.	Remember
CO2	**Classify** the equipment used for the refrigeration, air conditioning purposes with suitable materials and refrigerant pairs.	Understand
CO3	**Describe** the working principle of shell and tube condenser and state the advantages and disadvantages.	Understand
CO4	**Compare** automatic expansion valve, thermostatic expansion valve, low side float valve and high side float valve.	Analyze

Compressors

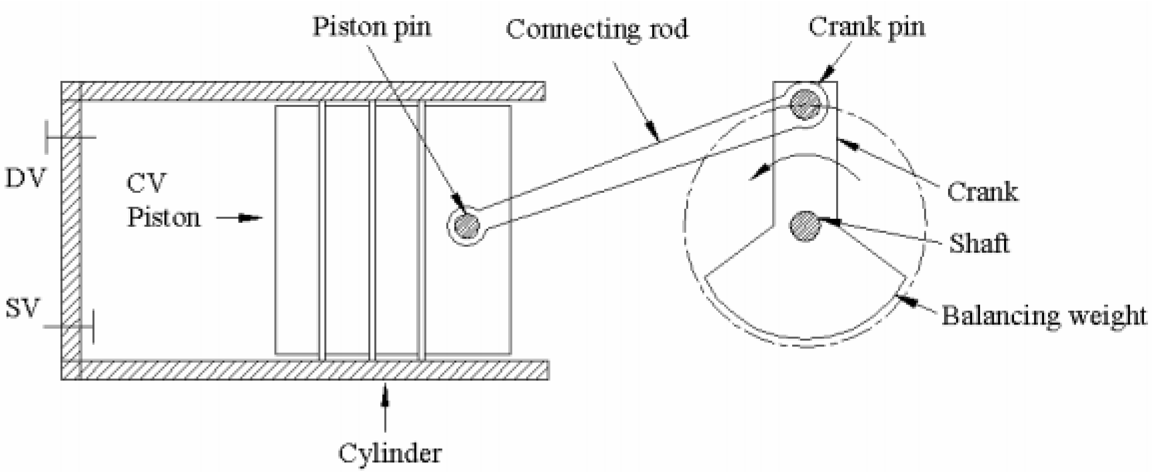
- A compressor is the most important and often the costliest component (typically 30 to 40 percent of total cost) of any vapour compression refrigeration system (VCRS). The function of a compressor in a VCRS is to continuously draw the refrigerant vapour from the evaporator, so that a low pressure and low temperature can be maintained in the evaporator at which the refrigerant can boil extracting heat from the refrigerated space. The compressor then has to raise the pressure of the refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser.

Classification of compressors

- **A compressor is the most important and often the costliest component (typically 30 to 40 percent of total cost) of any vapour compression refrigeration system (VCRS). The function of a compressor in a VCRS is to continuously draw the refrigerant vapour from the evaporator, so that a low pressure and low temperature can be maintained in the evaporator at which the refrigerant can boil extracting heat from the refrigerated space. The compressor then has to raise the pressure of the refrigerant to a level at which it can condense by rejecting heat to the cooling medium in the condenser.**

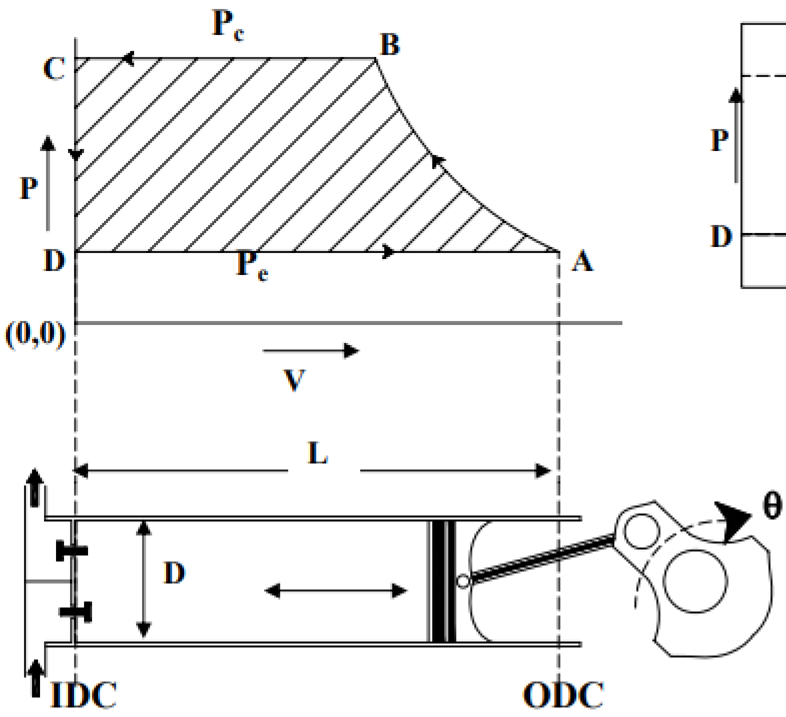
Reciprocating compressors

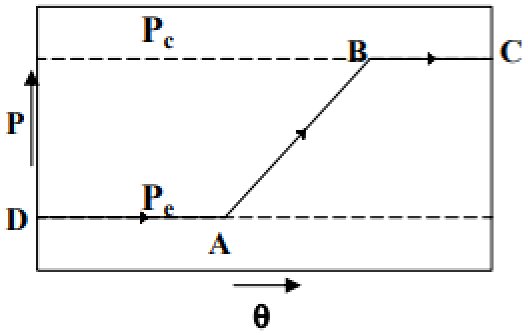
- Reciprocating compressor is the workhorse of the refrigeration and air conditioning industry. It is the most widely used compressor with cooling capacities ranging from a few Watts to hundreds of kilowatts. Modern day reciprocating compressors are high speed (≈ 3000 to 3600 rpm), single acting, single or multi-cylinder (upto 16 cylinders) type.



- Reciprocating compressors consist of a piston moving back and forth in a cylinder, with suction and discharge valves to achieve suction and compression of the refrigerant vapor. Its construction and working are somewhat similar to a two-stroke engine, as suction and compression of the refrigerant vapor are completed in one revolution of the crank.
- The suction side of the compressor is connected to the exit of the evaporator, while the discharge side of the compressor is connected to the condenser inlet. The suction (inlet) and the discharge (outlet) valves open and close due to pressure differences between the cylinder and inlet or outlet manifolds respectively.
- The pressure in the inlet manifold is equal to or slightly less than the evaporator pressure. Similarly the pressure in the outlet manifold is equal to or slightly greater than the condenser pressure.

Ideal reciprocating compressor on P-V and P-θ diagrams

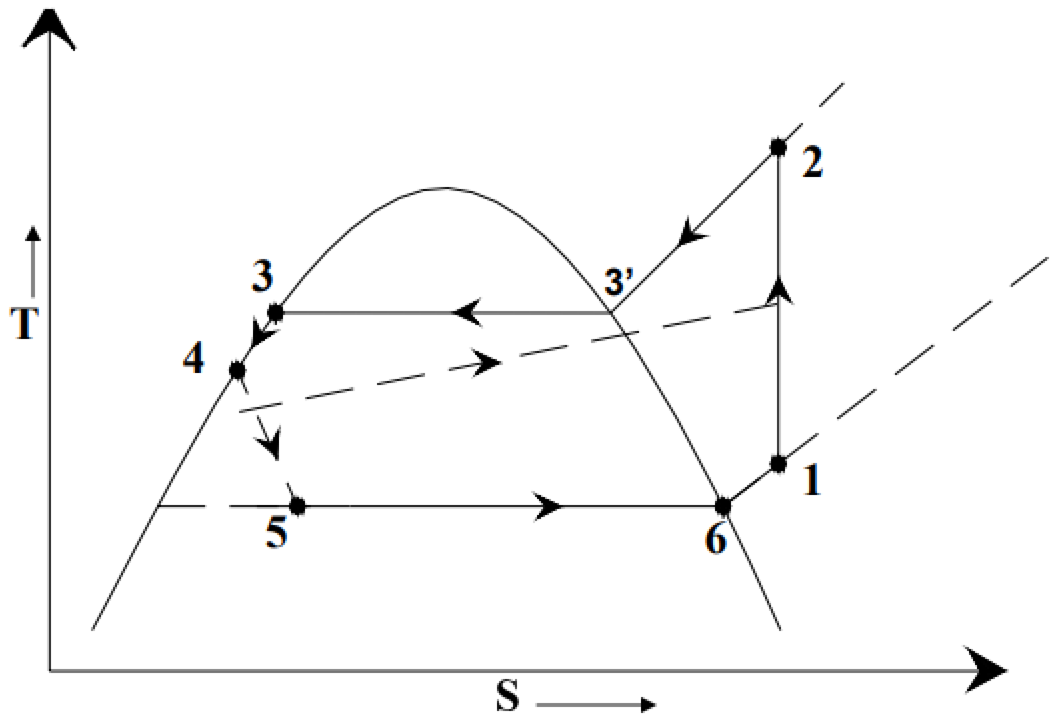




Condensers:

- condenser is an important component of any refrigeration system. In a typical refrigerant condenser, the refrigerant enters the condenser in a superheated state. It is first de-superheated and then condensed by rejecting heat to an external medium. The refrigerant may leave the condenser as a saturated or a sub-cooled liquid, depending upon the temperature of the external medium and design of the condenser.
- In the figure, the heat rejection process is represented by 2-3'-3-4. The temperature profile of the external fluid, which is assumed to undergo only sensible heat transfer, is shown by dashed line. It can be seen that process 2-3' is a de-superheating process, during which the refrigerant is cooled sensibly from a temperature T2 to the saturation temperature corresponding condensing pressure, T3'.

Condensers: T-S Diagram



Classification of condensers:

a) Air cooled condensers

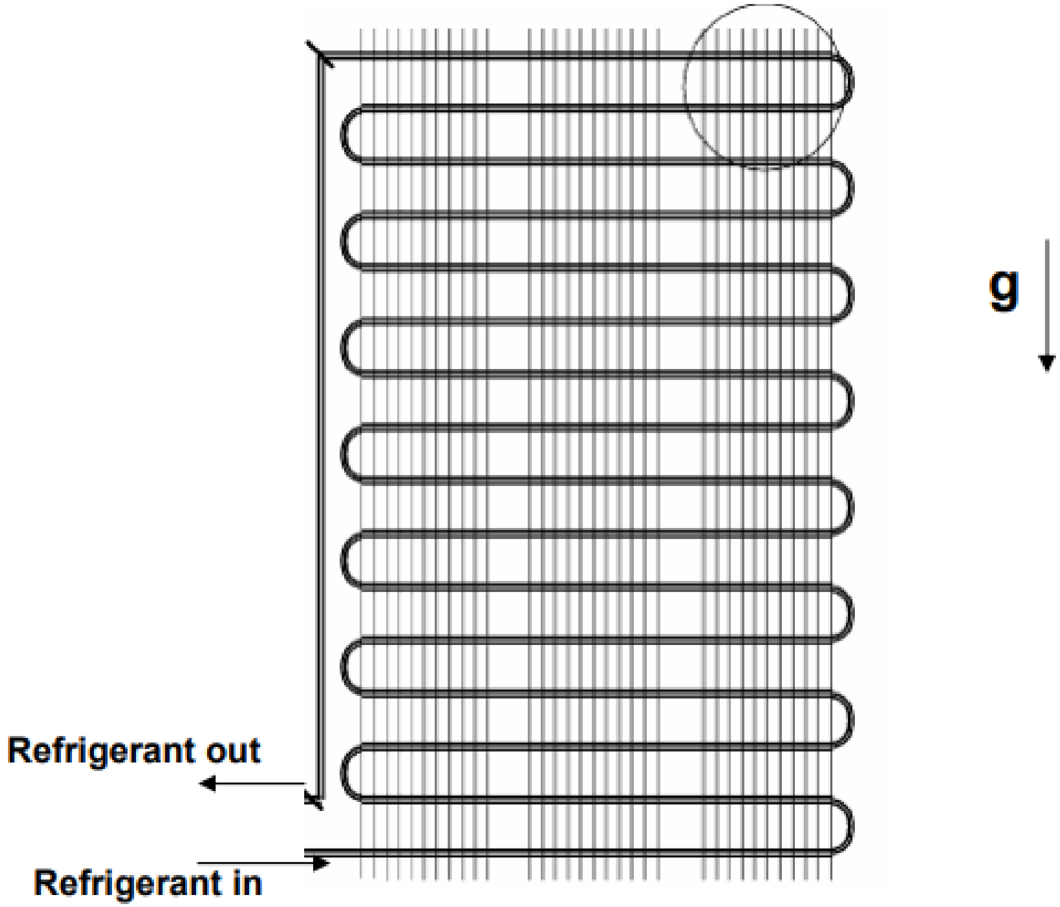
b) Water cooled condensers, and

c) Evaporative condensers

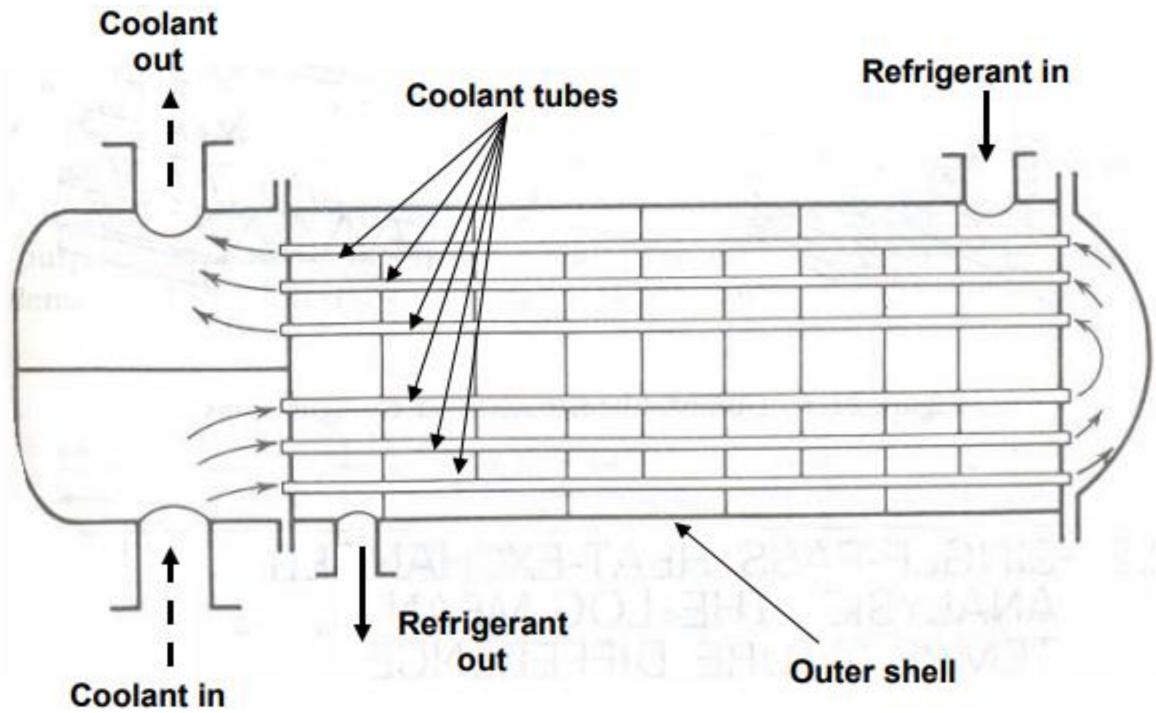
- **Air-cooled condensers:**

As the name implies, in air-cooled condensers air is the external fluid, i.e., the refrigerant rejects heat to air flowing over the condenser. Air-cooled condensers can be further classified into natural convection type or forced convection type.

Condensers:



Shell-and-tube type:



Classification of condensers:

- a) Air cooled condensers
- b) Water cooled condensers, and
- c) Evaporative condensers

- **Air-cooled condensers:**

As the name implies, in air-cooled condensers air is the external fluid, i.e., the refrigerant rejects heat to air flowing over the condenser. Air-cooled condensers can be further classified into natural convection type or forced convection type.

Expansion Devices

- **An expansion device is another basic component of a refrigeration system. The basic functions of an expansion device used in refrigeration systems are to:**

1. **Reduce pressure from condenser pressure to evaporator pressure, and**
2. **Regulate the refrigerant flow from the high-pressure liquid line into the evaporator at a rate equal to the evaporation rate in the evaporator**

Expansion Devices

- There are basically seven types of refrigerant expansion devices. These are:

1. Hand (manual) expansion valves
2. Capillary Tubes
3. Orifice
4. Constant pressure or Automatic Expansion Valve (AEV)
5. Thermostatic Expansion Valve (TEV)
6. Float type Expansion Valve

   a) High Side Float Valve b) Low Side Float Valve

7. Electronic Expansion Valve

Capillary Tube

- **A capillary tube is a long, narrow tube of constant diameter. The word "capillary" is a misnomer since surface tension is not important in refrigeration application of capillary tubes. Typical tube diameters of refrigerant capillary tubes range from 0.5 mm to 3 mm and the length ranges from 1.0 m to 6 m.**

Capillary Tube

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Advantages and disadvantages of capillary tubes

- **Some of the advantages of a capillary tube are:**

1. **It is inexpensive.**
2. **It does not have any moving parts hence it does not require maintenance**
3. **Capillary tube provides an open connection between condenser and the evaporator hence during off-cycle, pressure equalization occurs between condenser and evaporator. This reduces the starting torque requirement of the motor since the motor starts with same pressure on the two sides of the compressor. Hence, a motor with low starting torque (squirrel cage Induction motor) can be used.**
4. **Ideal for hermetic compressor based systems, which are critically charged and factory assembled.**

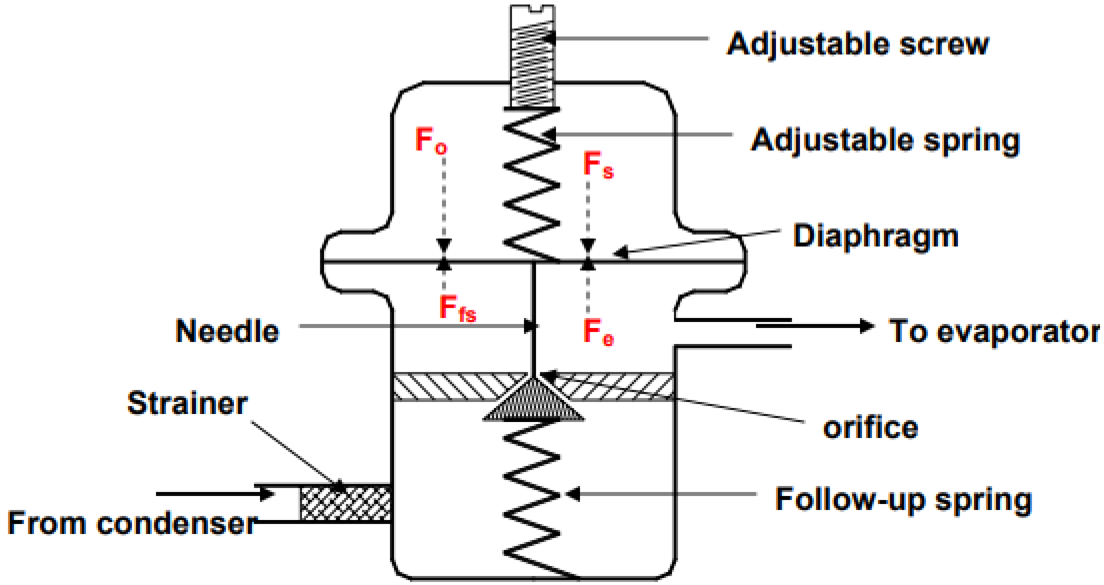
- **Some of the disadvantages of the capillary tube are:**

1. **It cannot adjust itself to changing flow conditions in response to daily and seasonal variation in ambient temperature and load. Hence, COP is usually low under off design conditions.**

2. **It is susceptible to clogging because of narrow bore of the tube, hence, utmost care is required at the time of assembly. A filter-drier should be used ahead of the capillary to prevent entry of moisture or any solid particles**

Automatic Expansion Valve (AEV)

An Automatic Expansion Valve (AEV) also known as a constant pressure expansion valve acts in such a manner so as to maintain a constant pressure and thereby a constant temperature in the evaporator. The schematic diagram of the valve is shown in Fig. The valve consists of an adjustment spring that can be adjusted to maintain the required temperature in the evaporator. This exerts force Fs on the top of the diaphragm.

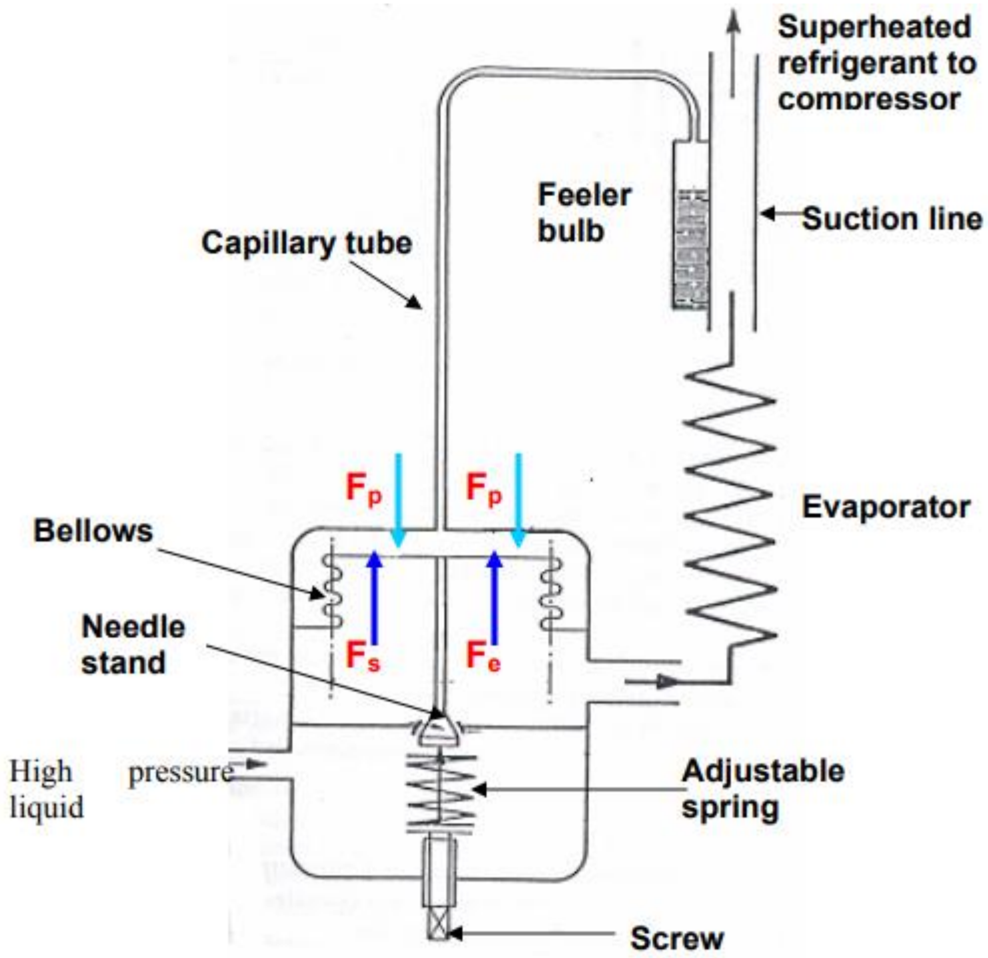


Thermostatic Expansion Valve (TEV)

- **Thermostatic expansion valve is the most versatile expansion valve and is most commonly used in refrigeration systems.**

- **A thermostatic expansion valve maintains a constant degree of superheat at the exit of evaporator; hence it is most effective for dry evaporators in preventing the slugging of the compressors since it does not allow the liquid refrigerant to enter the compressor.**

T.E.V



Superheated refrigerant to compressor
Feeler bulb
Suction line
Capillary tube
Evaporator
Bellows
Needle stand
High pressure liquid
Adjustable spring
Screw

Evaporators

- **An evaporator, like condenser is also a heat exchanger. In an evaporator, the refrigerant boils or evaporates and in doing so absorbs heat from the substance being refrigerated. The name evaporator refers to the evaporation process occurring in the heat exchanger.**

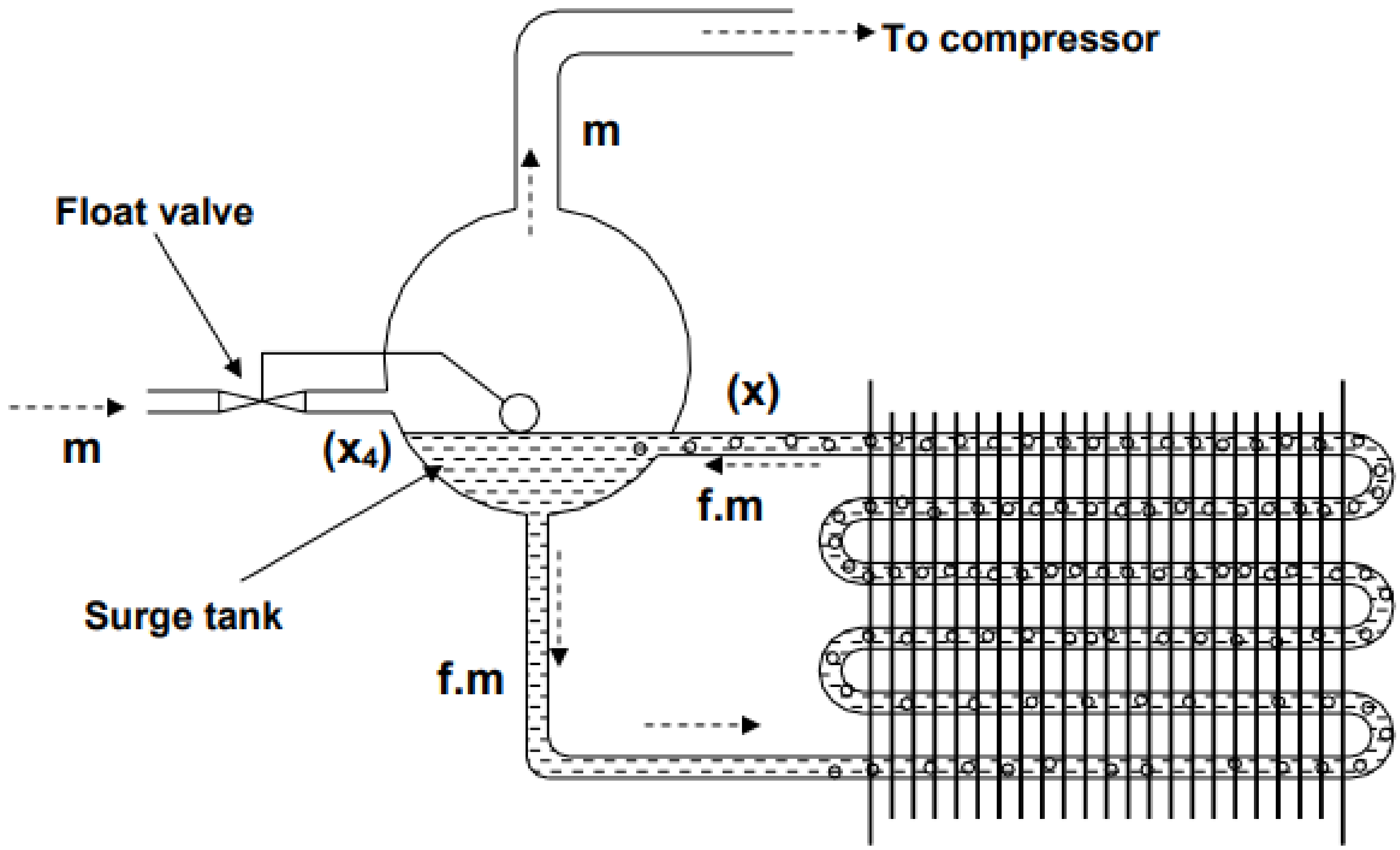
Natural and Forced Convection Type

- The evaporator may be classified as natural convection type or forced convection type. In forced convection type, a fan or a pump is used to circulate the fluid being refrigerated and make it flow over the heat transfer surface, which is cooled by evaporation of refrigerant.
- In natural convection type, the fluid being cooled flows due to natural convection currents arising out of density difference caused by temperature difference.
- The refrigerant boils inside tubes and evaporator is located at the top. The temperature of fluid, which is cooled by it, decreases and its density increases. It moves downwards due to its higher density and the warm fluid rises up to replace it.

Flooded Evaporator

- This is typically used in large ammonia systems. The refrigerant enters a surge drum through a float type expansion valve. The compressor directly draws the flash vapour formed during expansion. This vapour does not take part in refrigeration hence its removal makes the evaporator more compact and pressured drop due to this is also avoided. The liquid refrigerant enters the evaporator from the bottom of the surge drum. This boils inside the tubes as heat is absorbed. The mixture of liquid and vapour bubbles rises up along the evaporator tubes. The vapour is separated as it enters the surge drum. The remaining unevaporated liquid circulates again in the tubes along with the constant supply of liquid refrigerant from the expansion valve. The mass flow rate in the evaporator tubes is .f m where is the mass flow rate through the expansion valve and to the compressor.

FLOODED Evaporators

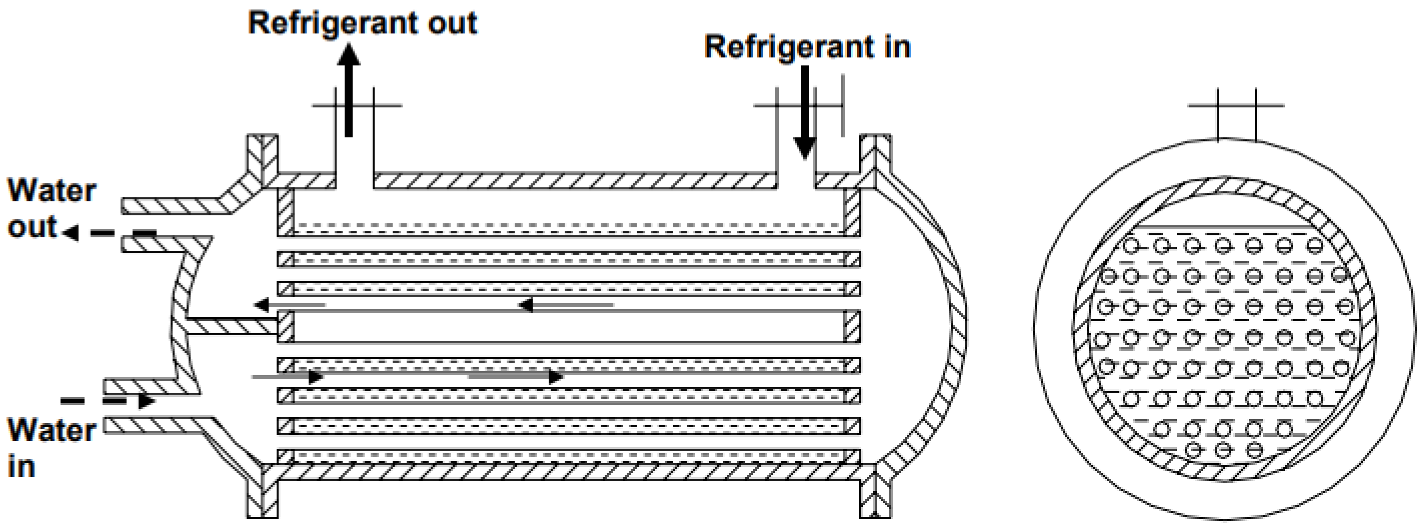


Flooded Type Shell-and-Tube Evaporator

- **a flooded type of shell and tube type liquid chiller where the liquid (usually brine or water) to be chilled flows through the tubes in double pass just like that in shell and tube condenser. The refrigerant is fed through a float valve, which maintains a constant level of liquid refrigerant in the shell.**

- **This is done to maintain liquid refrigerant level below the top of the shell so that liquid droplets settle down due to gravity and are not carried by the vapour leaving the shell. If the shell is completely filled with tubes, then a surge drum is provided after the evaporator to collect the liquid refrigerant.**

SHELL AND TUBE FLOODED TYPE EVAPORATOR



UNIT – IV

INTRODUCTION TO AIR CONDITIONING

PSYCHROMETRIC PROPERTIES

- The properties of moist air are called psychrometric properties and the subject which deals with the behaviour of moist air is known as psychrometry.

- Moist air is a mixture of dry air and water vapour. They form a binary mixture. A mixture of two substances requires three properties to completely define its thermodynamic state, unlike a pure substance which requires only two. One of the three properties can be the composition.

- Water vapour is present in the atmosphere at a very low partial pressure. At this low pressure and atmospheric temperature, the water vapour behaves as a perfect gas.

At the end of the unit students are able to:

	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	**Classify** the equipment used for the refrigeration, air conditioning purposes with suitable materials and refrigerant pairs.	Remember
CO2	**Construct** the sensible heat factor lines, locate alignment circle and SHF scale on a psychrometric chart for the cooling load calculations of air conditioning systems.	Understand
CO3	**Explain** thermal comfort conditions with respect to effective temperature, relative humidity, etc. and their impact on human comfort, productivity and health.	Understand
CO4	**Apply** the principles of psychrometry to calculate and design the air conditioning systems for particular purpose.	Analyze

- **Since the water vapour part is continuously variable, all calculations in air- conditioning practice are based on the dry air part.**

- **For calculating and defining the psychrometric properties, we may consider a certain volume V of moist air at pressure p and temperature T , containing ma kg of dry air and mv kg of water vapour as shown in Figure 6.3. The actual temperature t of moist air is called the dry bulb temperature (DBT). The total pressure p which is equal to the barometric pressure is constant**

Specific Humidity or Humidity Ratio

- Specific or absolute humidity or humidity ratio or moisture content is defined as the ratio of the mass of water vapour to the mass of dry air in a given volume of the mixture. It is denoted by the symbol ω.

Dew Point Temperature

- The normal thermodynamic state 1 as shown in the of moist air is considered as unsaturated air. The water vapour existing at temperature T of the mixture and partial pressure pv of the vapour in the mixture is normally in a superheated state.

Relative Humidity

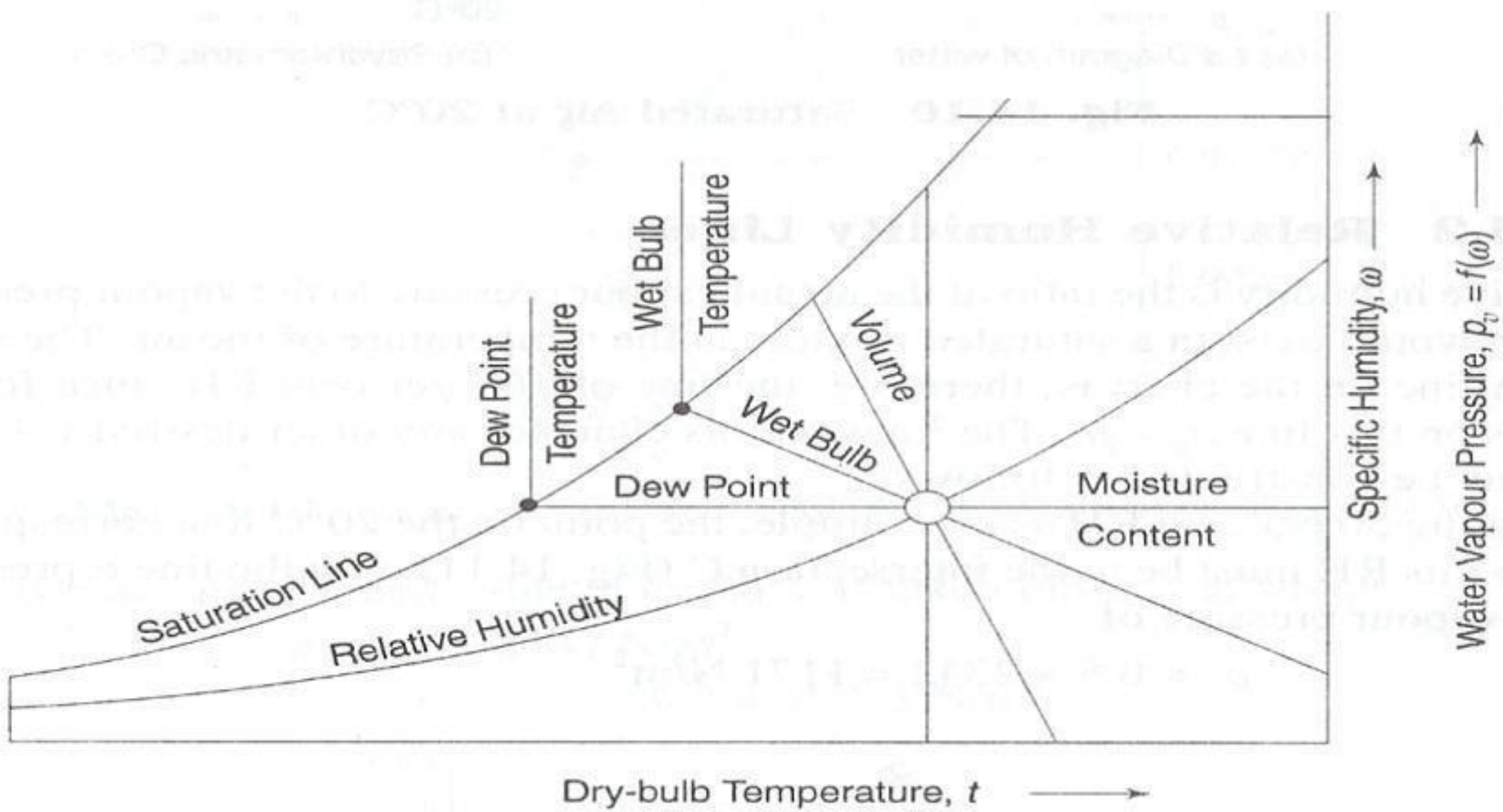
- **The relative humidity is defined as the ratio of the mole fraction of water vapour in moist air to mole fraction of water vapour in saturated air at the same temperature and pressure.**

PSYCHROMETRIC CHART

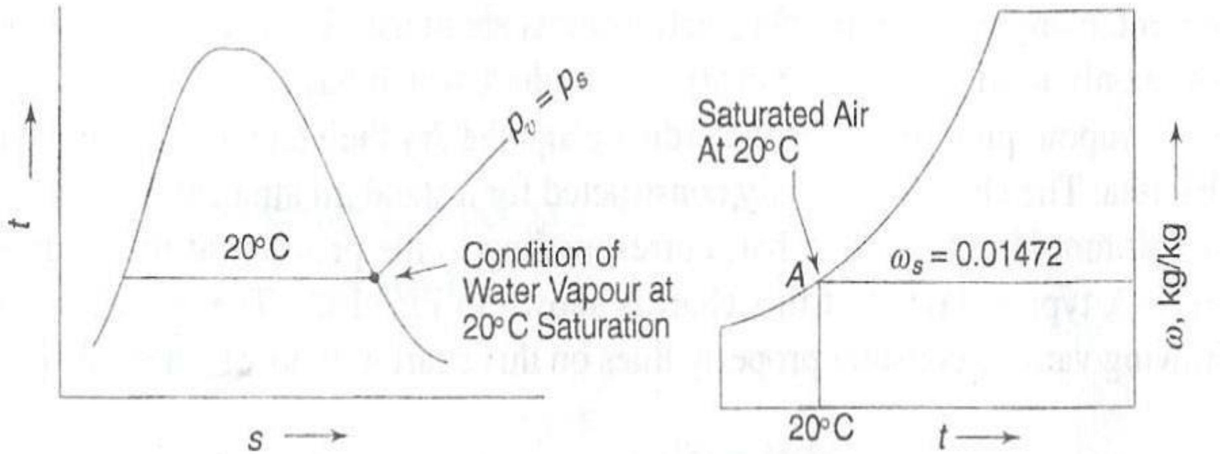
- **All data essential for the complete thermodynamic and psychrometric analysis of air- conditioning processes can be summarised in a psychrometric chart. At present, many forms of psychrometric charts are in use. The chart which is most commonly used is the ω-t chart, i.e. a chart which has specific humidity or water vapour pressure along the ordinate and the dry bulb temperature along the abscissa.**

- **The chart is normally constructed for a standard atmospheric pressure of 760 mm Hg or 1.01325 bar, corresponding to the pressure at the mean sea level. A typical layout of this chart is shown in Figure**

PSYCHROMETRIC CHART



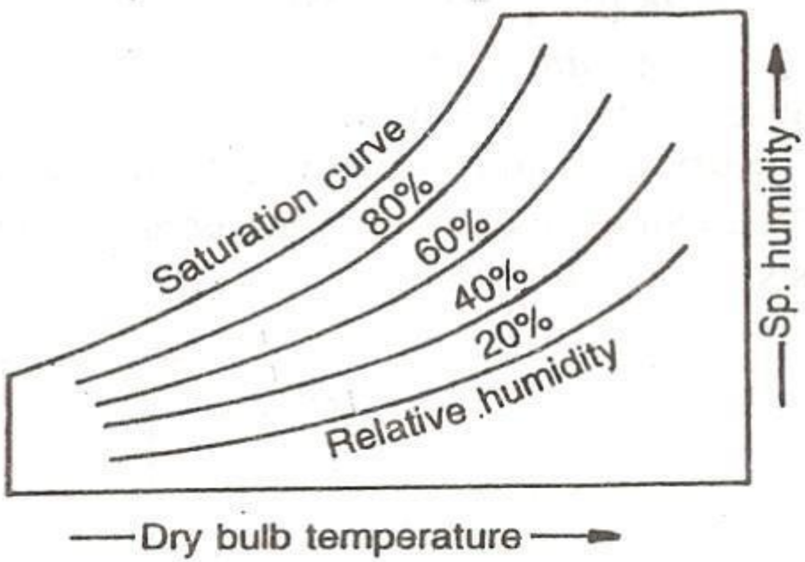
- The saturation line represents the states of saturated air at different temperatures. As an example of fixing such a state on the chart, consider an atmosphere A at 20^0C and saturation as shown in Figure 6.9. From the steam tables at 20^0C, water vapour pressure.



(a) t-s Diagram of water (b) Psychrometric Chart

Relative Humidity Lines

- **The relative humidity is defined as the ratio of the mole fraction of water vapour in moist air to mole fraction of water vapour in saturated air at the same temperature and pressure.**



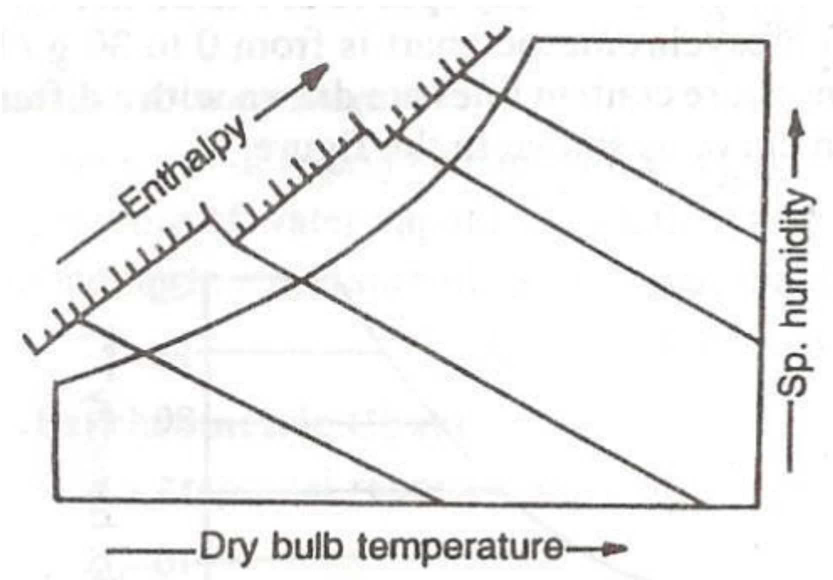
Constant Specific Volume Lines

- **The constant specific volumes lines are obliquely inclined straight lines and uniformly spaced as shown in Figure These lines are drawn up to the saturation curve.**

- **To establish points on line of constant specific volume, 0.90 m3/kg for example, From the perfect-gas equation, the specific volume v is substitute 0.90 for v, the barometric pressure for pt, and at arbitrary values of T solve for ps. the pairs of ps and t values then describe the line of constant v.**

Constant Enthalpy Lines

- The enthalpy (or total heat) lines are inclined straight lines and uniformly spaced as shown in Figure. These lines are parallel to the wet bulb temperature lines, and are drawn up to the saturation curve. Some of these lines coincide with the wet bulb temperature lines also.



CLASSIFICATION OF AIR CONDITIONING SYSTEMS

- **Individual room air conditioning systems or simply individual systems**
- **Evaporative cooling air conditioning systems**
- **Desiccant-based air conditioning systems or simply desiccant systems**
- **Thermal storage air conditioning systems or simply thermal storage systems**
- **Clean room air conditioning systems or simply clean room systems**
- **Space conditioning air conditioning systems or simply space systems**
- **Unitary packaged air conditioning systems or simply packaged systems**
- **Central hydronic air conditioning systems or simply central systems.**

INDIVIDUAL AIR CONDITIONING SYSTEMS

- **An individual room air conditioning system or simply an individual system uses a self-contained, factory-made packaged air conditioner to serve an individual room.**

- **It is ready to use after electric cable and necessary water drainage are connected. Individual systems always use a DX coil to cool the air directly. Individual systems can be subdivided into the two following air conditioning systems:**

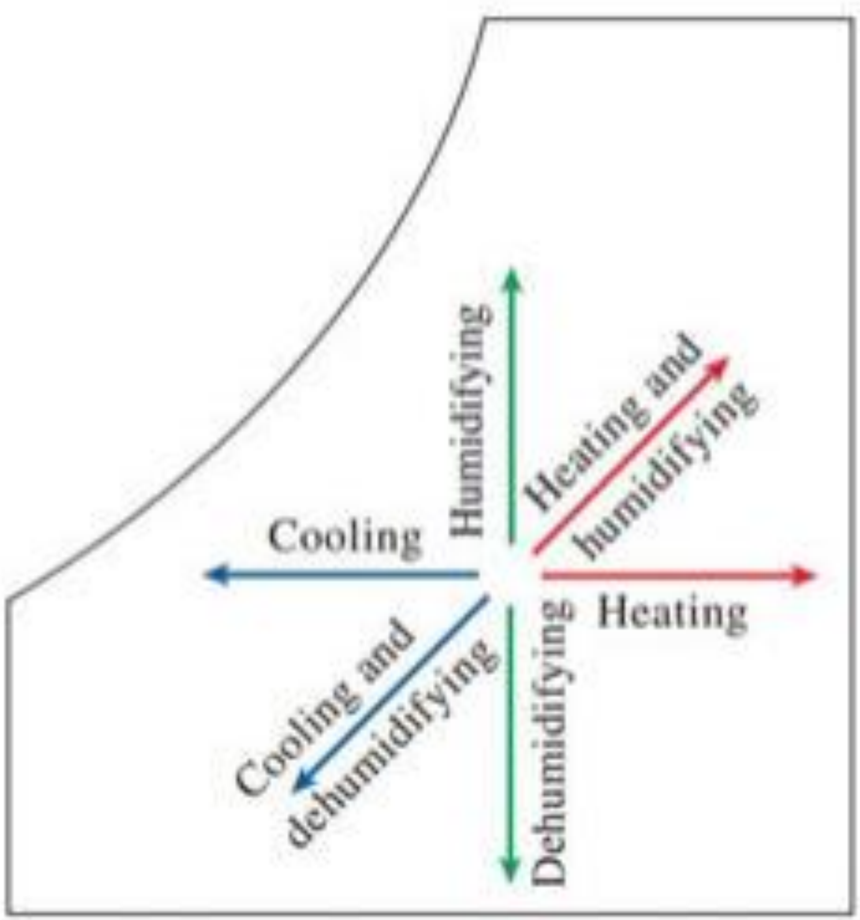
- **Room air conditioning (RAC) systems**
- **Packaged terminal air conditioning (PTAC) systems**

Psychrometric Processes

- **Air conditioning processes are most commonly used to achieve a more comfortable interior environment. This is done by controlling the temperature and humidity of the interior space and ensuring adequate amount of fresh air in the space.**

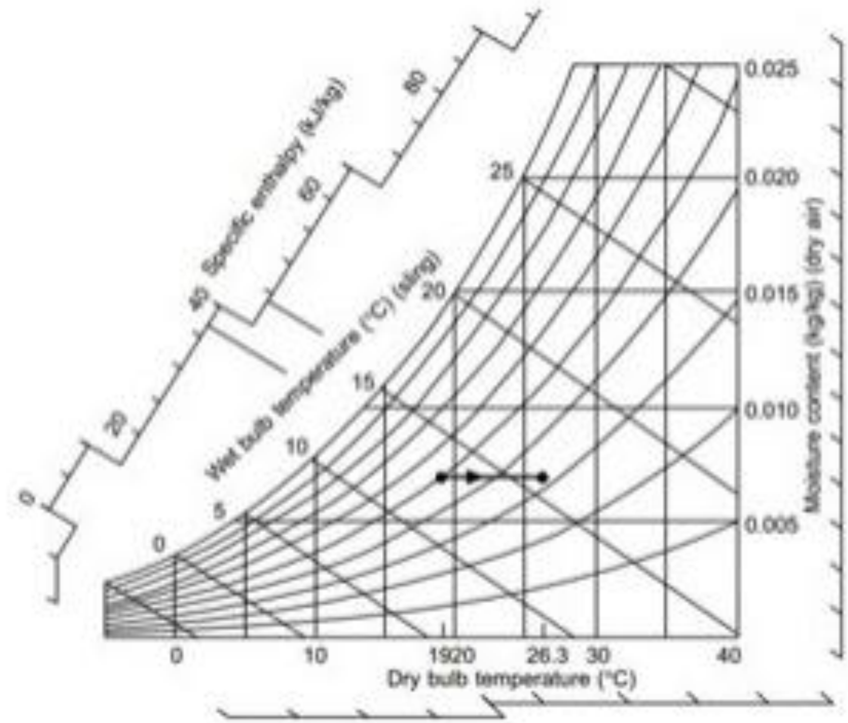
- **Temperature Control: Sensible Heating, Sensible Cooling**
- **Humidity Control: Adiabatic saturation, steam injection, air washer, cooling and dehumidifying coil**
- **Fresh air: Adiabatic Mixing of airstreams**

Psychrometric Processes



Sensible Heating of Air

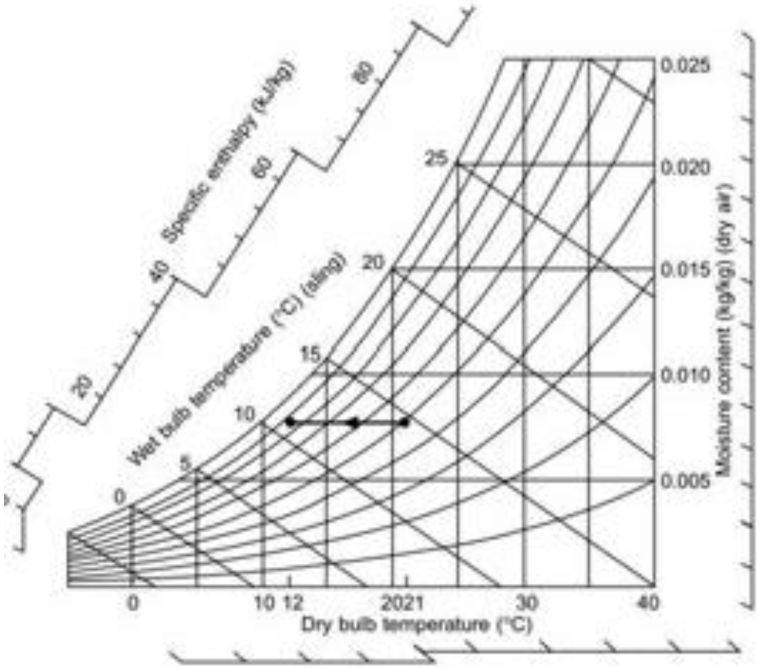
- ➢ **DBT increases, moisture content remains constant**
- ◉ **Note that RH of air decreases, which may cause dry skin, respiratory difficulties, and an increase in static electricity**



Sensible Heating

Sensible Cooling of Air

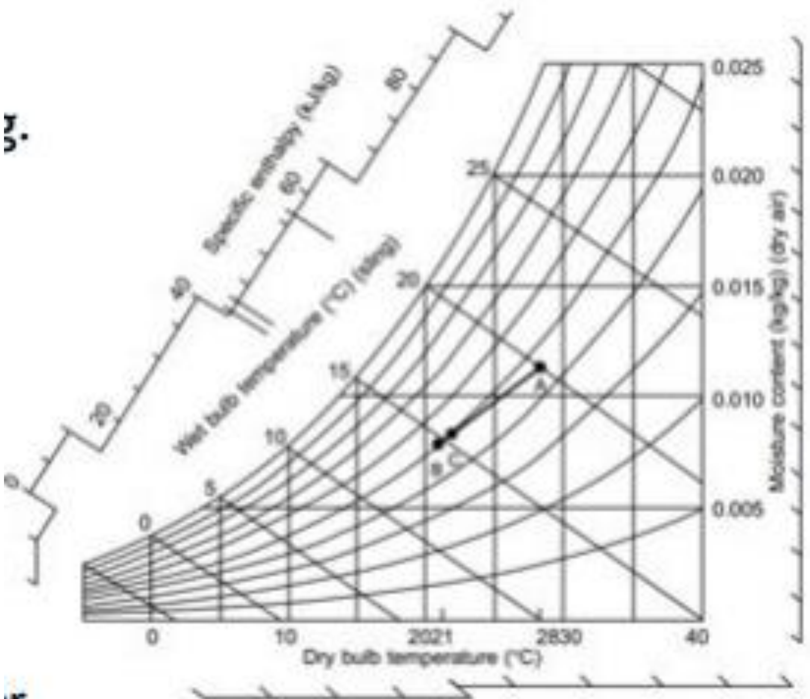
- DBT decreases, moisture content remains constant
- Note that RH of air increases
- Cooling can be achieved by passing the air over some coils through which a refrigerant or chilled water flows.



Sensible Cooling

Adiabatic mixing of airstreams

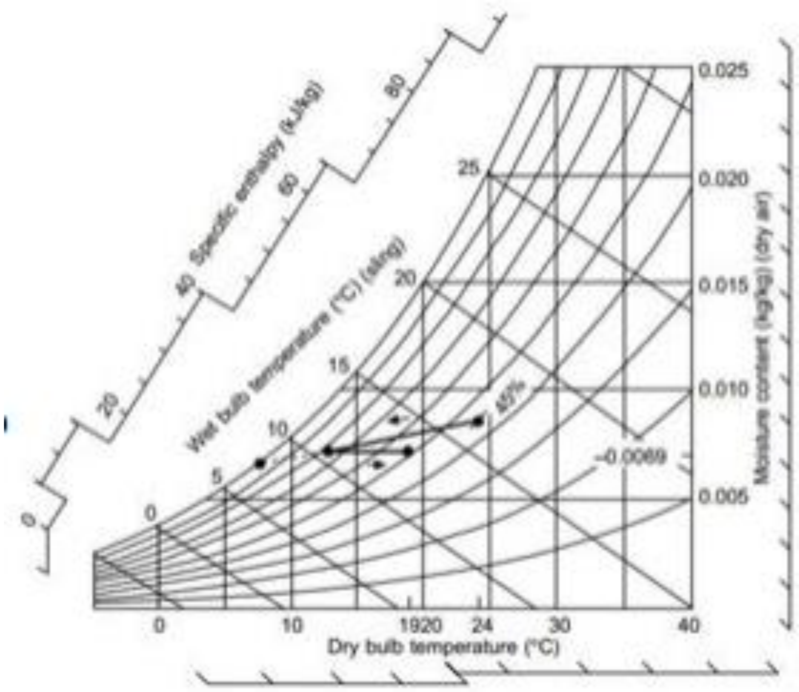
- Many air-conditioning applications require the mixing of two airstreams. E.g. Air conditioning in hospitals, large buildings etc. require that the conditioned air be mixed with a certain fraction of fresh outside air



Adiabatic mixing of airstreams

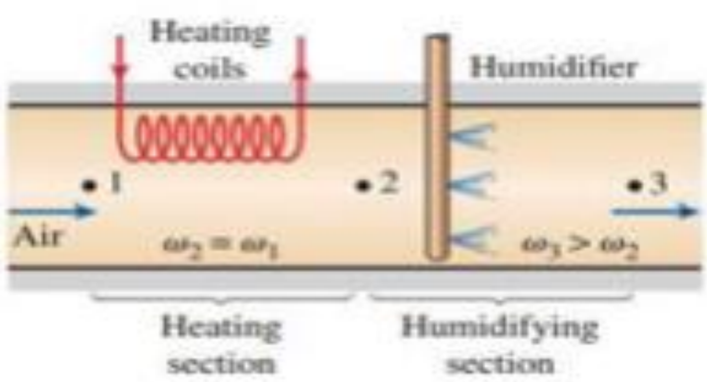
Cooling with Dehumidification followed by Reheating

- If air is to be cooled and dehumidified, it may be found that the process line joining the inlet and outlet conditions does not meet the saturation line, e.g. in cooling air from 24°C dry bulb, 45% saturation, to 19°C dry bulb, 50% saturation, the process line shows this to be impossible in one step.



Heating with Humidification

- Sensible heating decreases RH. This can be eliminated by humidifying the heated air. This is accomplished by passing the air first through a heating section (process 1-2) and then through a humidifying section (process 2-3)
- The properties of air at state 3 depend on how the humidification is accomplished – steam injection/adiabatic spraying. So, the heating (excess or lower) should be done accordingly in the heating section.



Advantages

- There are no supply, return, or exhaust ducts.
- Individual air conditioning systems are the most compact, flexible, and lower in initial cost than
- others, except portable air conditioning units.
- Building space is saved for mechanical rooms and duct shafts.
- It is easier to match the requirements of an individual control zone.
- They are quick to install.

Disadvantages

- **Temperature control is usually on /off, resulting in space temperature swing.**
- **Air filters are limited to coarse or low-efficiency filters.**
- **Local outdoor ventilation air intake is often affected by wind speed and wind direction.**
- **Noise level is not suitable for critical applications.**
- **More regular maintenance of coils and filters is required than for packaged and central systems.**

UNIT – V

AIR CONDITIONING SYSTEMS

At the end of the unit students are able to:

	Course Outcomes	Knowledge Level (Bloom's Taxonomy)
CO1	**Demonstrate** the working principle and coefficient of performance of a heat pump, heat engine and refrigerator.	Remember
CO2	**Classify** the equipment used for the refrigeration, air conditioning purposes with suitable materials and refrigerant pairs.	Understand
CO3	**Distinguish** the equipment required for air conditioning systems, study the operating principles, safety controls employed in air conditioning systems.	Understand
CO4	**Compare** the various heat pump circuits for heating, cooling purposes with suitable industrial applications.	Analyze

BASICS OF HEAT PUMP AND HEAT RECOVERY

- A heat pump extracts heat from a heat source and rejects heat to air or water at a higher temperature.

- During summer, the heat extraction, or refrigeration effect, is the useful effect for cooling, whereas in winter the rejected heat alone, or rejected heat plus the supplementary heating from a heater, forms the useful effect for heating.

- A heat pump is a packaged air conditioner or a packaged unit with a reversing valve or other changeover setup. A heat pump has all the main components of an air conditioner or packaged unit: fan, filters, compressor, evaporator, condenser, short capillary tube, and controls.

BASICS OF HEAT PUMP AND HEAT RECOVERY

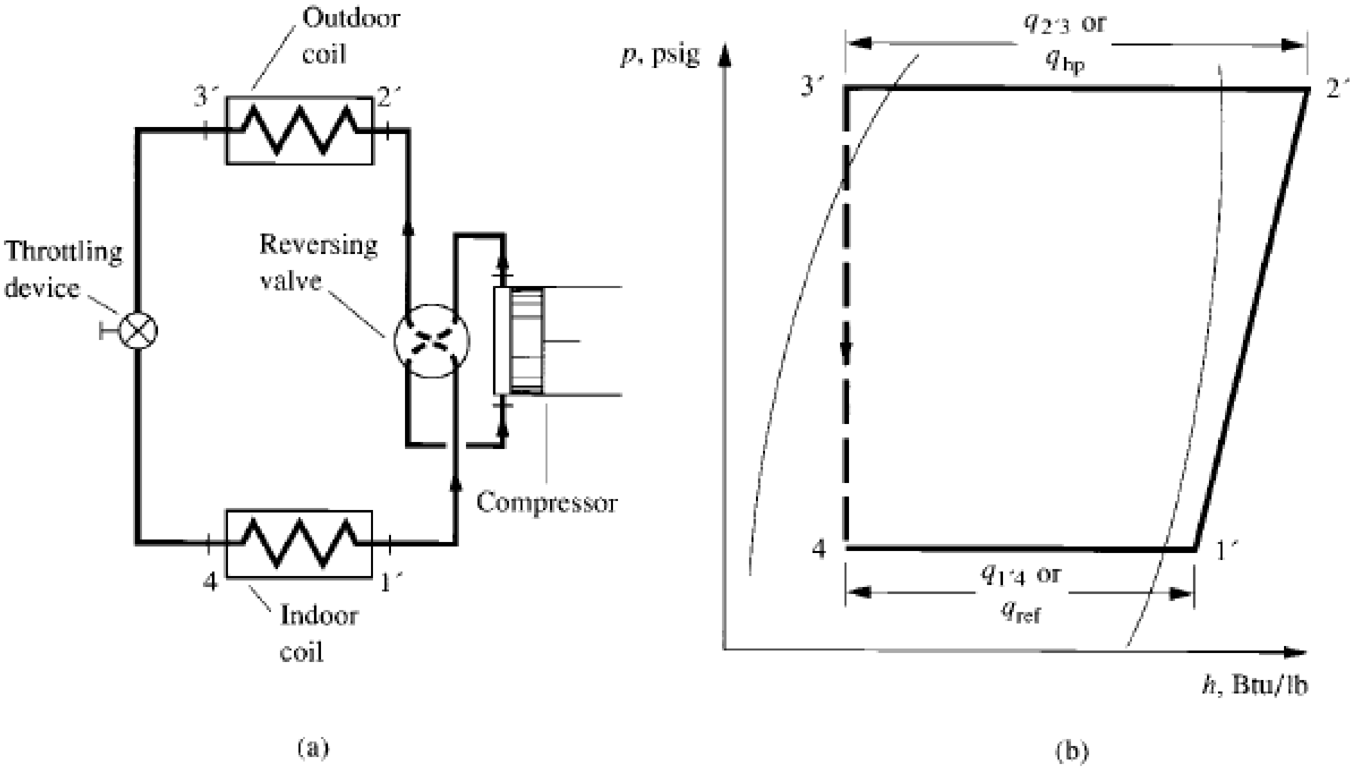
- The apparatus for changing from cooling to heating or vice versa is often a reversing valve, in which the refrigerant flow to the condenser is changed to the evaporator. Alternatively, air passage through the evaporator may be changed over to passage through the condenser.

- A supplementary heater is often provided when the heat pump capacity does not meet the required output during low outdoor temperatures.

- A heat pump system consists of heat pumps and piping work; system components include heat exchangers, heat source, heat sink, and controls to provide effective and energy-efficient heating and cooling operations.

Heat Pump Cycle

$$\text{COP}_{\text{ref}} = \frac{h_{1'} - h_4}{W} = \frac{q_{1'4}}{W_{\text{in}}}$$



- Here polytropic compression is a real and irreversible process. Both the sub-cooling of the liquid refrigerant in the condenser and the superheating of the vapor refrigerant after the evaporator increase the useful heating effect q23. Excessive superheating, which must be avoided, leads to a too-high hot-gas discharge temperature and to a lower refrigeration capacity in the evaporator.

Classification of Heat Pumps

- **According to the types of heat sources from which heat is absorbed by the refrigerant, currently used heat pump systems can be mainly classified into two categories: air-source and water-source heat pump systems. Water-source heat pumps can again be subdivided into water-source, groundwater, ground-coupled, and surface water heat pump systems.**

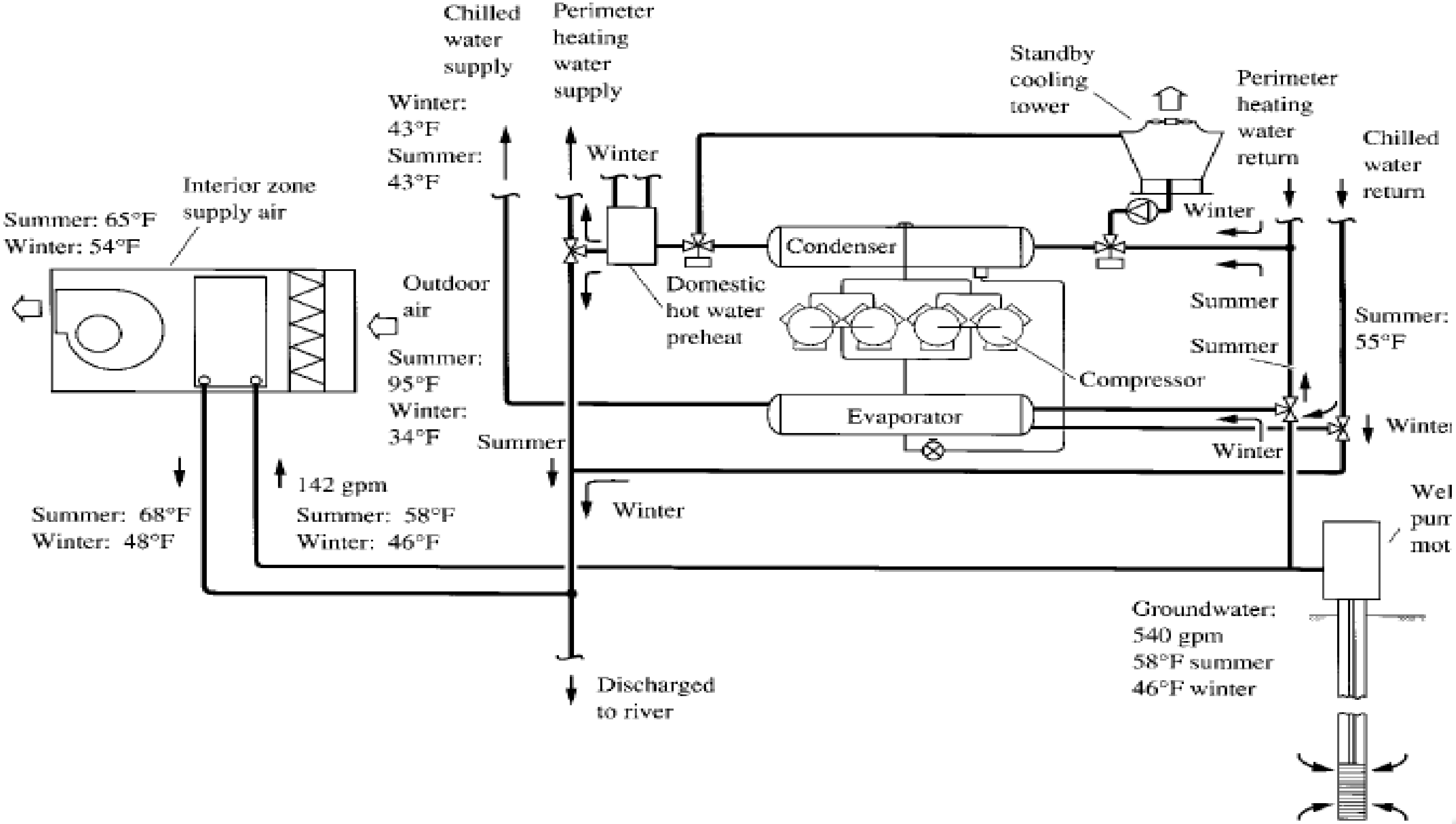
- **Heat pump systems are often energy-efficient cooling/heating systems. Many new technologies currently being developed, such as engine-driven heat pumps, may significantly increase the system performance factor of the heat pump system. Ground-coupled heat pumps with direct-expansion ground coils provide another opportunity to increase the COP of the heat pump system.**

GROUNDWATER HEAT PUMP SYSTEMS

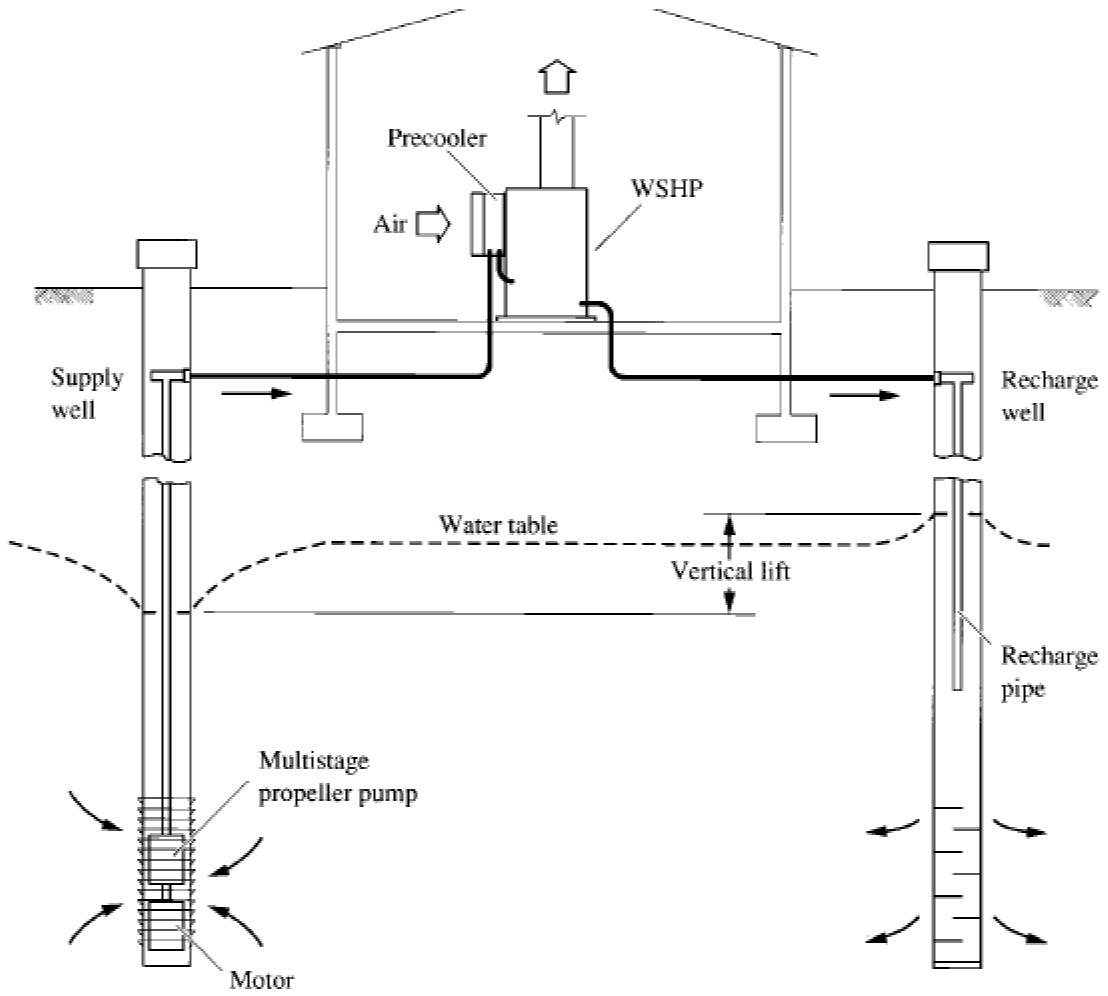
- Groundwater heat pump (GWHP) systems use well water as a heat source during heating and as a heat sink during cooling. When the groundwater is more than 30 ft (9 m) deep, its year-round temperature is fairy constant. Groundwater heat pump systems are usually open-loop systems.

- They are mainly used in low-rise residences in northern climates such as New York or North Dakota. Sometimes they are used for low-rise commercial buildings where groundwater is readily available and local codes permit such usage.

A typical groundwater heat pump system for a hospital.



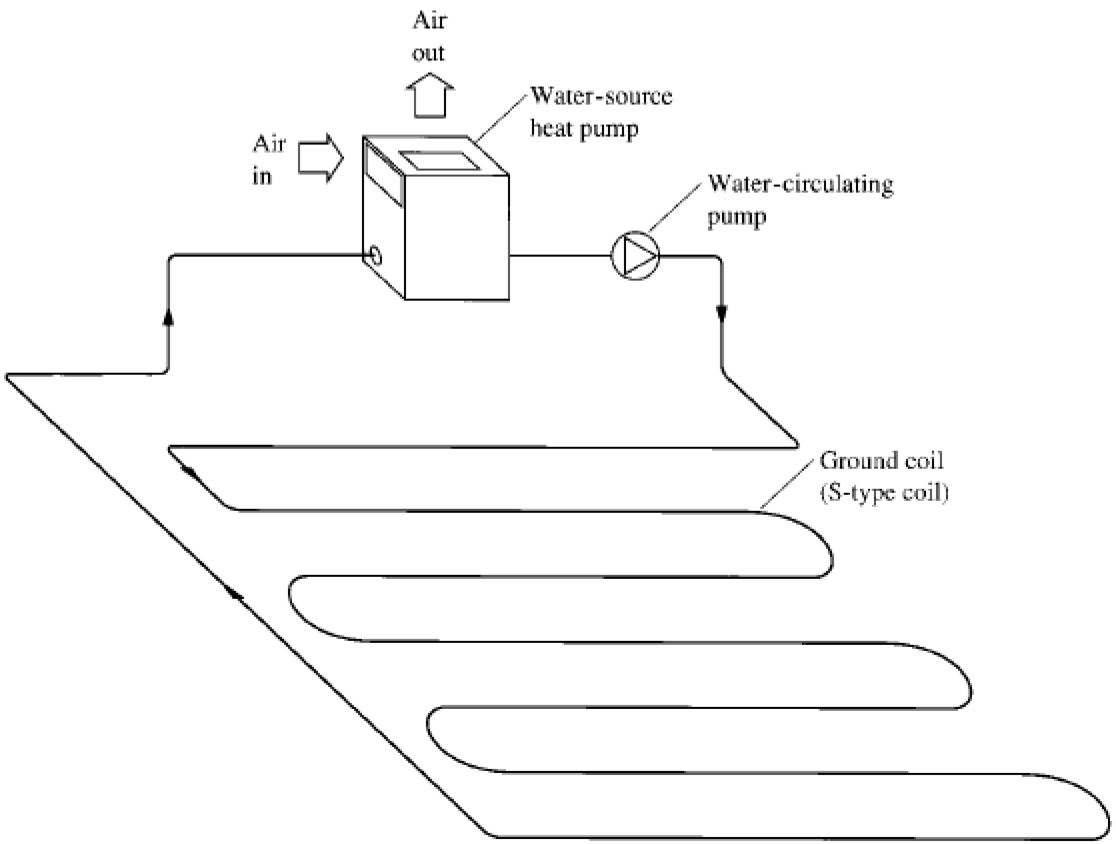
A typical residential groundwater heat pump system.



GROUND-COUPLED AND SURFACE WATER HEAT PUMP SYSTEMS

- **Ground-coupled heat pump systems can be categorized as ground coil heat pump systems and direct-expansion ground-coupled heat pump systems. Of the ground coil heat pump systems, both horizontal and vertical coils are used. Many types of direct-expansion ground-coupled heat pump systems are still being developed. In fact, horizontal ground coil heat pump systems are the most widely used ground-coupled heat pump systems.**

GROUND-COUPLED AND SURFACE WATER HEAT PUMP SYSTEMS



AIR-TO-AIR HEAT RECOVERY

- In HVAC&R systems, it is always beneficial if the cooling effect of the exhaust air can be used to cool and dehumidify the incoming outdoor air during summer, and if the heating effect can be used o heat the cold outdoor air during winter. Air-to-air heat recovery is used to recover the cooling and heating energy from the exhaust air for the sake of saving energy.

- In an air-to-air heat recovery system, the exhaust air is the airstream used to provide cooling capacity or heating energy. The other airstream used to extract heat energy from or release heat energy to the exhaust airstream is the outdoor airstream, which has a greater temperature and enthalpy difference between these airstreams than the supply airstream

FAN FUNDAMENTALS

- A fan is the prime mover of an air system or ventilation system. It moves the air and provides continuous airflow so that the conditioned air, space air, exhaust air, or outdoor air can be transported from one location to another through air ducts or other air passages.

$$R_{com} = \frac{p_{dis}}{p_{suc}}$$

- A blower is usually an enclosed multiblade rotor that compresses air to a higher discharge pressure. There is no clear distinction between a fan and a blower. Traditionally, blowers do not discharge air at low pressure as some fans do.

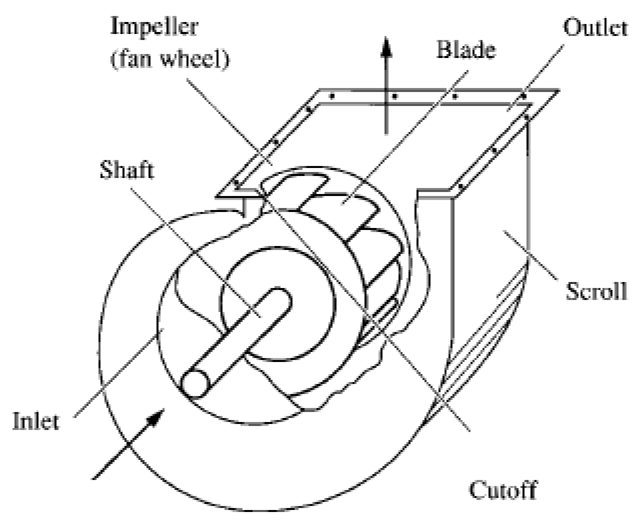
- A fan is driven by a motor directly (direct drive) or via belt and pulleys (belt drive). Some large industrial fans in power plants are driven by steam or gas turbines.

FAN FUNDAMENTALS

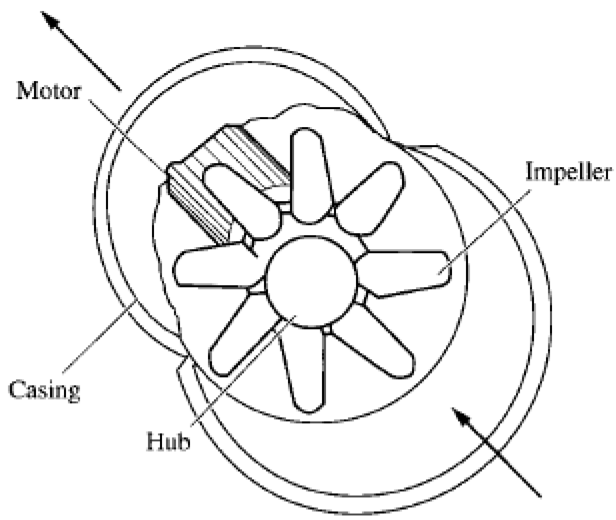
- Two types of fans are widely used in air conditioning and ventilation systems: centrifugal fans and axial fans. Fans can be mounted individually as ventilating equipment to provide outdoor air or air movement inside a building. They can also transport air containing dust particles or material from one place to another via air duct systems. In air conditioning systems, fans are often installed in air-handling units, packaged units, or other air conditioning equipment.

- In both centrifugal fans and axial fans, the increase of air static pressure is created by the conversion of velocity pressure to static pressure. In centrifugal fans, air is radially discharged from the impeller, also known as the fan wheel air turns 90° from its inlet to its outlet.

FAN TYPES



(a)



(b)

Types of fans: (a) centrifugal; (b) axial

FAN SELECTION

- **Pressure-volume flow operating characteristics: Selecting a fan to provide the required volume flow rate and total pressure loss for an air system or a ventilating system is of prime importance. Direction of rotation and discharge position for centrifugal fans. An undersized fan results in an uncontrolled indoor environment. An oversized fan wastes energy and money.**

- **Fan capacity modulation: A variable-air-volume system operates at a reduced volume flow rate during part-load operation. Effective and economical fan capacity modulation is an important factor that affects the operation of an air system.**

FAN SELECTION

- **Fan efficiency: Fan efficiency is closely related to the energy consumption of an air system. Fans should be selected so that they can operate at high efficiency during as much of their operation time as possible.**

- **Sound power level: Most commercial and public buildings and many industrial applications need a quiet indoor environment. Fans are the major source of noise in an air system. Usually, the higher the fan total efficiency, the lower the sound power level of the selected fan. A fan with a low sound power level and sound power level at high frequencies is preferable. High-frequency sound is more easily attenuated than low-frequency sound.**

FAN FUNDAMENTALS

- **Airflow direction: In many applications, a straight-through or in-line flow occupies less space and simplifies layout.**

- **Initial cost: The initial cost of the fan modulation device, sound attenuator(s), and space occupied by a particular type of fan, in addition to the cost of the fan itself, should be considered.**

Air Filtration and Industrial Air Cleaning

- **Air cleaning is the process of removing airborne particles present in the air. It can be classified into two categories: air filtration and industrial air cleaning. Air filtration involves the removal of airborne particles present in outdoor air as well as recirculated air from a given space.**

- **Most airborne particles removed by air filtration are smaller than 1 m, and the concentration of these particulates in the conditioned airstream is often less than 2 mg/m^3. The purpose of air filtration is to benefit the health and comfort of the occupants in the conditioned space as well as maintain the cleanliness required in manufacturing processes. Air filtration is one of the essential factors that affects the indoor air quality of the conditioned space.**

Air Filtration and Industrial Air Cleaning

- **Industrial air cleaning mainly involves the removal of dust and gaseous contaminants from the industrial manufacturing processes, and it provides pollution control to the exhaust gas and flue gas.**

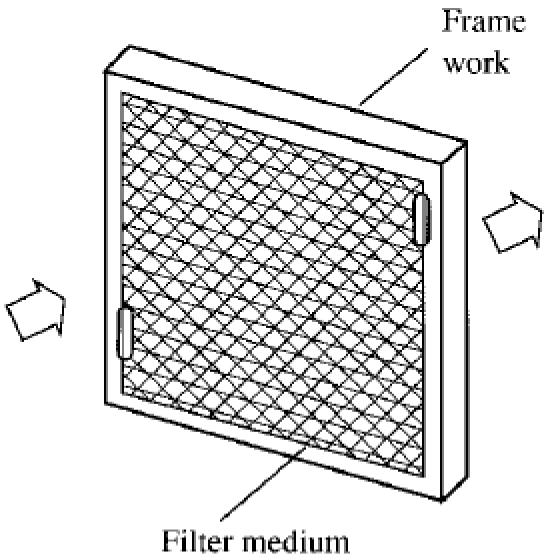
- **Air contaminants that are discharged to the outdoor environment are governed by the U.S. Environmental Protection Agency (EPA), and those that are exhausted to the indoor working space are regulated by the Occupational Safety and Health Administration (OSHA).**

The removal or collection of dust particles in air filtration is performed by various combinations of the following mechanisms.

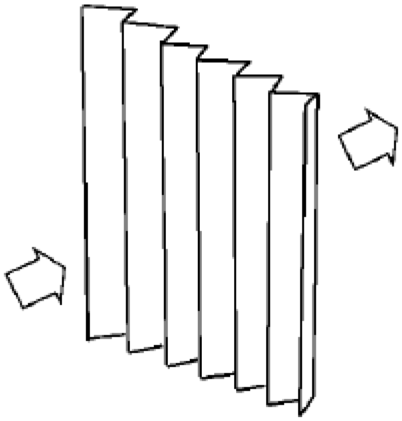
- **Inertial impaction:** A sudden change in direction causes a collision between the dust particles, and fibrous media.
- **Straining:** If the filter spaces are smaller than the size of the dust particles, the particles are trapped.
- **Diffusion:** For very fine dust particles, brownian movement causes the particles to settle.
- **Interception:** Dust particles may follow the airstream, contact the fibrous media, and remain there.
- **Electrostatic effects:** Particles and the filter medium are charged to collect the dust in the airstream.

FILTER TYPES

PANEL FILTER:

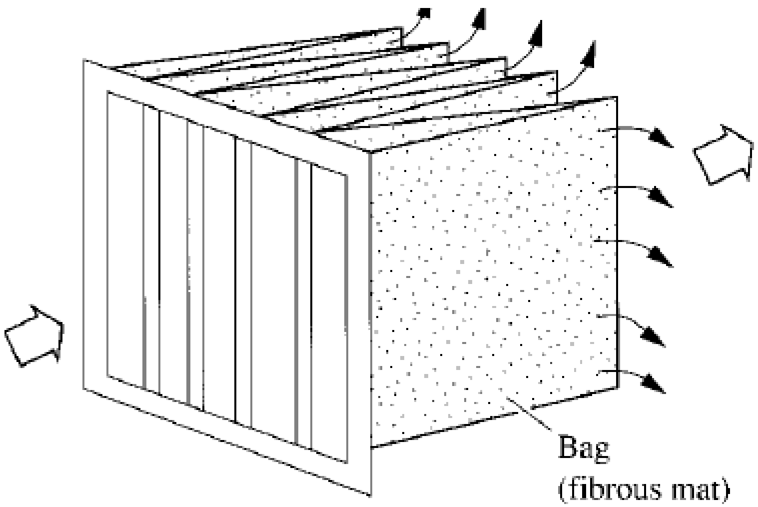


PLEATED FILTER

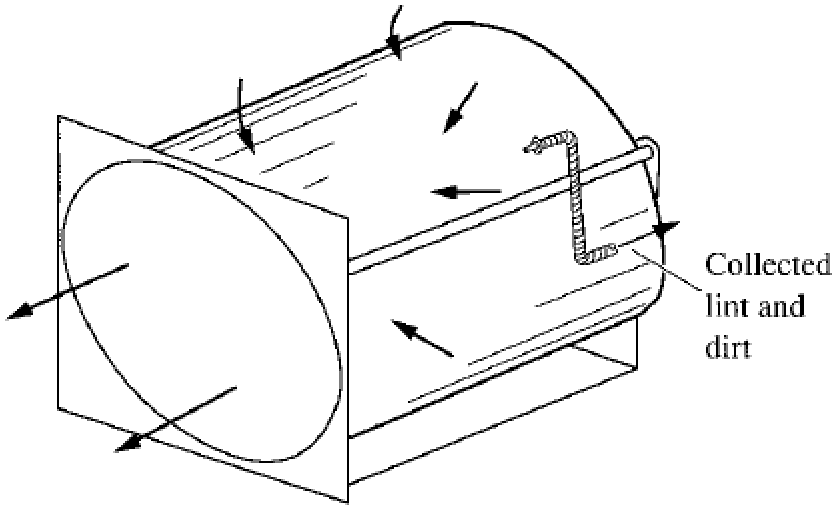


FILTER TYPES

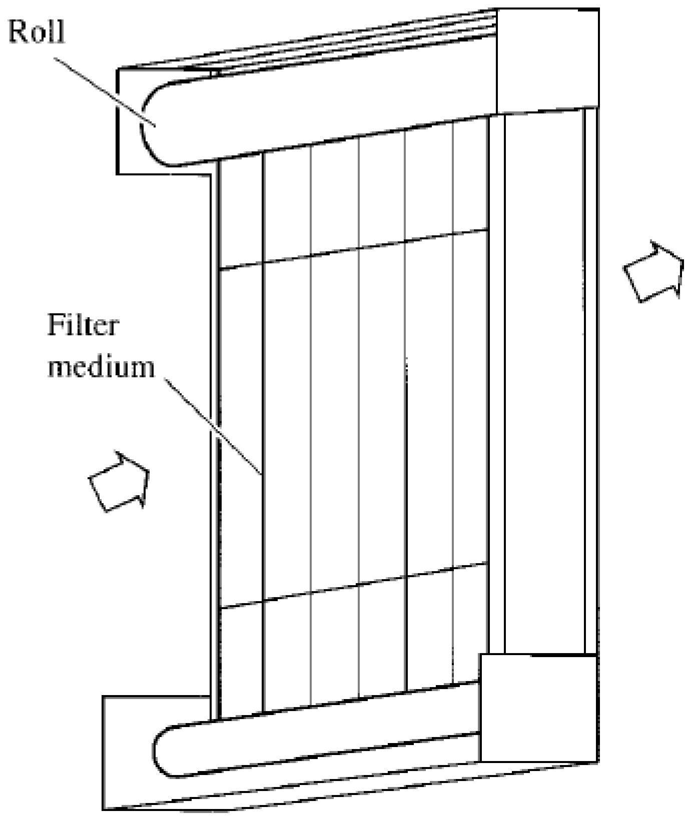
EXTENDED SURFACE FILTER



ROTARY FILTER

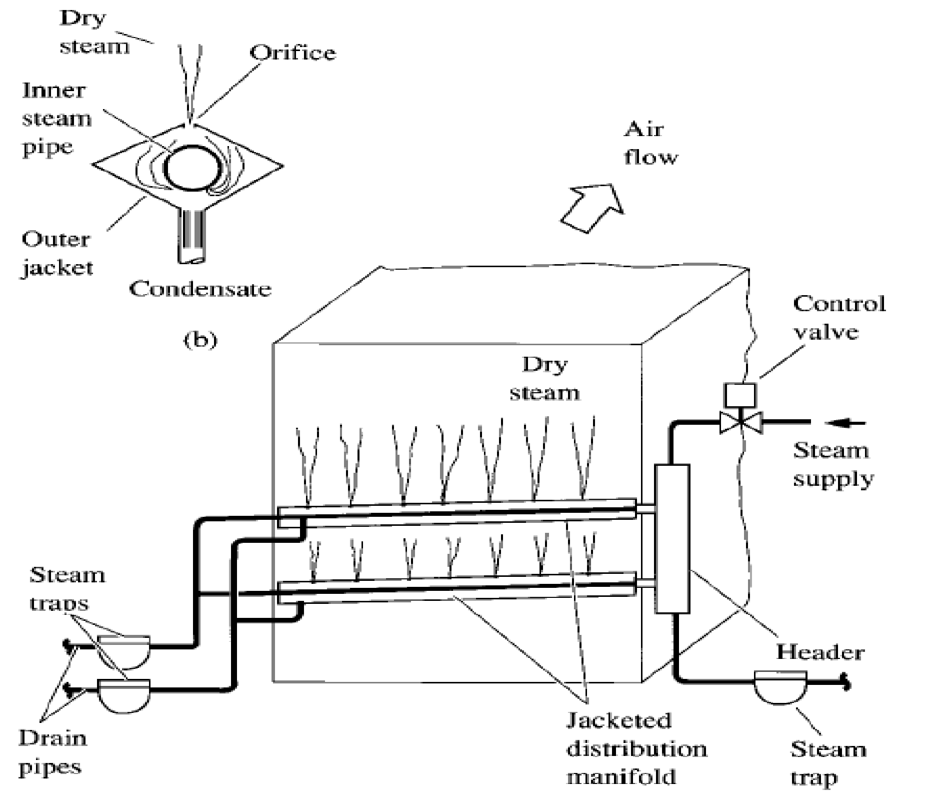


AUTOMATIC RENEWABLE ROLLING FILTER



Steam Grid Humidifiers

- A steam grid humidifier installed inside ductwork is shown in Fig. A steam grid humidifier may have a single distribution manifold or multiple manifolds.

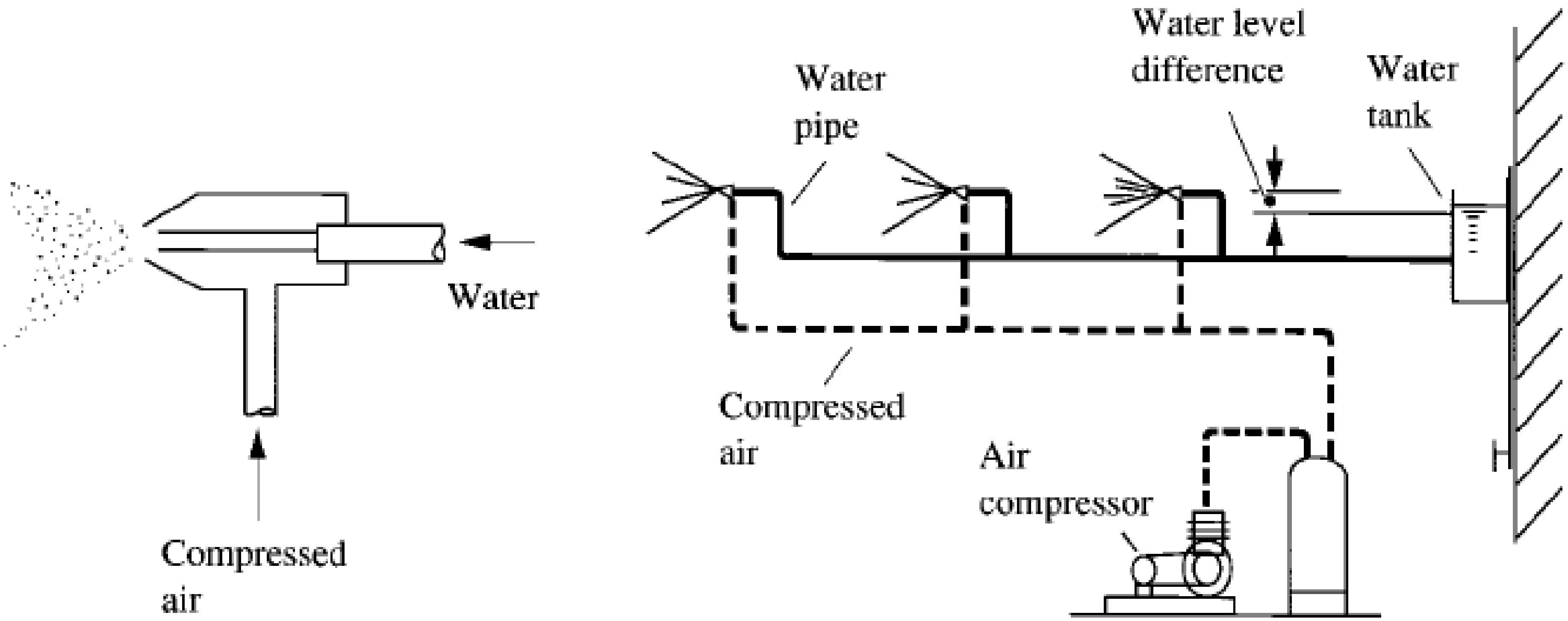


Wetted Element Humidifiers

- Wetted element humidifiers include a wetted element, such as an evaporative pad, plastic, or impregnated cellulose, that is dipped with water from the top. Such humidifiers have been installed in air-handling units and packaged units to humidify the air.

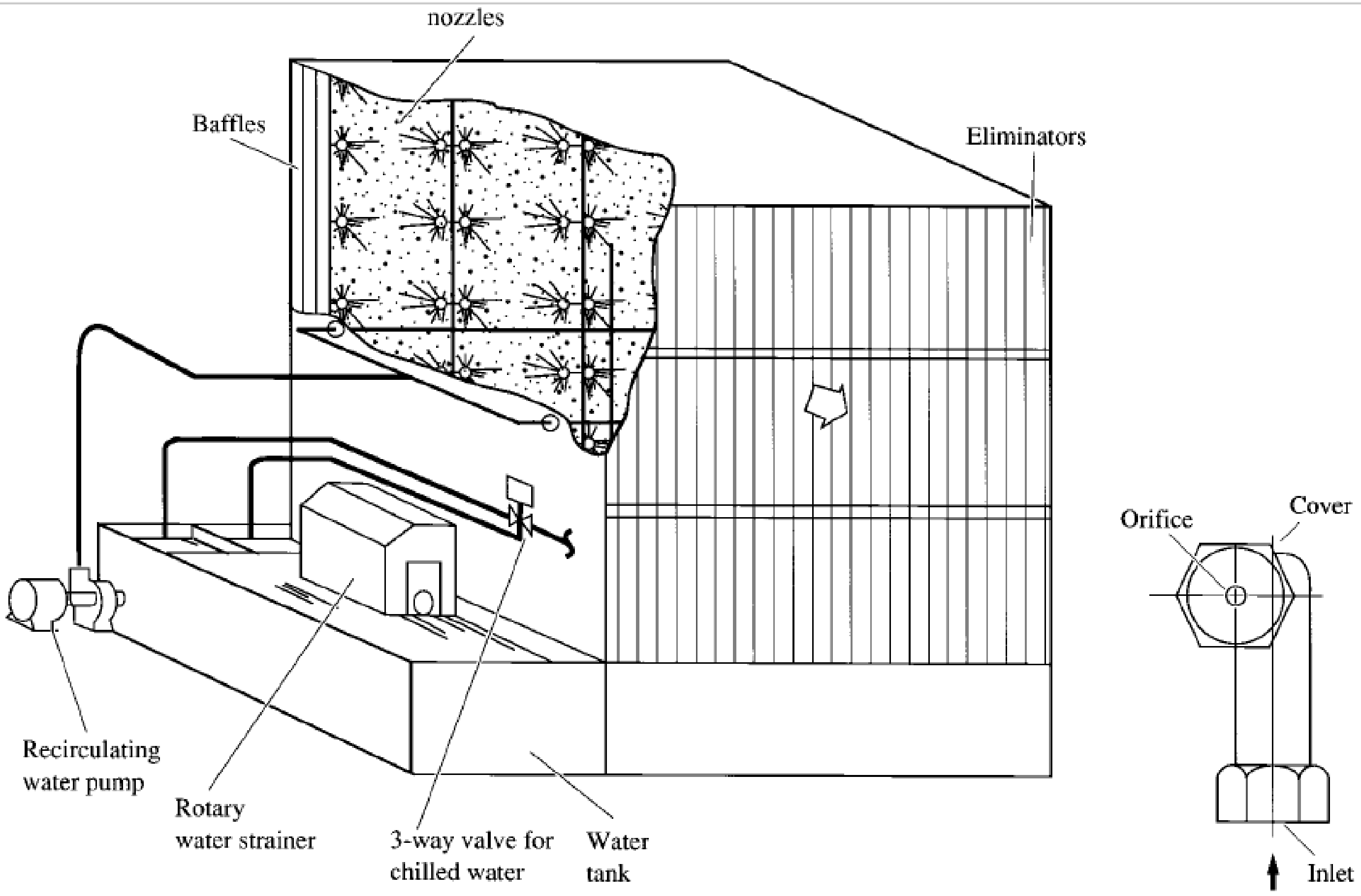
- Characteristics of wetted element humidifiers are similar to those of wetted element evaporative coolers. Modulation of the water supply to the water dipping device varies the humidifying capacity and maintains the desirable space relative humidity.

Pneumatic Atomizing Humidifier



AIR WASHERS

- The air washer was the first air conditioning equipment developed by Carrier in 1904, and it is still used today to humidify, cool, and clean the air in many factories.



Functions of an Air Washer

- Currently, air washers are used to perform one or more of the following functions:
  - Cooling and humidification
  - Cooling and dehumidification
  - Washing and cleaning

- Whether it is a cooling and humidification or cooling and dehumidification process is determined by the temperature of the spraying water.

- If recirculating water is used as the spraying water, the temperature of water then approaches the wet-bulb temperature of the air entering the air washer, and the air is humidified and evaporatively cooled.


Thank you