# UNIT 7 REFRIGERATION AND AIR-CONDITIONING

## Structure



## 7.1 INTRODUCTION

Creation of a temperature below normal temperature has been established as a need of human being. There are two reasons for it. Firstly, there are eatables which do not last long at normal temperature but survive at sufficiently low temperature. Secondly, at many geographical locations, the atmospheric temperature is too high to make living and working comfortable. When man became capable of creating low temperature then arose many other needs that could be satisfied by such devices. Refrigeration is commonly used to preserve food over days in home, over months in cold storage, for supplying cold water and beverages, for storing medicines in stores and in homes and many more things. The same device can be used in industry for preservation of chemicals and intermediary products. In medical practices the devices of low temperature are used to preserve samples of blood etc. for the period of testing.

Space cooling and maintaining certain air quality and circulation became the byproduct of low temperature creation. This practice is known as air-conditioning, and covers not only cooling of air but also maintaining moisture, odour and speed of circulation in closed space. Like refrigeration, air-conditioning also has found its use both in home and industry and with human being spending sufficient time in travel, air-conditioning has become an important component in automobiles, trains, ships and aeroplanes.

## Objectives

After studying this unit, you should be able to know and explain

- the basics of refrigeration,
- the various components of refrigerating system,
- the cycles of refrigeration,
- the types of refrigerator,
- the quality of air,
- the controlling of quality in air-conditioning, and
- the plants of air-conditioning system.

## 7.2 REFRIGERATION CYCLE

Refrigeration can be easily regarded as reverse process of an engine. Carnot cycle is a reversible cycle and hence can be used as a refrigeration cycle. Figure 7.1 shows a reversed Carnot cycle.

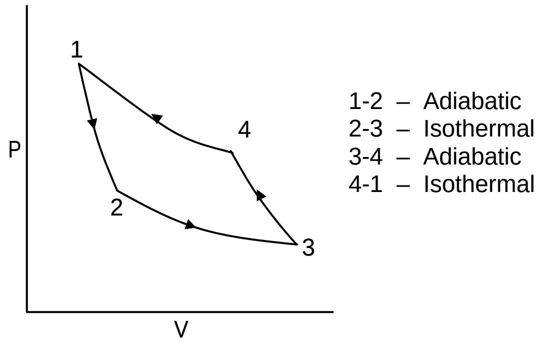



**Figure 7.1 : Reversed Carnot Cycle**

Air in space of cylinder is expanded adiabatically from 1 to 2, reducing temperature from $T_1$ to $T_2$. It is further expanded isothermally and during this expansion heat is absorbed from colder body at temperature $T_2$. The air is then compressed adiabatically in the cylinder for which work is supplied from outside. The temperature of the air rises from $T_2$ to $T_1$. Finally, air is isothermally compressed to pressure $p_1$.

Heat is removed from colder body during isothermal process 2-3. This heat

$$Q_{23} = RT_2 \ln \frac{V_3}{V_2}$$

The heated and compressed air rejects heat at $T_1$ to the hot body during isothermal compression 4-1.

$$Q_{41} = RT_1 \ln \frac{V_4}{V_1}$$

The work supplied is the difference of these two heats, $Q_{23} - Q_{41}$.

The *refrigeration effect* is the heat removed from colder body, i.e. $Q_{23}$.

The *coefficient of performance* of a refrigeration system is defined as the ratio of refrigerating effect/mechanical work.

$$\therefore \qquad COP = \frac{Q_{23}}{Q_{23} - Q_{41}}$$

$$= \frac{RT_2 \ln \left(\frac{V_3}{V_2}\right)}{RT_2 \ln \left(\frac{V_3}{V_2}\right) - RT_1 \ln \left(\frac{V_4}{V_1}\right)}$$

or $$COP = \frac{T_2}{T_2 - T_1} \qquad \text{. . . (7.1)}$$

Note that $$\frac{V_3}{V_2} = \frac{V_4}{V_1}$$

Yet another cycle used in air refrigeration is Bell-Colman or Brayton cycle. This in effect is reversed Joule cycle. The cycle is shown in Figure 7.2. Expansion and compression processes take place in separate cylinders. The work obtained during

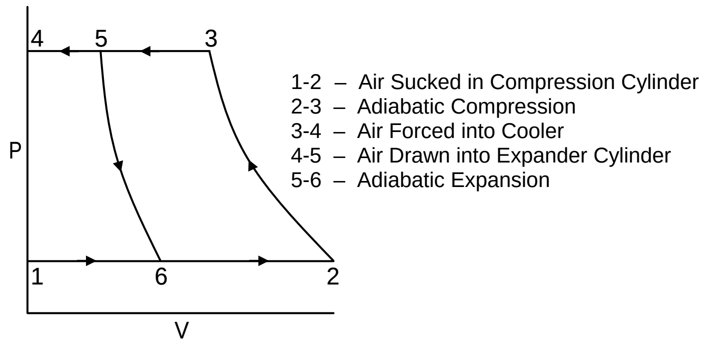



**Figure 7.2**

expansion is used to compress the air. The heat is abstracted from the cold body during part of the suction, i.e. 6-2, which is a constant pressure process.

$$Q_{62} = Cp\,(T_2 - T_6) = \text{Refrigerating effect}$$

The air is cooled in the cooler when it is forced into it at constant pressure during the process. The heat rejected to the cooler is $Q_{35} = Cp\,(T_3 - T_5)$. No heat is exchanged during adiabatic compression (2-3) and adiabatic expansion (5-6). Hence work supplied is

$$W = Q_{62} - Q_{35}$$

$$\therefore \qquad COP = \frac{Q_{62}}{Q_{62} - Q_{35}} = \frac{T_2 - T_6}{(T_2 - T_6) - (T_3 - T_5)} \qquad \text{. . . (7.2)}$$

The volume ratios of expansion and compression are same, i.e.

$$\frac{V_3}{V_2} = \frac{V_5}{V_6}$$

With the help of gas equation and equation for adiabatic process the relationship between temperatures can be established.

The above description only serves to show that air can be used as a medium in a refrigeration system. Such systems were used in earlier days but at the present time those media which readily change their states between liquid and vapour are preferred.

## 7.3 VAPOUR COMPRESSION REFRIGERATION

The vapour compression system of refrigeration will comprise four basic components :

(a) compressor,

(b) condenser,

(c) expansion device, and

(d) evaporator.

Into the compressor enter the vapours of the *refrigerant.* Compressor raises the pressure of the vapour such that the saturation temperature of the refrigerant is slightly above the temperature of the cooling medium used in the condenser. The condenser exchanges heat between vapour and cooling medium, the latter gains heat. The vapour condenses in the condenser and may leave it as saturated liquid or at temperature which is below the saturation temperature (subcooled liquid). Typical cooling media used in condenser are air and water. After leaving condenser the high pressure liquid expands in the expansion valve to a lower pressure. Expansion device can be capillary tube or a short tube orifice which are passive devices. Electronic thermal expansion valves may also be used and they are active devices. At the end of the expansion valve the refrigerant at a fairly low pressure is at a temperature which is lower than that of the product to be cooled. It may be a two-phase fluid with low quality and enters the evaporator which is in contact with the product or environment to be cooled. The refrigerant is able to absorb its latent heat from the surrounding and is converted in vapour which may be saturated or superheated. This vapour then enters the compressor which must keep sucking the vapour at sufficient rate to maintain a low pressure in the evaporator and this will keep the cycle going.

In this process, we have assumed that evaporator is in contact with the product or the environment to be cooled. Sometimes a *secondary refrigerant* may surround or flow around the evaporator and thus losing its heat to the evaporator. The cooled secondary refrigerant may be taken away through pipelines to other place for cooling purposes. The secondary refrigerant does not undergo compression and evaporation and normally is brine. The secondary refrigerant provides ease of control.

The vapour compression system is shown in Figure 7.3. Three places or components in the system must be identified very distinctly.

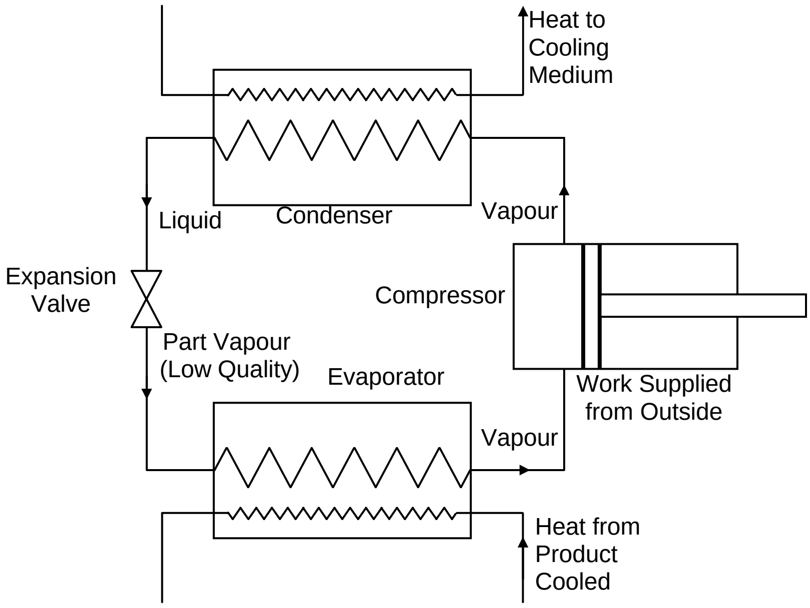



**Figure 7.3 : A Vapour Compression Refrigeration System**

## Evaporator

Heat is gained by the refrigerant in the evaporator. The product is cooled. The amount of heat lost by the product is called *refrigeration effect* ($H$). This refrigerating effect is used to define the capacity of the refrigerating system.

## Compressor

Compressor is run by work supplied from outside. The pressure and hence energy of the refrigerant (vapour) is increased, call it $W$.

## Condenser

The condensation of the vaopur is effected by exchanging heat with a cooling medium. The heat of cooling medium can further be used or just thrown into atmosphere. The system can be used in tandem, i.e. the refrigerating effect at evaporator and heating effect at condenser, both, are made useful. However, if only heat effect is used the system is regarded as heat pump. Call this heat as $Q$.

The performance of the refrigerating system is measured by *coefficient of performance* which has been defined earlier.

$$\text{COP} = \frac{\text{Refrigerating Effect}}{\text{Work Supplied}} = \frac{H}{W}$$

If system works as a heat pump

$$\text{COP} = \frac{\text{Heating Effect}}{\text{Work Supplied}} = \frac{Q}{W}$$

The state of the medium (refrigerant) undergoing cyclic variation in various properties can be described by any two of the state variables. In earlier studies we have found $p$ and $V$ as convenient variables to represent the state and it was convenient since the medium in most cases was homogeneous gas. However, in case of refrigeration cycle the medium (refrigerant) changes state and $p$ and $V$ may not be good representative properties. The two pairs that are commonly used in the study of refrigeration are temperature and entropy ($T$ and $S$) and pressure and enthalpy ($p$ and $h$).

### 7.3.1 Representing Cycle on T-S and p-h Charts

Figure 7.4 represent a typical T-S diagram for a refrigerant whereas Figure 7.5 represents a typical p-h diagram.

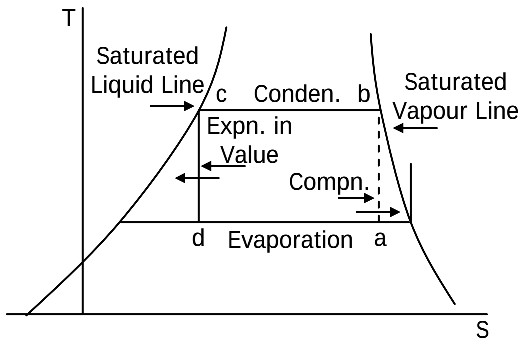



**Figure 7.4 : T-S Diagram of a Refrigeration Cycle (Vapour Compression)**

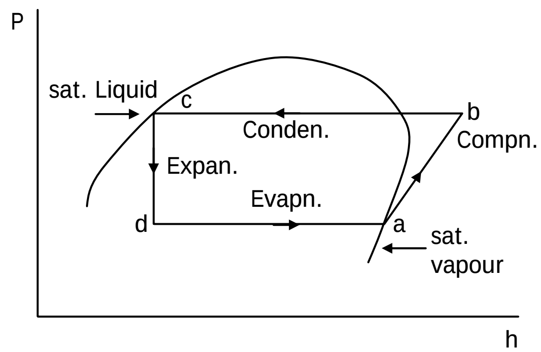



**Figure 7.5 : p-h Representation of Vapour Compression Refrigeration Cycle**

It can be noted that both evaporation and condensation are constant temperature and constant pressure processes (change of state). Evaporation may not produce saturated vapour in which case point *a* will be left to the saturated vapour line or it may be a superheated vapour in which case it will be to the right. After compression to point *b* the vapour may be just saturated (Figure 7.4) or superheated (Figure 7.5). Similarly, after passing through condenser the refrigerant may be very wet vapour, saturated liquid or sub cooled liquid. In each case proper conditions of state are to be considered.

Standard p-h charts for different commercially available refrigerants are provided by the manufacturers of the refrigerants. We will leave the description of properties of refrigerant for a latter course. We can, however note that

$$\text{Refrigerating effect, } H = h_a - h_d$$

$$\text{Work of compression, } W = h_b - h_a$$

$$\text{Heat taken away in Condn., } Q = h_b - h_c$$

$$\therefore \text{ COP of Refrigeration} = \frac{h_a - h_d}{h_b - h_a}$$

$$\text{and COP of heat pump} = \frac{h_b - h_c}{h_b - h_a}$$

### 7.3.2 Types of System

Refrigeration systems are classified as *closed* and *open*. In a closed system, same quantity of refrigerant goes round the system time over and again. If the refrigerant leaks the system fails to work. In an open system the refrigerant passes through the system only once. The refrigerant is used as a product or feed stock outside the refrigeration system. In separating heavier compounds from natural gas an open system is used. Heavier compounds condense and are separated.

Yet another classification of the refrigeration system is *simple cycle* and *compound cycle*. The cycle described in this section is simple. In compound cycle two or more simple cycles are compounded in such a way that evaporator of one takes away the heat of condensation of the other. For producing very low temperature compound cycles are used.

## 7.4 REFRIGERATION CAPACITY

This capacity has already been defined. The capacity of a refrigeration system is traditionally expressed in ton of refrigeration or TR. It basically refers to heat removed from the body to be cooled. But one TR has been standardized as heat of fusion of 1 T (907.19 kg) of ice at $0^o$ C over a period of 24 hours. This heat is 303.85 MJ. If converted to per second, the refrigeration capacity of 1 T is 3.5168 kW. The number of such tons produced by a refrigerating system is called the *standard capacity*. For practically measuring the standard capacity (or standard rating) following conditions are required to be maintained.

(a) Liquid only enters the expansion valve and vapour only enters the compressor.

(b) Liquid entering the expansion valve is subcooled $5^o$C and the vapour entering the compressor is superheated $5^o$C. These temperatures are to be measured within 3.05 m of the compressor cylinder.

(c) The pressure at the compressor inlet corresponds to a saturation temperature of $-15^o$C.

(d) The pressure at the compressor outlet corresponds to a saturation temperature of $30^o$C.

## 7.5 REFRIGERANTS

Very brief note on this topic is included for the sake of completeness.

History tells us that air, $CO_2$, $SO_2$ and $NH_3$ have been used as refrigerant. Out of these $SO_2$ and $NH_3$ are not tolerated by human being. A breakthrough occurred in 1930 when chloro fluro carbon (CFC) compounds were invented in General Motors of USA. From that time until recently CFC dominated the scene of refrigeration though these compounds also found additional application as cleaner of electronic and computer parts. Scientific evidence collected during decade of 1980-90 proved that CFC can cause depletion of ozone layer besides being proven greenhouse agent. The Montreal protocol that became effective in 1990 put a ban on use and production of CFC (chlorofluorocarbons). The proposed replacements are fluorocarbon (no chlorine) hydro chlorofluorocarbon (HCFC), $CO_2$, butane, isobutene, propane. Additionally some mixtures of old refrigerants are also being proposed.

Commercially refrigerant are identified by a number preceded by letter R. Thus R10, R11, R12, R13 and R113 and R114 are famous CFC substances which stand banned. R 50 is methane while R170 is ethane. Butane and iso-Butane are R 600 and R 600 a. $NH_3$ is R 717 while $CO_2$, known as R 744.

The properties for which we look in a refrigerant are :

(a) high latent heat, and

(b) evaporation and condensation near atmospheric pressure.

The first will cause the lesser amount of refrigerant to be required in the process, thus lesser displacement in compressor. The second will reduce compressor work.

Besides above two properties, a refrigerant should be non-toxic and non-damaging to metals, materials, food and environment. Dichloro-difluoro methane ($CCl\ F_2$), commercially known as Freon 12 or R-12 is clear, colourless liquid which boils at – 29.8$^o$C at atmospheric pressure. It is non-toxic, non-flammable, hence was highly preferable as refrigerant. It further has good miscibility with lubricants and good electric insulation. Table 7.1 describes a few refrigerants.

**Table 7.1 : Properties of Refrigerants**

| Refrigerant | Boiling pt. Temp (Atm Pressure) ($^o$C) | Spec. vol. At – 15$^o$C ($m^3$/kg) | Latenet heat at – 50$^o$C (kJ/kg) | Compr. Displ. Per T of Refrign. ($m^3$) | kW per T of Refrign |
|---|---|---|---|---|---|
| $NH_3$ (R 717) | – 33.3 | 0.51 | 1310 | 5.83 | 0.74 |
| $CO_2$ (R 744) | – 78.5 | 0.017 | 272 | 1.63 | 1.38 |
| $SO_2$ (R 764) | – 10.0 | 0.406 | 393.5 | - | 0.746 |
| CFC ( R 11) | – 29.8 | 0.093 | 161.3 | 9.85 | 0.75 |
| CFC ( R 22) | – 41.3 | 0.078 | 216.7 | 5.85 | 0.76 |

## 7.6 ABSORPTION SYSTEM

The first machine of this type was built in 1859. The system employed an ammonia/water solution. Another mixture of lithium bromide and water is also being employed now. $NH_3$/water absorption refrigerant system is successfully used in small refrigerators and chillers.

The system consists of an *absorber* A in which dry $NH_3$ vapour and weak $NH_3$ solution in water mix to produce strong $NH_3$ solution.

Another component of the system is the *interchanger* I in which heat from hot weak $NH_3$ solution is transferred to strong $NH_3$ solution from absorber. A pump P is used to draw strong $NH_3$ solution from absorber.

*Separator S* receives strong $NH_3$ solution which has been somewhat heated in interchanger. The solution is further heated from a heat source and separates $NH_3$ vapours from the strong $NH_3$ solution. If this vapour carries any moisture it is separated by passing through a *rectifier R*.

*Condenser C* receives hot and dry $NH_3$ vapour at a high pressure of 10 bar, and causes vapour to condense in liquid state at that pressure.

*Expansion Valve* (*EV*) throttles the high pressure liquid from 10 bar to 1.7 bar whereby ammonia vapour is cooled considerably, and becomes partly wet.

The partly wet ammonia vapour then passes into the evaporator E where it is dried and abstracts heat from surrounding, thus producing the refrigeration effect. The dry $NH_3$ then passes into the absorber.

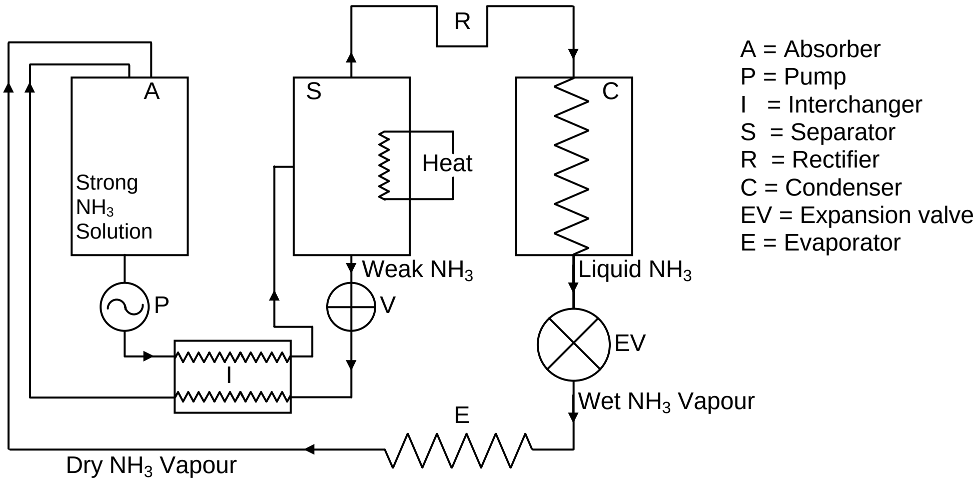



**Figure 7.6 : Absorption Refrigeration System**

Figure 7.6 shows the absorption cycle with all components marked. The energy in form of work ($W$) is supplied at pump $P$ and in form of heat ($Q$) in the separator. The refrigeration effect ($H$) is obtained at evaporator.

Hence, $$COP = \frac{H}{W + Q}$$

## 7.7 $NH_3$-$H_2$ REFRIGERATION SYSTEM

In this system, pump and expansion valve are not used. To facilitate the evaporation of high pressure liquid in the evaporator it is filled with hydrogen. The liquid $NH_3$ evaporates in the presence of $H_2$ and mixture flows into the absorber. From absorber the strong $NH_3$/water solution flows under gravity to the separator and on its way gains heat in the interchanger. The heater in the separator separates hydrogen from the solution. The hydrogen flows into evaporator. The weak $NH_3$/water solution drains into the absorber via interchanger. $NH_3$ vapour through rectifier and having been heated to high pressure passes into condenser. And the high pressure liquid $NH_3$ flows into evaporator where heat is absorbed from surrounding.

Thus, cycle is completed without any mechanical work. This system has been widely used in small refrigerator. The COP of the system will be as given below :

$$\text{COP} = \frac{\text{Heat absorbed in the evaporator}}{\text{Heat supplied in the separator}}$$

### 7.7.1 Advantages of Absorption System

The first advantage of the system is that it does not use CFC or HCFC refrigerant which stand banned at present.

The second advantage is that system can use any heat source. Several low grade energy sources like agricultural and other wastes have been used. Gas flames and electrical heaters are used for domestic refrigerators.

## 7.8 STEAM JET REFRIGERATION

This system uses vapour compression but compressor is not used. In place of compressor a steam jet ejector is used to eject steam from evaporator and to compress it slightly. All the water in the evaporator is not converted into vapour but vapour created cooling effect keeps on reducing its temperature as well. The ejected steam passes into condenser and water from condenser flows to the evaporator.

Though the ejector system is less complicated and does not use external power yet it is much less efficient than the compressor. In some applications the ejected steam may not be reused after condensation but discarded. The minimum temperature achieved in this type of refrigeration is above $0^{o}C$, generally it is $7^{o}C$. The condenser pressure is below atmospheric (~ 7.6 kPa) hence there are chances of air entering the system, which deteriorates the performance. To improve performance additional ejectors are used to extract non-condensable vapours from the condenser.

Steam jet refrigeration is used in process applications where direct vapourization can be used for drying of food and chemicals. The cooling effect produced by steam jet refrigeration reduces process temperature and helps preserve the product. Industries producing fruit juice, freeze dried food and fruits, dehydrated and pharmaceutical products use steam jet refrigeration. This system has been used to cool city gas to separate tar and other objectionable impurities and also in trains and boats.

## 7.9 THERMOELECTRIC COOLING

A temperature differential is created between two junctions of a closed loop formed by two dissimilar metals when an electric current is allowed to pass in the loop. This phenomenon is named as *Peltier Effect*, and is opposite of Joule’s Effect which is the flow of current when two end of loop formed by two dissimilar metals are kept at different temperatures. The capacities of such a systems is small though by cascading capacities have improved and temperatures have been reduced. Capacities of 25 T of thermoelectric refrigeration and temperature of $-166^{o}C$ have been produced.

The COP of thermoelectric refrigeration is very low.

However, in space programme this method has got wide acceptability because of following reasons :

(a) absence of moving parts,

(b) silent operation,

(c) ability to work in zero gravity,

(d) no pressurized vessels.

Electronics equipment, small units such as drinking water cooler and cooling in submarines have also used thermoelectric cooling.

For making loops of two different metals semiconducting materials such as bismuth-telluride-selenide and bismuth-antimony-telluride alloys are employed.

## 7.10 INDIRECT REFRIGERATION

There are several industrial applications of refrigeration and cooling in process heat exchangers is one example. These heat exchangers are designed for corrosive products, high pressures, or high viscosities. These conditions are not suited to evaporators in which refrigerants evaporate. For these reasons the evaporators need be situated away from process load. There may still be other reasons for separation of evaporators from the process load like remote location of the process load which will result in considerable loss of pressure in refrigerant if the evaporator is in contact with the load.

All these situations require what we term as *indirect* refrigeration which means some secondary liquid solution is made to pass through or in contact of evaporator and become cold. This liquid solution then takes heat of the process load by passing around in a kind of heat exchanger as shown in Figure 7.7.

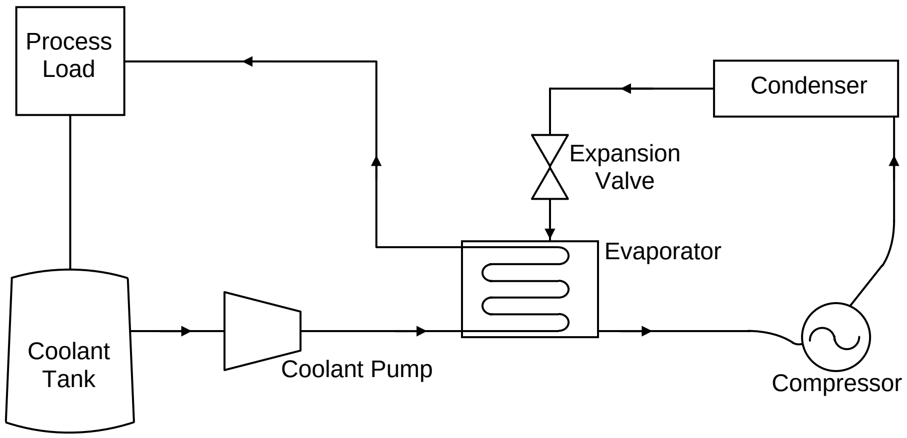



**Figure 7.7 : Indirect Refrigeration**

The secondary refrigerant (brine) is cooled in the evaporator and then pumped to the process load. The secondary coolant may be one of following four categories :

**Coolant with a Salt Base**

These are water solutions of various concentrations and include most common brines like calcium chloride and sodium chloride.

**Coolants with Glycol Base**

These are water solutions of various concentrations of ethylene glycol or propylene glycol.

**Coolants with Alcohol Base**

Alcohol water solutions are used for temperatures not too low.

**Coolants for Low Temperature Heat Transfer**

These are pure substances like methylene chloride, trichlorethylene, R-11, acetone or methanol.

Coolant with calcium chloride and sodium chloride are most commonly used in industrial processes and ice rink.

**Example 7.1**

An ice plant using water at $10^oC$ produces $4.8 \times 10^5$ kg of ice in 24 hours. Plant is supposed to follow Carnot cycle and works between temperatures of $-5^oC$ and highest temperature of $23^oC$. Calculate the capacity of plant in TR and also power required.

Assume ice is formed at $0^oC$ and that the latent heat of freezing of water is 336 kJ/kg and specific heat of water is 4.2 kJ/kg$^oC$.

**Solution**

The cooling or refrigeration effect per minute

= heat removed from water

= heat removed in cooling from $10^{o}$C to $0^{o}$C + latent heat of ice

$$= \frac{4.8\times10^{5}}{24\times60}[(10-0)\ 4.2+336]$$

$= 1.26\times10^{5}$ kJ

Removal of 210 kJ/min is equal to 1 T of refrigeration capacity.

$\therefore$ Capacity of the plant $= \frac{1.26\times10^{5}}{210}$

= 600 TR . . . (i)

The COP of Carnot cycle $= \frac{T_2}{T_1 - T_2}$

where, $T_1$ and $T_2$ are respectively higher and lower temperatures.

$T_1 = 23 + 273 = 296$ K

$T_2 = -5 + 273 = 268$ K

$$\therefore \quad COP = \frac{268}{296-268} = 9.57$$

Also $\quad COP = \frac{\text{Cooling Effect}}{\text{Work Supplied}}$

$$= \frac{1.26\times10^{5}}{\text{W}} = 9.57$$

$$\therefore \quad W = \frac{1.26\times10^{5}}{9.57} = 0.13\times10^{5} \text{ kJ/min}$$

$\therefore$ Power of ice plant = 219.4 kW . . . (ii)

**Example 7.2**

A Carnot cycle machine operates between the temperature limits of $T_1 = 30^{o}$C and $T_2 = -15^{o}$C. Determine the COP when it operates as

(a) a refrigeration machine,

(b) a heat pump, and

(c) and its efficiency if it operates as a heat engine.

**Solution**

$T_1 = 273 + 30 = 303$ K, $T_2 = 273 - 15 = 258$ K

Refrigeration machine

$$COP = \frac{T_2}{T_1 - T_2} = \frac{258}{303-258} = \frac{258}{45}$$

$COP = 5.73$ . . . (i)

Heat pump

$$COP = \frac{T_1}{T_1 - T_2} = \frac{303}{303-258} = \frac{303}{45}$$

$$COP = 6.73 \qquad \ldots \text{(ii)}$$

Heat engine

$$\eta = \frac{T_1 - T_2}{T_1} = \frac{303 - 258}{303} = \frac{45}{303}$$

$$\eta = 0.1485 \text{ or } 14.85\% \qquad \ldots \text{(iii)}$$

**Example 7.3**

In a vapour compression cycle the refrigerant is

(a) Saturated vapour at the end of evaporation and saturated liquid at the end of condensation.

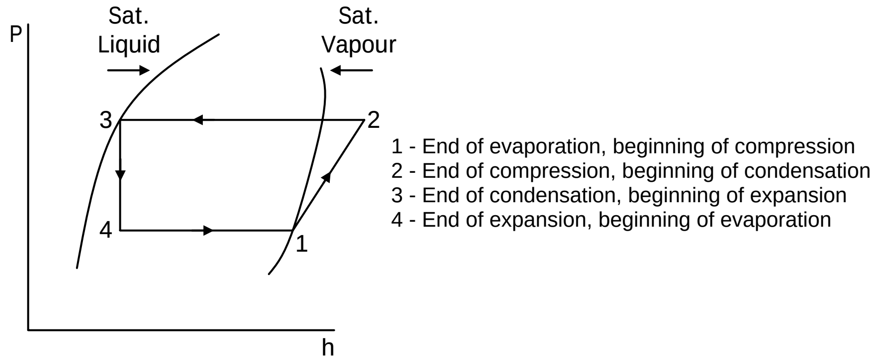
(b) Saturated vapour at the end of compression and subcooled liquid at the end of condensation.

(c) Superheated vapour at the end of evaporation and saturated vapour at the end of condensation.

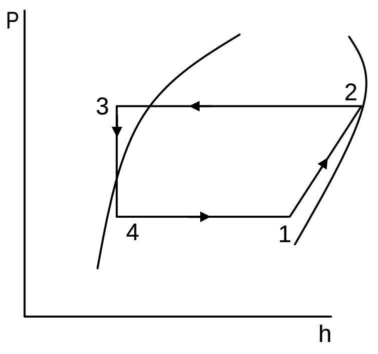
Draw the three cycles on p-h diagram.

**Solution**

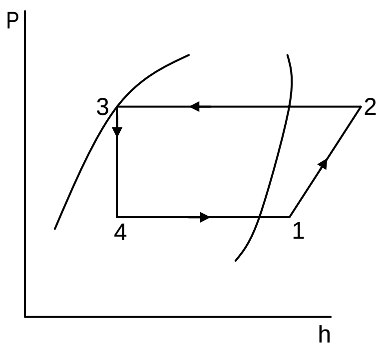
(a)




(b)




(c)



## SAQ 1

(a) Define *COP* of a refrigeration system working on vapour-compression cycle. Can this system be used as a heat pump?

(b) Describe a vapour absorption refrigeration system. Which refrigerants are used in this system?

(c) Which system works on Peltier effect? Give advantages and disadvantages of Peltier effect refrigeration system.

(d) What do you understand by secondary refrigerant? Why and which secondary refrigerants are used?

(e) Describe a steam jet refrigeration system with its application.

(f) A refrigerant has specific heat at constant pressure in vapour state of 0.62 kJ/kg K. It is compressed to a temperature of 16$^o$C in a compressor and cooled at constant pressure in a condenser to sat liquid at 0$^o$C. Its enthalpies in saturated vapour state at 0$^o$C and saturated liquid state are respectively 189 kJ/kg and 36 kJ/kg. It is expanded in evaporator to saturation where its enthalpy is 168 kJ/kg.

Calculate *COP* of the cycle.

## 7.11 AIR-CONDITIONING

Literally the combination of two words means *conditioning of air* for well defined purposes. The quality of air can be defined by its state parameters such as temperature, motion, odour (or degree of cleanliness) and moisture content. Two of these factors, viz. the temperature and water or moisture content seem to be much more important than other factors. In the stage of early development only these two factors were considered to be important for control. In further development other factors apparently started asserting their importance. Hence, the present day practice is to control all variables of air. The air here means that part of atmosphere which is in immediate contact or occupies the confined space. An air-conditioning system controls only this air.

Broadly speaking air-conditioning falls into two categories. They are *comfort air-conditioning* and *industrial air-conditioning.*

Comfort air-conditioning is the controlling of temperature and moisture of air along with its cleanliness and motion. It is our experience that temperature beyond 25$^o$C begins to make us uncomfortable. Similarly, more water vapour (moisture content is described as humidity and will be defined later) in air makes us feel uncomfortable. Stationary air and air moving with high velocity are also the source of discomfort. Odour may be yet another factor which would cause feeling of comfort or discomfort. The comfort air-conditioning pertains to control of these variables in respect of human being. The confined spaces where air-conditioning is performed are residences, offices, commercial establishments, trains, automobiles, air planes etc. Mere heating or cooling is not air-conditioning although man can draw comfort from controlled temperature or motion alone.

There are several industrial processes which require strict control of temperature and moisture. Textile and printing industries are two apparent example. There are many industrial processes that require totally controlled air and their standards may be much more rigid than for comfort air-conditioning. For example, pharmaceutical industry may follow very strict standard, in respect of cleanliness which will not simply be limited to odour but will include control of bacteria also. Certain industrial air-conditioning may not be good for human being and special design consideration may be involved.

However, for most part of our study of air-conditioning, we will confine ourselves to cooling of air to a temperature of around $25^oC$ and controlling of moisture (which will be described as humidity upto 65%) within comfortable limits. For this reason refrigeration system will play an important role in our air-conditioning. Most importantly understanding of water or moisture content of air and how this moisture content will affect the temperature of air or vice-versa becomes important. The study of air properties with moisture or properties of moist air has developed as a knowledge area in its own right and is known as *psychrometry*.

## 7.12 PSYCHROMETRY

Psychrometry is the art and science of understanding properties of moist air, i.e. an intimate mixture of dry air and water vapour. Although air itself is a mixture of a number of gases, they form a homogeneous substance and air as such can be regarded as pure substance since its constituents do not separate in different phases within the temperature limits of air-conditioning. On the other hand water vapour which is also a pure substance can separate from air at various temperatures. The moist air, therefore, is a homogeneous mixture of two pure substances which do not react with each other.

According to Dalton’s law of partial pressure both air and water vapour will occupy the same volume as that of the mixture, at the same temperature as that of the mixture but at their partial pressures.

If $V$ = volume of moist air,

$p_a$ = partial pressure of dry air,

$p_v$ = partial pressure of water vapour,

$p$ = pressure of moist air,

$m_a$ = mass of dry air,

$m_v$ = mass of moisture or water vapour in moist air, and

$m$ = mass of moist air.

then

$$m_a + m_v = m$$

$$P_a + p_v = p$$

The temperature of moisture (water vapour) and dry air and volume of both respectively are $T$ and $V$, same as temperature and volume of moist air.

Both dry air and water vapour are regarded as ideal gases

Hence

$$pV = mRT \text{ (mixture or moist air)} \qquad \ldots (7.8)$$

$$p_aV = m_aRT \text{ (dry air)} \qquad \ldots (7.9)$$

$$p_v V = m_v RT \text{ (water vapour)} \quad \text{. . . (7.10)}$$

or

$$m_a + m_v = \frac{V}{RT}(p_a + p_v) = \frac{pV}{RT} = m \quad \text{. . . (7.11)}$$

**Some Definitions**

The air without any moisture is referred to as *dry air* (da). The mixture of dry air and water vapour is called *moist air*. *Saturation capacity* of moist air is defined as the maximum amount of water vapour that is held by the air, at a particular temperature. The air is then called saturated.

In *saturated air* the partial pressure of water vapour will be the saturation pressure of water vapour at air temperature. If air is not saturated (i.e. the maximum amount of water vapour is not present in moist air) then the water vapour is superheated.

*Dry bulb* and *wet bulb* temperature of air are important characteristics of moist air.

A normal thermometer if exposed to air will record *dry bulb temperature* (DBT). However, if the bulb of the thermometer is covered with a wet cloth, the thermometer records *wet bulb temperature* (WBT).

The difference between DBT and WBT is known as *wet bulb depression*.

If air is cooled the moisture begins to separate. The temperature at which separation begins is known as *dew point temperature* (DPT).

For saturated air the three temperatures, i.e. DBT, WBT and DPT are same.

The mass of water vapour per kg of dry air is termed as *specific* or *absolute humidity* or *humidity ratio* or *moisture content*. The specific humidity is denoted by $\omega$, and one can see that

$$\omega = \frac{m_v}{m_a} \quad \text{. . . (7.12)}$$

The mass, $m_v$, is taken in *g* whereas mass $m_a$ is taken in kg.

Thus, $\omega$ is expressed in unit of g/kg (da).

The *relative humidity* is defined as the ratio of actual mass of moisture to the mass of the moisture which will saturate the given volume of the air at the same temperature. It can be seen that this is also the ratio of actual partial pressure ($p_v$) of water vapour to the partial pressure of water vapour when the air will be saturated ($p_{vs}$).

Relative humidity is denoted by $\phi$

$$\phi = \frac{m_v}{m_{vs}} = \frac{p_v}{p_{vs}} \quad \text{. . . (7.13)}$$

where suffixes mean the following

$v$ = vapour, and

$vs$ = saturated vapour.

The specific humidity when air is saturated is denoted by $\omega_s$. The ratio of actual specific humidity to saturation specific humidity, $\omega_s$, is known as degree of saturation and denoted by $\mu$. Thus

$$\mu = \frac{\omega}{\omega_s} \quad \text{. . . (7.14)}$$

Enthalpy of moist air is the sum of sensible heat of air, sensible heat of water vapour and latent heat of water vapour.

Thus $$h = h_a + h_v$$

$h_a$ = Enthalpy of dry air which is sensible heat

$= C_{pa} t$

$h_v$ = Enthalpy of vapour

= sensible heat of vapour + latent heat of vapour

$= \omega\, (C p_v + h_g)$

Take $C_{pa}$ = specific heat of dry air at constant pressure = 1.005 kJ/kg$^{o}$C

$C_{pv}$ = specific heat of water vapour at constant pressure
= 1.88 kJ/kg$^{o}$C

$h_g$ = heat of evaporation or latent heat of moisture = 2500 kJ/kg

Therefore, $h = [1.005\, t + \omega\, (1.88t + 2500)]$ kJ/kg da.

### 7.12.1 Psychrometric Chart

The psychrometric chart is the graphic representation of several properties of moist air. The simplest way to look at the psychrometric chart is as a graph between DBT (abscissa) and humidity ratio or specic humidity (ordinate). Most of the psychrometric properties and some thermodynamic properties of moist air can be read from this chart. The psychrometric processes can be easily visualized on this chart. Similar properties can also be read from air tables but use of the chart is much more convenient.

Following lines can be identified on psychrometric chart of Figure 7.8.

(a) Lines of constant DBT are vertical lines.

(b) Constant WBT lines are inclined to abscissa.

(c) Constant humidity ratio lines are horizontal.

(d) Lines of constant specific volume are inclined.

(e) Enthalpy of air is read on a scale on line 5 which is an inclined line. For convenience this scale is also duplicated on abscissa and ordinate.

(f) Lines of *constant relative humidity* are curves. One of these lines is for $\omega_s$ and forms the boundary of the psychrometric chart.

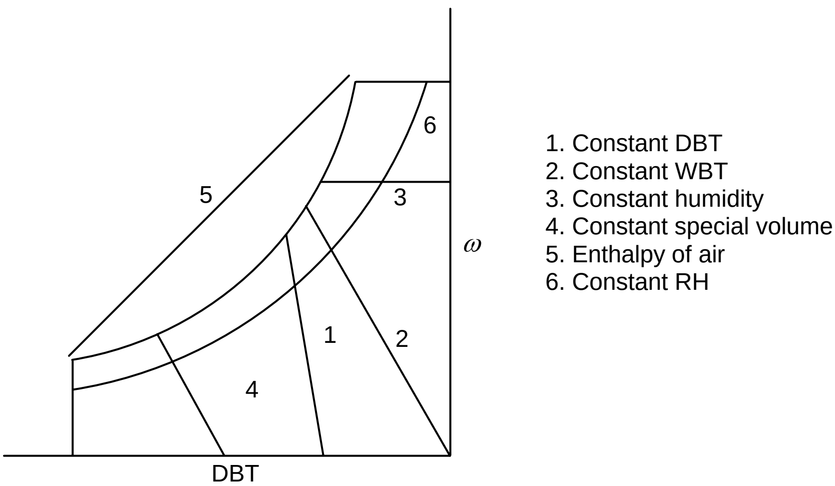



**Figure 7.8 : Psychrometric Chart**

## 7.12.2 Air-conditioning Processes on Psychrometric Chart

Several processes involved in air-conditioning can be represented conveniently on psychrometric chart and variables, thus, can be directly read. The chart is made at normal atmospheric pressure of 760 mm Hg or 1.01325 bar. It may be remembered that air-conditioning processes occur at atmospheric pressure.

### Sensible Heating and Cooling

This process involves no change of moisture content hence it is represented by a horizontal line. The DBT increases to right hence, heating line is a horizontal line pointing to the right. The cooling will be a horizontal line pointing to left. In this process, air is brought in contact with hot or cold surface which may be a surface of pipe or duct. In sensible heating, relative humidity (RH) is lowered while it increases in cooling. Figure 7.9 depicts the process.

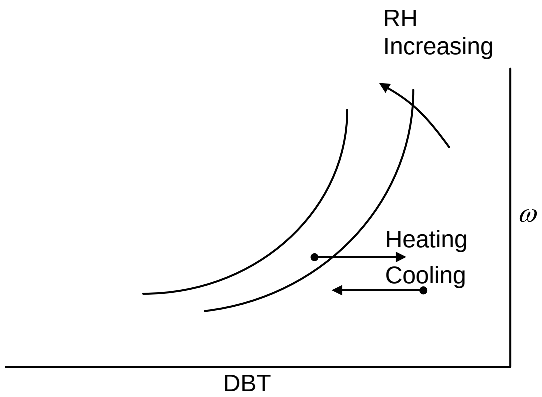



**Figure 7.9 : Sensible Heating and Cooling**

### Cooling and Dehumidification

The process involves lowering of temperature and specific humidity which means some moisture is removed. It is represented by a curve from right to left with final point below the initial point. In the process, some moisture separates while RH increases. Summer air-conditioning is the example of such a process. The moist air is passed over a cold coil or through water spray. Figure 7.10 depicts the process.

### Heating and Humidification

In this process, DBT and $\omega$ of air will increase. On psychrometric chart the process is shown by a curve from left to the right with final point being higher than initial. This process is used in winter to make air warmer. Figure 7.10 shows the processes of cooling and dehumidification and heating and humidification on psychrometric chart.

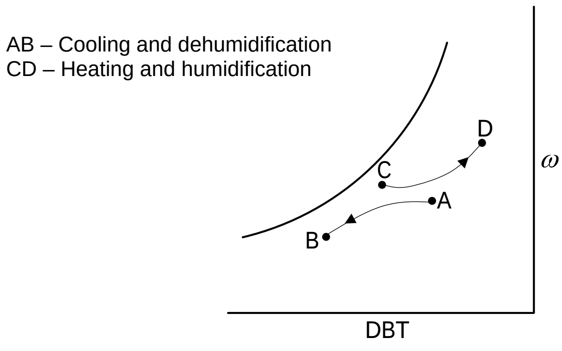



**Figure 7.10**



### Evaporative Cooling

This process takes place at constant wet bulb temperature. In this process, the RH increases and DBT is lowered, hence it will move from right to left along an inclined line (line (2) in Figure 7.8). In dry hot climate, this cooling is used to reduce DBT and increase humidity of air, as shown in Figure 7.11.

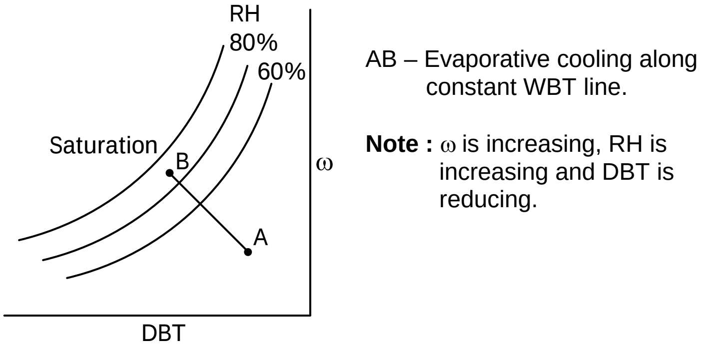



**Figure 7.11**

## Adiabatic Mixing

This is a very common process in air-conditioning that air stream corresponding to point A is allowed to mix with another air stream corresponding to point B on psychrometric chart as presented in Figure 7.12. The two streams after mixing will reach a condition at point C such that C will lie on the line joining A and B. The position of point C defined by the ratio AB to AC such that

$$\frac{AB}{AC} = \frac{\text{Mass of total dry air in mixture}}{\text{Mass of dry air at B}}$$

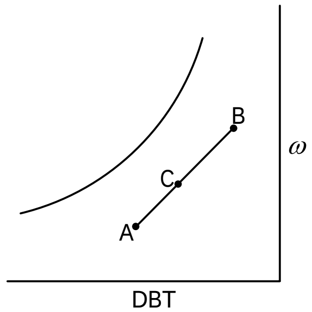



**Figure 7.12 : Adiabatic Mixing**

## Chemical Dehumidification

Many industrial applications require removal of moisture from the air and they permit consequent rise in DBT. There are chemicals which cause condensation of moisture when a stream of air passes over them. The heat of condensation released by the moisture is absorbed by the air whereby its temperature increases. The process, shown in Figure 7.13, is predominantly used in industrial air-conditioning.

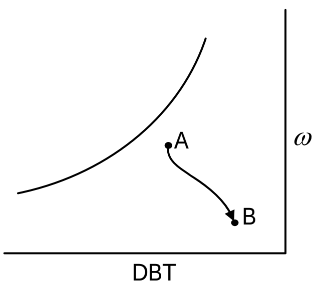



**Figure 7.13 : Chemical Dehumidification**

## 7.13 COMFORT AIR-CONDITIONING

Air conditioning for all those variables of air that make human life comfortable is often referred to as comfort air-conditioning. Although air-conditioning will mean both raising and lowering of air temperature, in larger part of our country it is cooling that is required. For human beings to feel comfortable, the temperature variation between 19°C and 30°C seem to be permissible. Between 19°C and 25°C it is the cool side of temperature and between 25°C and 30°C it is the hot side of the temperature. For defining comfort level mainly to correlate with hotter climatic zone an index called tropical summer index has been devised. TSI is expressed as

$$TSI = 0.745\, t_a + 0.308\, t_w - 2v + 0.841 \qquad \ldots (7.16)$$

where, $t_a$ and $t_w$ respectively are DBT and WBT of air in °C, and

$v$ is the speed of air in m/s.

An air-conditioning system will be required to make adjustment both in temperature and RH and produce required air movement. Further the building which is conditioned should be properly insulated because it is through the wall that the heat will be conducted inside or outside depending upon whether the inside of the building is hotter or cooler.

A designer of air-conditioning system has to first calculate the load on the system which could be heat to be removed from or added to the conditioned air. The man emits heat. The heat emitted by human body is 420 kJ/hr if the man is at rest. An active man will emit more heat. The surrounding air absorbs this heat and gets warmer. The temperature of the surrounding air must be less than 36.4°C if it has to absorb this emitted heat. The human body further emits heat in the form of latent heat of sweat. The contribution of latent heat is about 30% in total emitted heat.

Important to note is the fact that heat from human body will be carried away by the surrounding air only if it passes over the body at certain speed. If speed is too low all heat will not be carried away and too high speed will again cause feeling of discomfort.

The method of calculating load on an air conditioner is deferred to yet another course exclusive on the subject. Yet here an attempt is made to mention the components of load.

Load is divided into two groups – sensible heat load and latent heat load.

**Sensible Heat Load**

Heat sources are

(a) Occupants (human).

(b) Products brought in at higher temperature.

(c) Heat producing equipment like lighting, motors etc.

(d) Fresh air added to space.

(e) Heat conduction through walls, roofs, doors and windows. Heat radiated through glass covers.



**Latent Heat Load**

Heat sources are

(a) Occupants (human).

(b) Products or appliances that may add water.

(c) Fresh air added to space.

The heat leakage through walls is normally considerable. Therefore, the walls must be properly insulated. If roof is exposed then it must also be properly insulated. Cork, polystyrene foam, thermocole, glass wool, felt celotex and wood are commonly used insulating materials for walls and roofs. External surface finish of walls is so done that it reflects most of radiation falling upon it. Aluminium finish is best in this respect in reflecting and retaining heat. White colour finish is good in reflecting but not so good in retaining heat. Data on most available finishes are now available so that air-conditioning engineers can design the best possible system.

## 7.14 SUMMER AIR-CONDITIONING (HUMID AIR)

In our country it is the summer during which air-conditioning is often needed. The practice is also confined to a few big cities like Mumbai, Delhi, Kolkata, Chennai, Bangalore, Hyderabad, etc. Most of them may require year round cooling except Delhi. The cities on seacoast present problem of dehumidification more than that of cooling.

The summer air-conditioning in humid climate uses a particular system. The outside air normally has temperature in the range of 35 to 40$^{o}$C and RH between 75-80%. Both the ranges are very discomforting and conditioning has to lower the temperature around 27$^{o}$C and RH around 55%.

The system used is shown in Figure 7.14. The sequence of operation and relevant equipment are described below.

(a) The air which is drawn from the atmosphere is filtered in a filter.

(b) The filtered air passes over the cooling coil and water eliminator. The air is cooled and dehumidified. The water separated in the process is drained off.

(c) The air is heated to temperature which is in the comfort zone.

(d) Air passes to the conditioned space through ducts.

It may be understood that only a small amount of air is sucked in continuously. Part of this air is mixed with cooled air drawn into circulation from the conditioned space. This mixed air is then passed over the cooling coil. The mixing may be adiabatic. The fresh air is drawn to cover the leakage losses.

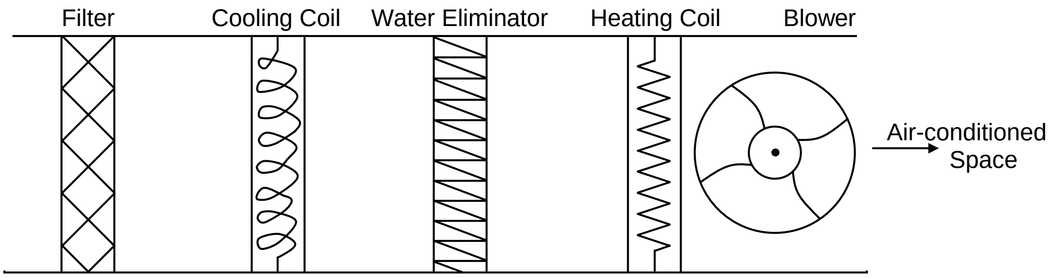



**Figure 7.14 : Summer Air-conditioning (Humid Air)**

The cooling coil is the part of the refrigerating system whose evaporator may serve as cooling coil. The water eliminator may be a baffler. The cooling is done to the extent that desired RH is achieved which means that objective is not to achieve a low temperature but to remove moisture to a desired level and in achieving this RH the temperature is reduced to a level which is below the desired temperature. If we make desired temperature as our objective, the RH of the cooled air will be higher than desirable.

## 7.15 WINTER AIR-CONDITIONING

The temperature of atmospheric air is in the range of 5-10$^{o}$C.

The different steps are described below:

(a) The air is drawn through the filter.

(b) The air is passed over a heating coil. This reduces the relative humidity.

(c) The air passes through a spray humidifier. The fine water particles are absorbed by air and they absorb the latent heat from water and convert into vapour. The air is cooled.

(d) The air is further heated to the desired temperature. This air is then passed into the conditioned space through ducts.

The system is shown in Figure 7.15.

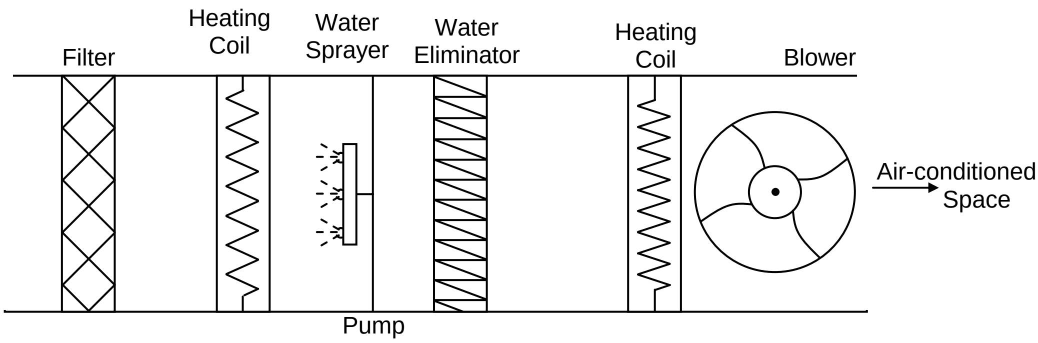



**Figure 7.15 : Winter Air-conditioning**

## 7.16 SUMMER AIR-CONDITIONING (DRY AIR)

Situations arise in geographical locations where air is too dry and warm. The temperature may be in the range of 40-50$^{o}$C and RH limited to 20% or even less. To reach comfort zone air needs cooling as well as humidification. Following steps are involved in air-conditioning :

(a) Air is made to pass through filter.

(b) Air is then cooled by passing over cooling coil.

(c) Air is then passed through water sprayer to increase RH.

(d) Air is passed through water eliminator to remove excess water.

(e) Air is mixed with already conditioned air being circulated through ducts.



Figure 7.16 schematically shows the system.

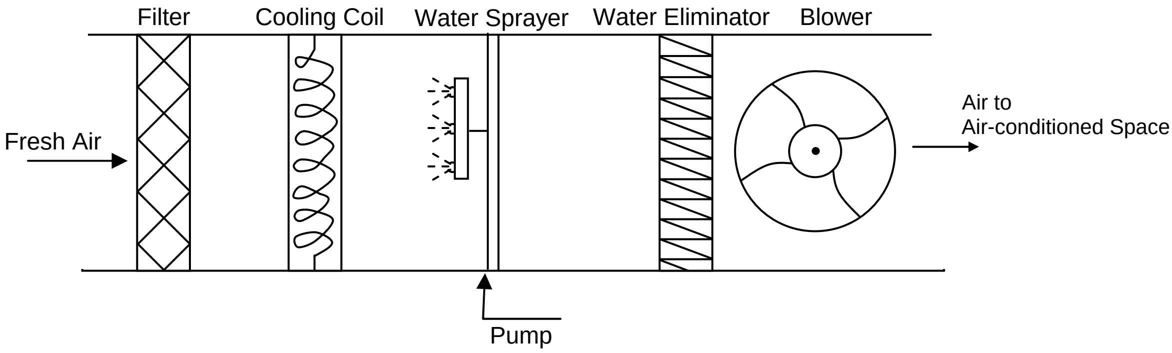



**Figure 7.16 : Summer Air-conditioning (Dry Air)**

## 7.17 PACKAGE AIR-CONDITIONING

These are also known as room air conditioner or window type air conditioner. In comparison with central air-conditioning system described earlier, these are complete plants packed in a unit which can be fitted into window opening of conventional size. They come all packed up in ready to use state. They are placed in a window and power unit plugged, the room air conditioners begin to cool.

The plant contains a refrigeration unit which creates low temperature in the evaporator. The filtered air passes over the evaporator and gets cooled. During cooling process certain water vapour from fresh air will condense and separate from the air. This water is drained off from a tray. Sealed compressor and condenser of refrigeration unit are housed in the same unit but separated from the compartment in which air blower and evaporator are placed. A separate fan is used to draw air from outside and circulate over the condenser. The room employing window AC must be sealed.

## 7.18 EVAPORATIVE COOLER

Evaporative cooling was described earlier. This cause DBT to reduce but RH to increase Figure 7.11. This system is also known as desert air cooler. It is suited to hot dry air which is drawn from outside by a fan. While entering the fan blades the air passes through porous medium through which water flows continuously. The air absorbs moisture and increases in RH but reduces in temperature. The fan pushes this moist air into room. This air once thrown by fan is laden with moisture hence cannot be allowed to accumulate in the room. Hence the room need to be properly ventilated. Separate motor is used to run the pump for bringing water to the porous walls. The source of water has to be maintained as water is continuously lost. On the whole, though the system can be fitted in the wall opening, it is quite large and clumsy.

## 7.19 DUCTING

In centralized air-conditioning, the air intake from outside and from air conditioned space and circulation and distribution of conditioned air is done through specially designed passage, called ducts.

The ducts are generally made in GI sheet metal. Aluminium ducts are also sometimes made because of their lighter weight and corrosion resistance. The moisture is corrosive in nature. The duct are normally provided overhead, adjacent to beams or hung from roof. They are supported on extruded aluminium sections but if free length is small they can be provided sheet reinforcement.

The ducts are loaded due to

(a) static load caused by small pressure differential between inside and outside,

(b) air turbulence which may exist due to induced flow by blower.

The ducts may be designed as

(a) low pressure system in which air velocity is less than 600 m/min and pressure is less than 50 mm $H_2O$ gauge.

(b) Medium pressure system in which velocity of air is below 600 m/min but static pressure does not exceed 150 mm $H_2O$ gauge.

(c) High pressure system in which air velocity is limited to 600 m/min and pressure is confined to 250 mm $H_2O$ gauge.

Low pressure system of ducting finds favour in most design situations. The construction is simple and thin sheets can be used, the gauge depending upon dimension of the longest side. The ducts are mostly made rectangular section with outlets cut in the vertical or horizontal sides. The high and medium pressure ducting need thicker sheets and proper supports and transverse reinforcement. The GI sheet gauges normally used for low pressure system are 26 to 18, for medium pressure system are 24-18 and for high pressure they are 22-16.

There are certain general rules to be followed in designing ducts. They are enumerated here.

(a) Air should have as small distance to travel as possible. This will economize power, sheet material and space.

(b) Pressure loss due to sudden change in direction should be avoided. Whenever direction has to be changed, it should be very gradual and turning vanes may be incorporated.

(c) Air velocities inside duct should be within limit otherwise noise and vibrations are likely to be produced.

(d) Whenever the duct has to diverge, the divergence angle should not exceed $20^o$.

(e) Rectangular ducts should not lend to become flat box structure. The aspect ratio of 4 : 1 or less is recommended. It is better to make them square to minimize surface area.

(f) Rougher surfaces will exert additional resistance to flow and if it becomes necessary to use such material proper allowance in design should be incorporated otherwise smooth material like GI sheet or aluminium should be preferred for making ducts.

(g) Dampers are used to control the flow through ducts. Each branch of duct should be provided with a damper so that the system may be balanced.

(h) The duct should not become obstruction to normal activity in the air-conditioning space.

## SAQ 2

(a) Distinguish between comfort air-conditioning and industrial air-conditioning. How is the cooling achieved in central air-conditioning?

(b) Define absolute humidity of moist air. If 1 kg of moist air contains $m_v$, g of water vapour, what is its specific humidity in unit of g/kg (da)?

(c) Assuming that molecular mass of water is 18.016 and that of air is 28.966, show that

Absolute humidity, $\omega = 0.622 \dfrac{p_v}{p_a} = 0.622 \dfrac{p_v}{p - p_v}$

where, $p_v$ = partial vapour pressure, and

$p_a$ = partial air pressure in the moist air.

(d) Define relative humidity and show that it is also given by $p_v/p_{vs}$

where, $p_v$ = partial pressure of vapour in air under actual condition, and

$p_{vs}$ = partial pressure of vapour in air at saturation.

(e) Define enthalpy of moist air. Air at 20$^o$ DBT has RH of 60%, calculate its enthalpy. The saturation pressure of water vapour at 20$^o$C is 2342 MPa.

(f) Describe summer air-conditioning system for humid and dry air.

(g) What is ducting? What considerations are made in designing duct system? Which materials you would propose to build duct from?

## 7.20 SUMMARY

Refrigeration is a process by way of which heat is removed from colder body and rejected at higher temperature. For this to occur work is supplied from outside. The coefficient of performance of a refrigeration system is the ratio of heat removed from colder body (refrigerating effect) to the work supplied to the system.

A Carnot cycle run in reversed order can generate refrigerating effect with air as medium to be compressed and expanded. In practice, vapour compression cycle is used. In such a cycle, cooling effect is generated in the evaporator in which liquid evaporates and absorbs its latent heat from surrounding which is cooled. The vapour from evaporator enters the compressor which compresses the vapour to small volume and increases its temperature. The condenser condenses the vapour into liquid at high pressure and heat is rejected at higher temperature. The high pressure liquid expands through a valve and gets cooled at low pressure. This liquid enters the evaporator and cycle continues.

Absorption system is an alternate to the compression system. In this, a liquid solvent acts as a carrier for transferring the vapour of the refrigerant which remains absorbed in the liquid. Heat is used to separate absorbed vapour from the liquid in which process the temperature and pressure of the vapour increases. The vapour is condensed into liquid or mixture of liquid and vapour which is expanded in the evaporator to produce the cooling effect. The energy supplied is in form of pump work (which is small) and in form of heat to separate absorbed vapour from solvent.

There are other systems also like one working on Peltier effect needs no refrigerant, nor it needs moving parts. The steam jet system uses water as refrigerant and evaporation of very low pressure water in the evaporator creates cooling effect. The steam is ejected through ejector pump from the evaporator partly and remaining cold liquid is again circulated to evaporator.

Refrigerant is the working substance in compression and absorption system. A series of them are commercially available. Ammonia, $CO_2$, and $SO_2$ have been used during earlier development. Chloro-fluoro-carbons (CFC) were found to be most efficient refrigerants but due to their ozone depletion property their use has been phased out. New generation refrigerants include hydrocarbons like butane, iso-butane and propane.

Air-conditioning is a process of controlling temperature, humidity and motion of air in a confined space occupied by human being or equipment performing some industrial activity. Apparently comfort air-conditioning (in respect of human) and industrial air-conditioning (in respect of equipment and processes) can be regarded as two categories. Cooling of air (or its heating) is the most important objective of air-conditioning and, therefore, the system would incorporate refrigeration. Increasing or decreasing of water content of air will be another important activity in the air-conditioning. Further, imparting motion to air is yet another aspect. In a centralized system these various activities are performed in certain order.

The amount of heat and water content to be added or removed will depend upon the atmospheric conditions in which air may be humid or dry or the temperature may be above or below the required level. The system is designed on the basis of such requirement.

In the conditioned space, the conditioned air is circulated through ducting which are especially designed passages for air and opening in them allow the air to exit and damper in them control the amount of air. They are designed for strength, less loss in flow of air and aesthetics of the space also kept in mind.

## 7.21 ANSWERS TO SAQs

**SAQ 1**

(f) 1-2 – Compression, 2 is superheated state at $16^{o}$C.

2-2′ – Cooling of superheated vapour in condenser. 2′ is saturation state of vapour at $0^{o}$C.

2′-3 – Condensation of vapour to saturated liquid at constant temperature of $0^{o}$C and at constant pressure.

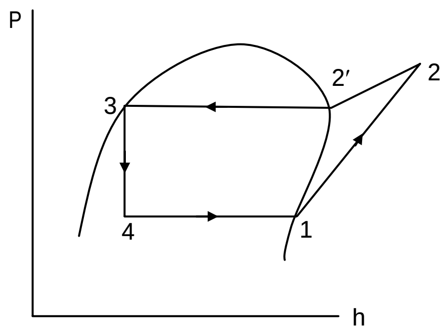



**Figure 7.17**

Note that $h_3 = h_4$ = enthalpy of saturated liquid at 3 = 36 kJ/kg.

$$h_2 = h'_2 + c_p\,(T_2 - T_2')$$

$$T_2 = 16^{o}\text{C},\ T_2' = 0^{o}\text{C}$$

$$\therefore \quad h_2 = 189 + 0.62\,(16 - 0) = 198.92 \text{ kJ/kg}$$

$$h_1 = 168 \text{ kJ/kg.}$$

Work of compression, $(h_2 - h_1) = 198.92 - 168 = 30.92$ kJ/kg

Refrigerating effect, $(h_1 - h_4) = h_1 - h_3$

$$= 168 - 36 = 132 \text{ kJ/kg.}$$

$$\therefore \qquad COP = \frac{h_2 - h_1}{h_1 - h_4} = \frac{132}{30.92} = 4.26$$

**SAQ 2**

(b) Absolute humidity, $\omega = \dfrac{m_v \times 10^{-3}}{m_a}$

If $m_v$ is in g and $m_a$ in kg.

$$m = m_v \times 10^{-3} + m_a = 1 \text{ kg.}$$

$$\therefore \qquad m_a = (1 - m_v \times 10^{-3}) \text{ kg.}$$

$\therefore$ Specific or absolute humidity

$$\omega = \frac{m_v}{1 - m_v \times 10^{-3}} \text{ g/kg (da)}$$

(c) From Eq. (7.9) $\quad m_a = \dfrac{p_a V}{R_a T}$

From Eq. (7.10) $\quad m_v = \dfrac{p_v V}{R_v T}$

Here $R_a$ and $R_v$ are gas constants for air and vapour respectively.

$$\therefore \qquad \omega = \frac{m_v}{m_a} = \frac{p_v}{p_a} \cdot \frac{R_a}{R_v}$$

But $\quad R_a = M_a R_u$

$$R_v = M_v R_u$$

where $R_u$ is universal gas constant and $M$ is molecular mass.

$$\therefore \qquad \omega = \frac{p_v}{p_a} \cdot \frac{18.016}{28.966} = 0.622\,\frac{p_v}{p_a}$$

(d) The relative humidity is defined as ratio of actual mass of vapour $m_v$ to that mass of vapour which will saturate the air, $m_{vs}$

$$\phi = \frac{m_v}{m_{vs}}$$

From Eq. (7.10)

$$\phi = \frac{p_v \,.\, V}{RT} \cdot \frac{RT}{p_{vs} V} = \frac{p_v}{p_{vs}}$$

(e) Enthalpy of air, $h = 1.005\,t + \omega\ (1.88\,t + 2500)$ kJ/kg (da)

$$\phi = 0.6 = \frac{p_v}{p_{vs}}$$

But $p_{vs} = 2342$ MPa

$$p_v = 0.6 \times 2342 = 1405.2 \text{ MPa}$$

Also $\omega = 0.622\,\dfrac{p_v}{p_a} = 0.622\,\dfrac{p_v}{p - p_v}$

Use standard atmospheric pressure $p = 101325$ MPa

$$\therefore \quad \omega = 0.622 \times \frac{1405.2}{101325 - 1405.2}$$

$$= \frac{874}{999198} = 0.875 \times 10^{-3} \text{ kg/kg (da)}$$

$$\therefore \quad h = 1.005\,(20) + 0.875 \times 10^{-3}\,(1.88 \times 20 + 2500)$$

$$= 20.1 + 0.875 \times 10^{-3}\,(37.6 + 2500)$$

$$= 20.1 + 2.22$$

or $h = 22.32$ kJ/kg (da)