Chapter

4

Refrigeration and Air-conditioning

4.1. REFRIGERATION: WHAT IS IT?

Science of providing and maintaining temperatures below that of surroundings

Refrigeration and air conditioning is the fascinating branch of science which deals with the chilling or freezing of a substance by removing some of its heat. This artificial withdrawl of heat produces within the substance or within a space a temperature below the general temperature of its surroundings. Refrigeration essentially means continued abstraction of heat from a substance (perishable foods, drinks and medicines etc.) at low temperature level and then transfer this heat to another system at high potential of temperature. To accomplish this, mechanical work must be performed to satisfy the second law of thermodynamics.

Air conditioning refers to the simultaneous control of temperature, humidity, cleanliness and air motion within a confined region or space.

A brief review is given in this chapter about the basic principles of certain refrigeration systems and the properties of primary and secondary refrigerats used in them. Mention also has been made of the eco-friendly refrigerants which have become a necessity to prevent depletion of ozone layer.

4.2. HEAT ENGINE, REFRIGERATOR AND HEAT PUMP

A heat engine is a thermodynamic device used for continuous production of work from heat when operating in a cyclic process. Both heat and work interactions take place across the boundary of this cyclically operating device. Essentially a heat engine takes heat from the combustion of fuel and converts part of this energy into mechanical work.

A heat engine is characterised by the following features:

- reception of heat Q_1 from a high temperature source at T_1
- partial conversion of heat received to mechanical work W
- rejection of remaining heat Q_2 to a low temperature sink at temperature T_2
- cyclic/continuous operation and
- working substance flowing through the engine.

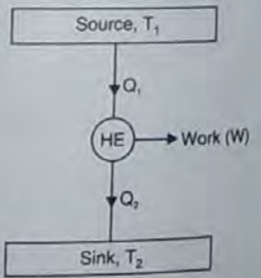


Fig. 4.1. Energy interactions in a heat engine

The performance of any machine is expressed as the ratio of 'what we want ' to 'what we have to pay for`. In the context of an engine, work is obtained at the expense of heat input. Accordingly, the performance of a heat engine is given by net work output to the entire amount of heat supplied to the working medium, and this ratio is called ***thermal efficiency***, η_{th} (Thermal efficiency is a measure of the degree of useful utilization of heat received in a heat engine).

$$\eta_{th} = \frac{\text{net work output}}{\text{total heat supplied}}$$

Application of the principle of energy conservation (First law) to the heat engine, which undergoes a cycle gives : $W = Q_1 - Q_2$

$$\therefore \qquad \eta_{th} = \frac{Q_1 - Q_2}{Q_1} = 1 - \frac{Q_2}{Q_1} \qquad ...(4.1)$$

Obviously, thermal efficiency of a heat engine operating between two thermal reservoirs is always less than unity. To increase the thermal efficiency, it is necessary to reduce Q_2 (heat rejected) with Q_1 (heat supplied) remaining constant. Thermal efficiency could be equal to unity if $Q_1 \to \infty$ and $Q_2 = 0$ which, however, can not be realized in practice.

Refrigerators and heat pumps are ***reversed*** heat engines. The adjective reversed means operating backwards. The direction of heat and work interactions are opposite to that of a heat engine, *i.e.*, work input and heat output. These machines (refrigerators and heat pumps) are used to remove heat from a body at low temperature level and then transfer this heat to another body at high potential of temperature. When the main purpose of the machine is to remove heat from the cooled space, it is called a ***refrigerator***. A refrigerator operates between the temperature of surroundings and a temperature below that of the surroundings. Refrigerators are essentially used to preserve food items and drugs at low temperature.

The term *heat pump* is applied to a machine whose objective is to heat a medium which may already be warmer than its surroundings. A heat pump thus operates between the temperature of the surroundings and a temperature above that of the surroundings. Heat pumps are generally used to keep the rooms warm in winter.

The transfer of heat against a reverse temperature gradient in a refrigerator and heat pump is accomplished by supplying energy to the machine. A schematic representation of heat pump and a refrigerator has been shown in Fig. 4.2.

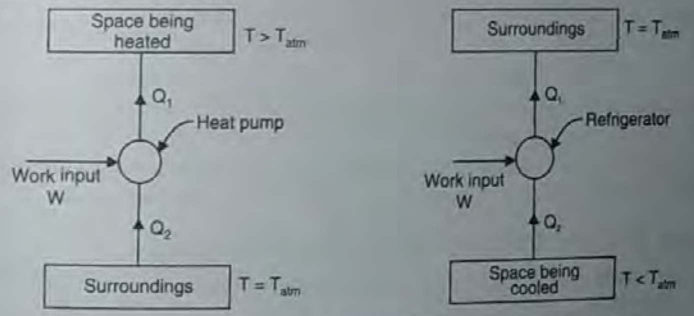


Fig. 4.2. Functional difference between a heat pump and a refrigerator

In the context of refrigerators and heat pumps, the performance is expressed in terms of ***coefficient of performance*** *(COP)* which represents the ratio of desired effect to work input

$$COP = \frac{\text{desired effect}}{\text{work input}}$$

In a *refrigerator*, the desired effect is the amount of heat Q_2 extracted from the space being cooled, *i.e.*, the space at low temperature.

$$(COP)_{ref} = \frac{\text{heat extracted at low temperature}}{\text{work input}} = \frac{Q_2}{W}$$

From the principle of energy conservation :

$$W = Q_1 - Q_2$$

$$\therefore \quad (COP)_{ref} = \frac{Q_2}{Q_1 - Q_2}$$

For most of the refrigerating machines, the values of *COP* lie between 3 and 4, and the *COP* are greatest when temperature differences are least.

In a ***heat pump***, the desired effect is the amount of heat Q_1 supplied to the space being heated.

$$(COP)_{heat\ pump} = \frac{\text{heat rejected at high temperature}}{\text{work input}} = \frac{Q_1}{Q_1 - Q_2}$$

$$= 1 + \frac{Q_2}{Q_1 - Q_2} = 1 + (COP)_{ref}$$

Thus the *COP* of a machine operating as a heat pump is higher than the *COP* of the same machine when operating as a refrigerator by unity.

Note : In the context of a refrigerator system :

1. The amount of heat extracted from the body at low temperature *i.e.*, the space being cooled is called *refrigerating effect*.
2. The *COP* of a refrigerator based on the theoretical values of refrigerating effect and work input is termed as *theoretical COP*. The theoretical refrigerating effect and work input are calculated by applying the laws of thermodynamics to the refrigeration cycle.
3. The *COP* of a refrigerator based on actual values of refrigerating effect and work input is termed as *actual COP*. The actual refrigerating effect and work input are obtained during test run on a refrigerating plant.
4. The ratio of actual *COP* to theoretical *COP* is known as *relative COP*.

$$\text{Relative } COP = \frac{\text{actual } COP}{\text{theroretical } COP}$$

5. ***Refrigeration efficiency*** is defined as the ratio of *COP* of a cycle to the *COP* of a Carnot cycle operating in the same temperature range.
6. A single machine can fulfil both the functions of cooling and heating simultaneously. For example, cool a food storage space as a refrigerator and heat a water system as a heat pump.

4.3. RATING OR CAPACITY OF A REFRIGERATING UNIT

The refrigerating machines are usually rated in terms of their cooling capacity; the standard unit being ***ton of refrigeration***.

One ton of refrigeration is defined as the refrigerating effect that freezes one ton (2000 pound mass) of liquid water during a period of 24 hours. The water is to be liquid at 0°C before and ice at 0°C after the process.

$$2000 \text{ pound mass} = \frac{2000}{2.205} = 907 \text{ kg}$$

Enthalpy of fusion of water at 0°C = 333.43 kJ/kg

$$\therefore \quad 1 \text{ ton of refrigeration} = \frac{907 \times 333.43}{24 \times 60} = 210 \text{ kJ/min} = 3.5 \text{ kJ/s} = 3.5 \text{ kW}$$

A ton of refrigeration is thus not a unit of mass but a measure of the rate of cooling. The refrigerating capacity decides the mass flow rate of a given working substance (refrigerant) working under specified conditions.

$$\text{Mass flow rate of refrigerant} = \frac{\text{refrigeration capacity}}{\text{refrigerating effect per unit mass}}$$

Quite often, power needed to produce a refrigeration effect equivalent of 1 ton of refrigeration is used as a measure to calculate the cost of operation or motor size of the refrigerating unit. Then

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

Further, the ratio of heat removal rating (kJ/hr) of a refrigeration system to energy input (kWhr) of the machine is called energy efficiency ratio (EER).

EXAMPLE 4.1

(*i*) The capacity of a refrigeration system is specified to be 12 tons. What is then the cooling rate of the machine ?

(*ii*) 250 litres of drinking water is required per hour at 10°C. Would the use of 1.5 ton refrigerating system be justified if the available water is at 30°C ?

(*iii*) A refrigerating machine takes 1.25 kW and produces 25 kg/hr of ice at 0°C from water available at 30°C. Determine refrigerating effect, tonnage and coefficient of performance of machine. Take

Specific heat of water = 4.18 kJ/kg K

Enthalpy of solidification of water from and at 0°C = 335 kJ/kg

Solution : (*i*) 1 ton of refrigeration ≡ 3.5 kJ/s

∴ Cooling rate of machine = 12 × 3.5 = 42 kJ/s

(*ii*) Refrigeration effect required for cooling the water

$$= mc_p \Delta T = 250 \times 4.18 \times (30\text{-}10) = 20900 \text{ kJ/hr}$$

1 ton of refrigeration ≡ 3.5 kJ/s = 12600 kJ/hr

$$\therefore \quad \text{Tonnage required} = \frac{20900}{12600} = 1.658$$

As such, the use of 1.5 ton machine will not serve the purpose.

(*iii*) Refrigeration effect

$$\equiv \text{removal of heat from water at 30°C to convert into ice at 0°C}$$

$$= m[c_{pw} \Delta T + L] = 25[4.18(30\text{-}0) + 335] = 11510 \text{ kJ/hr}$$

1 ton of refrigeration ≡ 3.5 kJ/s = 12600 kJ/hr

$$\therefore \quad \text{Tonnage required} = \frac{11510}{12600} = 0.913$$

$$COP = \frac{\text{refrigerating effect}}{\text{work input}}$$

$$= \frac{11510/3600}{1.25} = 2.558$$

4.4. METHODS OF REFRIGERATION

Refrigeration is the technique of producing cooling effect by abstraction/withdrawl of heat so that temperature below that of surroundings is produced in a substance or within a space. The desired cooling effect can be produced by :

1. Evaporation

When a liquid evaporates, it absorbs heat from the surroundings equivalent to its latent heat of vaporisation, and that results in lowering the temperature of surroundings. For example, we feel cooling effect when there is evaporation of a drop of spirit placed on the palm of hand. Likewise, the evaporation of moisture from the skin of a human body helps to keep it cool. There is a common practice to cool the water for drinking purposes by keeping it in the porous earthen pots. The water evaporates through the pores and that produces cooling effect. The army people keep small water containers made of metal and covered with water soaked namada; the walls of the metallic container get cooled and that cools the water kept inside it. In the refrigeration literature, there is mention of an experiment where a pump was used to create partial vacuum over a container of ethyl ether. The liquid then boiled by absorbing heat from the surrounding air. The cooling effect so created even produced a small amount of ice.

The principle of evaporative refrigeration is employed in desert (room) coolers. The dry atmospheric air is made to pass through water soaked packings. When this water evaporates, it takes heat from the air causing it to cool.

With reference of Fig. 4.3, a volatile liquid (liquid nitrogen, liquid carbon dixoide) contained in a flask evaporates and gets converted into gas. For evaporation, it absorbs heat from the chamber and cooling effect is produced. The chamber is insulated to restrict the infiltration of heat from outside. The liquid N_2 and CO_2 are non-toxic and as such the liquid gas refrigeration finds application for keeping the perishable food articles cool when being transported.

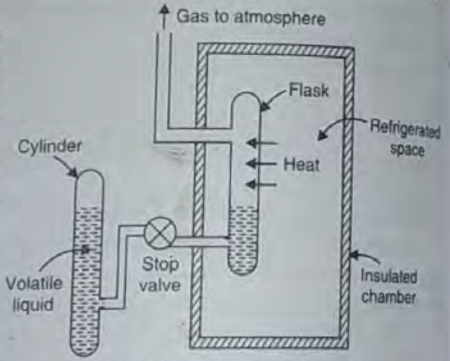


Fig. 4.3. Liquid gas refrigeration

2. Dissolution of salts in water

When certain salts are dissolved in water, they absorb heat and lower the temperature of water and create a sort of refrigeration bath for cooling substance. Sodium chloride lowers the water temperature upto – 20°C while calcium chloride upto – 50°C. The salt can be recovered by evaporation of water from the solution.

The method of producing cooling effect by dissolution of salt in water could not become feasible for commercial pursoses because,

(*i*) the refrigeration effect produced is quite small

(*ii*) the process of regaining salt is cumbersome.

There has been a practice in France to produce cold drinks and liqueurs (a strong alcoholic drink with a sweet taste) by spinning long necked bottles in water with dissolved saltpeter.

3. Ice refrigeration (change of phase)

The use of ice to refrigerate and thus preserve food goes back to the prehistoric times and the ancient cultures of Chinese, Greeks, Romans and Persians. Ice and snow were stored in caves or dugouts lined with straw or other insulating materials. This practice worked well down through the centuries, with ice houses remaining in use. Greater work was done on developing better insulation products for long distance shipment of ice and the ice harvesting became a big business.

The natural ice or artificially produced ice is brought into contact with the substance to be cooled. The ice melts and the heat required for melting of ice is supplied by the substance being cooled. The cooling effect produced by ice is

$$Q = \dot{m} \times h_{sf}$$

where $\dot{m}$ and h_{sf} are the rate of fusion of ice and enthalpy of fusion respectively. At normal atmospheric pressure of 1.01325 bar (1 atm), h_{sf} equals 335 kJ/kg.

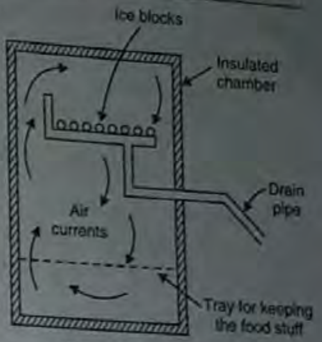


Fig. 4.4. Ice refrigeration

The ice refrigerator consists of a cabinet which is completely insulated. The ice is kept in a container at the top, and a number of shelves are provided in the space below the ice container for storing the food stuff. When air comes in contact with ice, it becomes cool, dense and flows down over the shelves. It absorbs heat from the food stuff which gets cooled. On absorption of heat, the air becomes warm. The warm air expands and returns back to the ice container from bottom, sides and back of the cabinet. When this warm air flows past the ice, it gives its heat to the ice and gets cooled. On cooling, the air becomes dense and once again flows down over the food shelves. Temperatures in the range of 5 to 10° can be obtained with ice refrigeration. In case, temperatures below this range are required, salt is mixed with ice and that results in reducing the temperature level to 0°C.

Ice refrigeration prevents dehydration and preserves the fresh appearance of eatable products like fruit and vegetables. However, ice has to be fed to the refrigerator of and on and that is neither convenient nor economical. Further, water coming out of the refrigerator poses a problem in its disposal.

Though the ice-harvesting industry had grown immensely by the turn of 20th century, pollution and sewage had begun to creep into natural ice and eventually breweries began to complain of tainted ice. This raised demand for more modern and consumer ready refrigeration and ice making machines.

4. Dry ice refrigeration (sublimation)

Solid carbon dioxide (called dry ice) has a peculiar characteristics that it changes from solid state to vapour state without passing through liquid state. During change of phase, it absorbs heat equivalent to its latent heat of vaporisation and produces cooling effect. This process occurs when the solid is maintained below triple point. Then,

$$Q = m\, h_{sv}$$

where h_{sv} is the enthalpy of evaporation.

At one atmospheric pressures, solid CO_2 produces 573 kJ/kg of refrigeration maintaining a temperature of – 78.5°C. Dry ice is used to preserve food stuff during transportation. The slabs of ice are usually packed on either side or on top of food packages in cartons. When dry ice evaporates, it absorbs heat from the food stuff and preserves it in frozen state.

The refrigeration methods (1) to (4) as mentioned above are called the ***natural methods***. These methods are non-cyclic and the temperatures attainable are limited. Further, there is continuous consumption of the refrigerating substance and that necessitates replenishment. However, these methods are sometimes convenient forms of cooling where small refrigeration is required such as in the laboratory and workshop.

5. Chemical methods

Here the heat required for the completion of chemical reaction is taken from the substance being cooled.

The chemical method for producing cooling effect cannot be followed on a commercial scale.

6. Air or gas refrigeration

Expansion of gas lowers its pressure and temperature. This cooling effect results without change in the phase of gas.

Consider air initially compressed isentropically from atmospheric conditions (p_1 = 1 atm and T_1 = 15°C) to 5 atm. The temperature after compression then would be

$$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = 288\left(\frac{5}{1}\right)^{\frac{1.4-1}{1.4}} = 456.3 \text{ K}$$

The compressed air may be next cooled to initial (presume) temperature of 15°C in a heat exchanger without any loss of pressure. Then at state point 3, T_3 = 288 K and p_3 = 5 atm. Subsequently the cooled high pressure can be expanded in a suitable device to original pressure of 1 atm (state point 4). Then temperature after expansion will be

$$T_4 = T_3\left(\frac{p_4}{p_3}\right)^{\frac{\gamma-1}{\gamma}} = 288\left(\frac{1}{5}\right)^{\frac{1.4-1}{1.4}} = 181.8 \text{ K} = -91.2°\text{C}$$

The different air refrigeration systems use this thermodynamic principle for producing low temperatures.

7. Throttling process

Throttling is the expansion of fluid from high pressure to low pressure. This process occurs when fluid passes through an obstruction (partially opened valve or a small orifice) placed in the fluid flow passage.

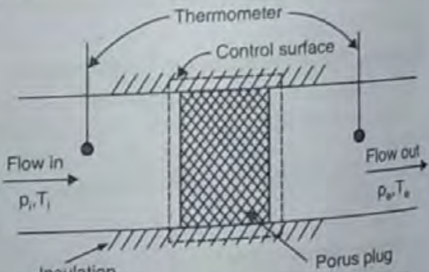


Fig. 4.5. Schematic of porous plug apparatus

Fig. 4.5. shows the schematics of porous plug experiment performed by Joule and Thomson in 1852. A stream of incompressible fluid (gas) is made to pass steadily through a porous plug placed in an insulated and horizontal pipe. The upstream conditions of pressure p_i and temperature T_i are held constant and the corresponding values at exit are measured. The friction of the narrow passage causes the pressure to drop and accordingly the exit pressure p_e is less than the intake pressure p_i.

A throttling process is characterised by the following features :

- no shaft work is involved
- no heat interaction as the pipe is thermally insulated
- no change in potential energy ($z_1 = z_2$) as the pipe is placed horizontally
- negligible changes in kinetic energy.

With these stipulations the steady flow energy equation,

$$h_1 + \frac{V_1^2}{2} + gz_1 + q = h_2 + \frac{V_2^2}{2} + gz_2 + w_s$$

transforms to

$h_1 = h_2$ *i.e.*, enthalpy of fluid remains constant during throttling.

Thus the throttling expansion process is an ***isenthalpic process***. If the fluid undergoing throttling behaves as an ideal gas for which $h = c_pT$, we get

$$c_pT_1 = c_pT_2\ ;\ T_1 = T_2$$

Again for a perfect gas, internal energy is a function of temperature alone and equality of temperature implies that $u_1 = u_2$. Apparently a throttling process takes place at constant enthalpy, constant temperature and constant internal energy.

Throttling is an irreversible process and involves degradation of energy and its dissipation in turbulence.

Joule- Thomson Coefficient, Inversion Point and Inversion Curve

For real gases, enthalpy is a function of both temperature and pressure. As such even though enthalpy remains constant during throttling, the temperature need not remain the same. Experimental test-runs can be conducted by keeping upstream conditions constant but with different down stream pressures. This is achieved by having porous plugs of different sizes. The exit temperature of the fluid at different exit pressures is measured. Since the upstream pressure and temperature conditions are kept constant, the enthalpy of the fluid for all measured conditions of exit pressure and temperature would be constant. The results are plotted as a constant enthalpy (isenthalpy) curve on $T-p$ diagram. Several enthalpy curves can be obtained by repeating the experiments with several inlet conditions.

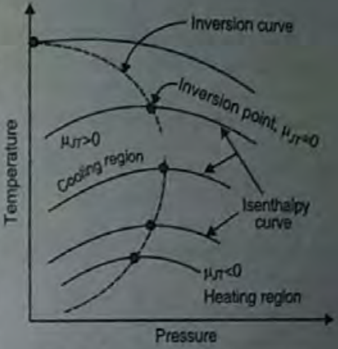


Fig. 4.6. Isenthalpy and inversion curves for a real gas

The slope of an isenthalpic curve is called the Joule-Thomson coefficient, μ_{JT}. That is

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_{h=\text{constant}}$$

This coefficient may be +ve, -ve or zero. The point on the isenthalpic curve where $\mu_{JT} = 0$ is called the ***inversion point***. Thus the inversion point denotes the maximum value of temperature on $T-p$ plot. The locus of all inversion points is called the ***inversion curve***. The Joule - Thomson coefficient is positive on the left side of inversion curve, is zero at the inversion point, and is negative on the right side of inversion curve.

Throttling is always accompanied by pressure drop, *i.e.*, Δp is -ve. That leads to drop in temperature when μ_{JT} is +ve. Accordingly when a real gas is throttled at the condition such that its state lies to the left of inversion curve, the gas will get

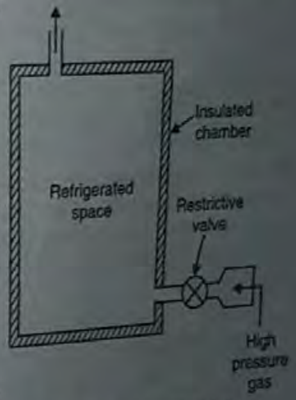


Fig. 4.7. Refrigeration by throttling of gas

cooled. Thus the region of $\mu_{JT} > 0$ represents the region of cooling. Likewise, when μ_{JT} is –ve, the temperature change is +ve and therefore, the throttling of real gas would produce heating effect.

A knowledge of the inversion temperatures and inversion curves of real gases is of considerable importance in the design of refrigeration and liquefaction equipment. The use of positive values of Joule-Thomson coefficient is made in the liquefication of gases such as air, nitrogen and oxygen.

Refer Fig. 2.9 which shows a simplified arrangement of refrigeration by throtting of a gas. The throtting process occurs when the gas at high pressure with its temperature below its critical temperature is made to pass through a valve with restricted opening. Upon throttling, the temperature of gas reduces and cooling effect is produced.

8. Mechanical refrigeration

The natural and chemical methods have been successfully replaced by mechanical or heat energy refrigeration techniques. In these methods, the heat is abstracted from the substance or space (which is to be cooled) is pumped to a system (which is at high temperature level) by taking energy from an external source as input to refrigerating machine. The refrigeration system consists of a cycle of processes with the same quantity of working fluid (refrigerant) in continuous circulation.

The first commercial hand operated refrigeration system was developed in UK by Perkins. The system consisted of a hand operated compressor, a water cooled condenser, a throttle valve and an evaporator. The working substance (ether) was compressed in the hand operated compressor and then condensed in the water cooled condensing unit. Thereafter, the liquid ether was throttled to low pressure and taken to the evaporator where heat was absorbed and cooling effect was produced. The refrigerant ether was used again and again in the cyclic process with negligible wastage. Subsequent developments took place in United States where steam engine was used as a prime mover to drive the compressor. The scope got further widened with the development of electric motors and consequent high speeds of the compressor. Ether too was replaced by new working substances.

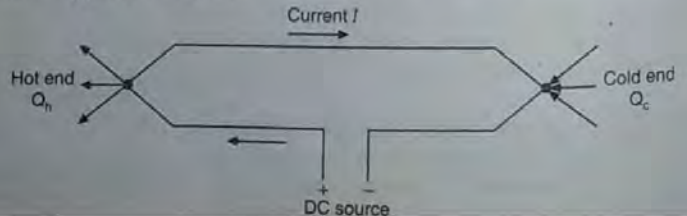
Mechanical refrigeration systems are broadly classified into

- air or gas refrigeration
- vapour compression system
- vapour absorption system, and
- steam jet refrigeration.

Energy needed for the mechanical systems is essentially in the form of mechanical, electrical or thermal. Due to world energy crisis, concerted efforts are being made by various agencies to develop refrigeration systems which utilize waste heat, solar energy, wind energy and bio-energy etc for their functioning. A lot of research is being done to devise ways and means which make the refrigeration systems more energy efficient.

9. Non-conventional refrigeration systems

- *Thermo-electric* cooling uses the Peltier effect to create a heat flux between the junction of two different types of materials.



When a direct current is made to pass through electrical junctions between unlike metals, heating or cooling effect is produced depending on the direction of flow of current. One junction gets heated and the other gets cooled. The cold junction is located inside the space desired to be cooled and the warmed junction lies outside in the surroundings. The hot and cold junctions get reversed when a change occurs in the direction of flow of current. Apparently the same setup can be used for heating and cooling of an insulated space.

With respect to Fig. 4.8, the energy balance of the system is,

$$Q_h - Q_c = EI$$

where E is the emf applied, I is the current, Q_h and Q_c are the actual amount of heat flows at the hot and cold junctions respectively.

This effect is commonly used in camping and portable coolers, and for cooling electronic components and small instruments.

- *Magnetic refrigeration* (adiabatic demagnetisation) is a cooling technology based on magnet caloric effect, an intrinsic property of magnetic solids. A strong magnetic field is applied to the refrigerant, forcing its various magnetic dipoles to align and putting these degrees of freedom of the refrigerant into a state of lowered entropy. A heat sink then absorbs the heat released by the refrigerant due to its loss of entropy. Thermal contact with the heat sink is then broken so that the system is insulated and the magnetic field is switched off. This increases the heat capacity of the refrigerant, thus decreasing its temperature below the temperature of heat sink.

  The refrigerant is often a paramagnetic salt such as cerium magnesium nitrate, and the active magnetic dipoles are those of electron shells of the paramagnetic atoms.

- *Thermo acoustic* refrigeration which uses sound waves in a pressurised gas to drive heat exchange.
- *Vortex tube* that operates with compressed air and is used for spot cooling. A high pressure gas is allowed to expand through a nozzle fitted tangentially to a pipe. This causes simultaneous discharge of cool air at the core and hot air at the periphery.

The mechanical refrigeration and the non-conventional refrigeration systems have been dealt with in details at appropriate places.

4.5. APPLICATIONS OF REFRIGERATION

Refrigeration has played an important role in the growth and attainment of the present-dayu standard of living. Its various applications can be essentially grouped into the following categories :

1. **Domestic refrigeration** deals with providing a low temperature place for preserving eatables, drinks and medicines. The use of refrigerators in our kitchens for the storage of fruits and vegetables has allowed us to add fresh salads to our diets year round, and to store fish and meats for long periods.

2. **Commercial refrigeration** is related to refrigeration fixtures of the type used by restaurants and hotels, retail stores and institutions for storing, displaying, processing and dispensing of perishable commodities of different types.

3. **Industrial refrigeration** is concerned with systems which are much larger in size and cooling capacity that those for commercial applications. Typical industrial applications are :

   - Ice and large food plants
   - Chilling and storage of food stuffs including beverages, meat, poultry products, dairy products, vegetables, fruits and fruit juices etc
   - Processing of food products and farm crops
   - Processing of textiles, printing work and photographic materials

- Oil refineries and synthetic rubber manufacturing. In oil refineries, chemical manufacturing and petrochemical plants, refrigeration is used to maintain processes at their required low temperatures.

Refrigeration is also used to liquefy gases like oxygen, nitrogen, propane and methane. Further, in compressed air purification, it is used to condense water vapour from compressed air to reduce its moisture air content.

4. **Transport refrigeration** applies to refrigerated railway cars and trucks for local delivery and long distance transport of temperature sensitive food stuffs and other materials.

5. **Air-conditioning** refers to the simultaneous control of temperature, humidity, cleanliness and air motion. The conditioning of a space done to provide comfortable and healthy conditions for the occupants is called comfort air conditioning. Residences, offices, theatres and hospitals are the spaces air-conditioned for this purposes.

There are some manufacturing processes which need to be done under controlled environmental conditions. Even some of the sophisticated and precision instruments need controlled conditions for their effective working and upkeep. The conditioning done for this purpose is called industrial air-conditioning and this is concerned with production of environment suitable for :

- computer centres
- pharmaceutical units
- printing works and photographic products
- precision devices and production shop laboratories etc.

The applications cited above clearly indicate that refrigeration and air-conditioning which was considered luxury in the society a few decades ago has become the necessity of the present society and a tool for higher productivity.

4.6. DOMESTIC REFRIGERATOR

A domestic refrigerator serves to preserve food products (fruits and vegetables, meat and fish, milk and ice cream, cold drinks, etc). The unit absorbs heat from these products and dissipates that heat to the surroundings by taking power of a compressor.

The domestic refrigerator works on vapour compression refrigeration cycle, and consists of the following parts :

compressor, condenser, capillary tube and evaporator

These components are schematically arranged as shown in Fig. 4.9 and mounted on the refrigerator which has enamel painted metallic body with interior plastic lining of polystyreme.

The system works on closed cyclic operation and transfers heat through a medium called refrigerant which is usually Freon-12. The refrigerant changes its phase when it passes through condenser and evaporator.

The sequence of operation of the refrigeration cycle is :

1. *Reversible adiabatic compression (1-2):* The refrigerant vapour at low pressure and temperature and preferably in the dry state is drawn from the evaporator during suction stroke of the compressor. The compressor constricts the vapour raising its pressure and temperature.

The compression is of reciprocating type and is hermetically sealed which means that the compressor and electric motor are a single unit enclosed in a container.

2. *Constant pressure condensation (2-3):* The vapour refrigerant at high pressure and temperature (state 2) coming from the compressor is pushed into the condenser coils which are painted black and are located on the back of the refrigerator. The hot refrigerant passes through these coils meets the cooler air of the kitchen and become a liquid.

3. *Throttling (3-4):* The high pressure refrigerant in the liquid state is throttled in the capillary tube. The capillary tube is a simple copper tube of low diameter and long length. This increases friction and that causes pressure drop leading to conversion of high pressure liquid into low pressure liquid.

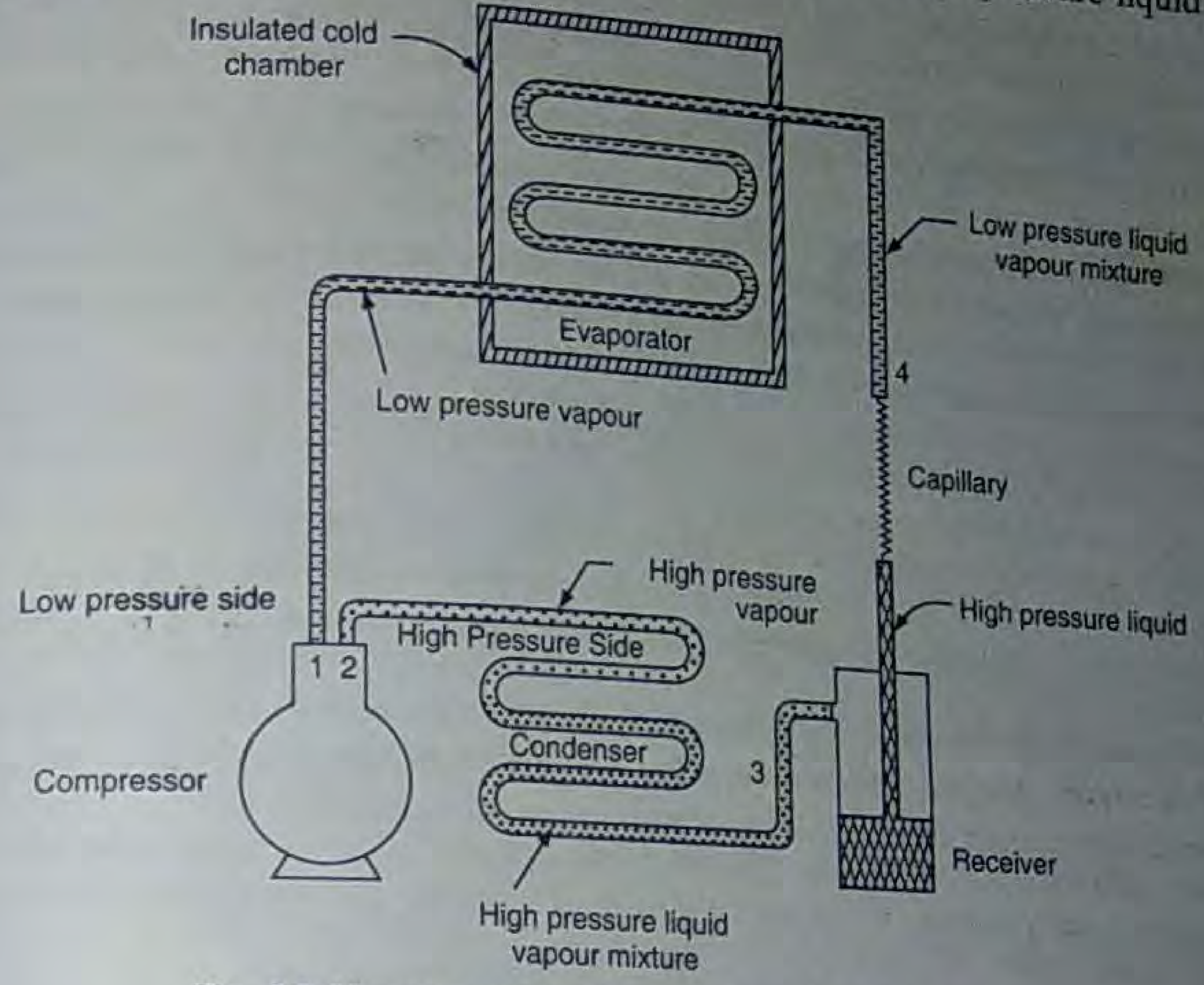


Fig. 4.9. Vapour compression cycle for a domestic refrigerator

4. *Constant pressure evaporation (4-1):* The wet vapour after throttling passes through evaporator coils placed inside the refrigerator. The refrigerant absorbs heat from the food staff which gets cooled. The refrigerant itself vaporises to gaseous state at constant pressure and flows to the compressor.

The cycle is completed and the process starts all over again.

The condenser and evaporator are the simple heat exchangers where the refrigerant changes the phase by rejecting heat (to the condenser) and accepting heat (from the evaporator). The unit has a thermostate which controls the cooling process by monitoring the temperature and then switching the compressor on or off. When the sensor senses that it is cold enough inside the refrigerator, it turn off the compressor. If two much heat is sensed, it switch the compressor and the cooling process begins again.

The domestic refrigerators are available in wide range of sizes and design, and are specified by cooling capacity (refrigerating effect in tons), cooling in litres, overall dimensions (height, width and depth), refrigerant used, and voltage range and power source (AC 230 V, 50 hertz). The refrigerant Freon-12 is now being replaced by HFC-134a which does not deplete the ozone layer.

4.7. PSYCHROMETRY

Psychrometry is the science of studying the thermodynamic properties of moist air and the use of these properties to analyse the conditions and processes involving moist air.

For many purposes, the composition of real air can be assumed to be a mixture of two components:

Standard dry air : Dry air is a mixture of number of gases such as oxygen, nitrogen, carbon dioxide, hydrogen, argon etc. Oxygen and nitrogen are the main constituents with the following composition

21% oxygen and 79% of nitrogen ..... by volume
23% oxygen and 77% nitrogen ..... by mass

The molecular mass of dry air is taken as 20.966 and gas constant equal to 287 J/kgK. For psychrometric purpose, dry air is assumed to be a pure substance and not a mixture.

Water vapour : Air has affinity for water and consequently the atmospheric air always contains some water; water vapour content varies from 0 to 3% by mass.

The moist air is essentially a mixture of dry air and water vapour. The amount of water vapour present depends on the absolute pressure and temperature of the mixture.

For the **moist air**, which is a mixture of dry air and water vapour

$$p_t = p_a + p_v$$

where p_t = total pressure of moist air
p_a = partial pressure of dry air
p_v = partial pressure of water vapour

The ***saturated air-mixture*** is the mixture of dry air and water vapour in which the partial pressure of the water vapour is equal to its saturation pressure corresponding to the temperature of the mixture.

The ***unsaturated air mixture*** is the mixture of dry air and water vapour in which the partial pressure of the water vapour is less than its saturation pressure corresponding to the temperature of the mixture.

The ***super saturated air mixture*** is mixture of dry air and water vapour in which the partial pressure of the water vapour is greater than its saturation pressure corresponding to the temperature of the mixture.

4.8. PARTIAL PRESSURE AND DALTON'S LAW

Consider a homogeneous non-reacting mixture of ideal gases *a, b, c* ... etc at temperature *T*, pressure *p* and occupying a volume *V*. (Fig. 4.10)

Further, let it be presumed that each constituent of the mixture exists separately at temperature *T* and volume *V*, and pressures p_a, p_b, p_c ... exerted by individual gases are measured separately. Each of these pressures would be less than the total pressure *p* of the mixture.

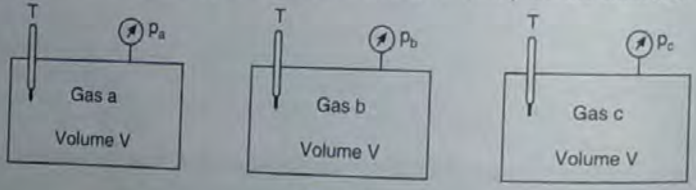


Fig. 4.10.

When the equation of state for an ideal gas is applied to the gas mixture as well as the constituent gases, we have

For the mixture :

$$pV = mRT$$
$$= nMRT = nR_{mol}T \qquad ...(4.2)$$

where R_{mol} is the universal gas constant (R_{mol} = 8314 J/kg mole K) and *M* is the molecular mass

For the constituent gases

$$p_a V = n_a R_{mol}T$$
$$p_b V = n_b R_{mol}T$$
$$p_c V = n_c R_{mol}T \text{ etc.}$$

Upon adding for the components

$$(p_a + p_b + p_c + ...) V = (n_a + n_b + n_c + ...) R_{mol}T$$
$$= nR_{mol}T \qquad ...(4.3)$$

From expressions 7.4 and 7.5,

$$p = p_a + p_b + p_c + ...$$
$$p = \Sigma p_i \qquad ...(4.4)$$

where $p_i = \dfrac{n_i R_{mol}T}{V}$ represents the pressure the component *i* would exert if it alone occupied the volume *V* at temperature *T*. This is called the **partial pressure** of the ith component of the gas mixture. Thus

Partial pressure is defined as the pressure which each individual component of a gas mixture would exert if it alone occupied the volume of the mixture at the same temperature.

Further, the equation 4.4 stipulates that total pressure of a mixture of ideal gases is equal to the sum of the partial pressures of the individual gas components of the mixture.

This is known as **Dalton's law of partial pressures.**

The following relations are implicit in the Dalton's law:

$$t = t_a = t_b = t_c$$
$$V = V_a = V_b = V_c$$

and

$$m = m_a + m_b + m_c \qquad ...(4.5)$$

where *t*, *V* and *m* respectively represent the temperature, volume and mass. In terms of specific volume *v*,

$$m\,v = m_a\,v_a = m_b\,v_b = m_c\,v_c \qquad ...(4.6)$$

Combining expressions 7.7 and 7.8, we may write

$$\frac{m}{mv} = \frac{m_a}{m_a v_a} + \frac{m_b}{m_b\,v_b} + \frac{m_c}{m_c v_c}$$

or

$$\frac{1}{v} = \frac{1}{v_a} + \frac{1}{v_b} + \frac{1}{v_c} \qquad ...(4.7)$$

The reciprocal of specific volume is density and so we can write

$$\rho = \rho_a + \rho_b + \rho_c \qquad ...(4.8)$$

which means that density of the mixture is equal to the sum of the densities of the components.

4.9. SPECIFIC HUMIDITY, RELATIVE HUMIDITY AND DEGREE OF SATURATION

Humidity refers to the dampness, *i.e.*, the water content of air. *Absolute humidity* represents the amount of water vapour actually present in the air, expressed as gram per cubic meter of air.

The ***specific humidity*** or ***humidity ratio*** or ***moisture content*** is the ratio of mass of water vapour to the mass of dry air in a given volume of the mixture. Consider a mixture consisting of m_a kg of dry air and m_v kg of water vapour contained in a vessel of volume *V* at total pressure p_t and temperature *T*. Then

$$\text{Specific humidity, } \omega = \frac{m_v}{m_a}$$

Since both masses occupy volume V,

$$\omega = \frac{m_v/V}{m_a/V} = \frac{\rho_v}{\rho_a} = \frac{v_a}{v_v}$$

where ρ is the density and v is the specific volume

If both the vapour and dry air are considered as perfect gases, then from the characteristic gas equation,

$$m_a = \frac{p_a V}{R_a T} \quad \text{and} \quad m_v = \frac{p_v V}{R_v T}$$

That gives : $\omega = \dfrac{m_v}{m_a}$

$$= \frac{p_v V}{R_v T} \times \frac{R_a T}{p_a V} = \frac{R_a}{R_v} \times \frac{p_v}{p_a}$$

Taking, $R_a = 287$ J/kgK and $R_v = 461$ J/kgK

$$\omega = \frac{287}{461}\frac{p_v}{p_a} = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p_t - p_v} \qquad \text{...(4.9)}$$

The above relation shows that if the total pressure remains constant, the specific humidity is a function of partial pressure of water vapour only. This relationship has been obtained by assuming that behaviour of water vapour is identical with that of an ideal gas. Such an assumption is quite valid at low pressure and normal humidity conditions.

The ***relative humidity*** is the ratio (expressed as a percentage) of the amount of water vapour actually present in a given volume of air to the maximum amount that the air could hold under the same pressure and temperature conditions.

Relative humidity

$$\phi = \frac{\text{mass of water vapour in a given volume}}{\begin{array}{c}\text{mass of water vapour in the same volume}\\ \text{if saturated at the same temperature}\end{array}}$$

With the assumption that vapours behave as perfect gases, we have

$$m_v = \frac{p_v V_v}{R_v T_v} \quad \text{and} \quad m_{vs} = \frac{p_{vs} V_{vs}}{R_{vs} T_{vs}}$$

where vs subscript is used for saturated vapour.

$$\therefore \qquad \phi = \frac{m_v}{m_{vs}} = \frac{p_v V_v}{R_v T_v} \times \frac{R_{vs} T_{vs}}{p_{vs} V_{vs}}$$

Also $V_v = V_{vs}$; $R_v = R_{vs}$ and $T_v = T_{vs}$.

That gives

$$\phi = \frac{p_v}{p_{vs}} \qquad \text{...(4.10)}$$

where p_{vs} is the saturation pressure at the temperature of the mixture. This saturation pressure is obtained from the steam tables corresponding to the given temperature.

Apparently, the relative humidity can also be defined as the ratio of the partial pressure of water vapour in a given volume of mixture to the partial pressure of water vapour when the same volume of mixture is saturated at the same temperature. This implies that ϕ equals unity for saturated air; 100 percent relative humidity means that air contains the maximum moisture it can hold.

Essentially, the term relative humidity compares the humidity of the given air with the humidity of saturated air at the same pressure and temperature. For saturated air, the relative humidity is 100 percent.

The ***degree of saturation*** μ represents the ratio of mass of water vapour associated with unit mass of dry air to the mass of water vapour associated with unit mass of dry air saturated at the same temperature.

$$\mu = \frac{\text{mass of water vapour with unit mass of dry air}}{\text{mass of water vapour with unit mass of dry saturated air}}$$

This relation implies that μ represents the ratio of specific humidity of moist air to specific humidity of saturated air at the same temperature. That is

$$\mu = \frac{\omega}{\omega_s} = \frac{0.622\dfrac{p_v}{p_t - p_v}}{0.622\dfrac{p_{vs}}{p_t - p_{vs}}}$$

$$= \frac{p_v}{p_{vs}}\,\frac{p_t - p_{vs}}{p_t - p_v} = \frac{p_v}{p_{vs}}\left[\frac{1 - \dfrac{p_{vs}}{p_t}}{1 - \dfrac{p_v}{p_t}}\right] \qquad \text{...(4.11)}$$

The following observations can be made from the above relation:

(i) If the air is dry, then $p_v = 0$ and therefore $\mu = 0$.

If the relative humidity $\phi = p_v/p_{vs} = 1$, then $p_v = p_{vs}$ and accordingly $\mu = 1$.

Thus the degree of saturation varies between 0 and 1.

(ii) The degree of saturation is a measure of the capacity of the air to absorb moisture.

When $\mu = 1$, then $\omega = \omega_s$

which implies that air is holding the maximum amount of water vapour.

(iii) The expression for the degree of saturation can be recast as

$$\mu = \frac{p_v}{p_{vs}}\left[\frac{1 - \dfrac{p_{vs}}{p_t}}{1 - \dfrac{p_v}{p_{vs}} \times \dfrac{p_{vs}}{p_t}}\right] = \phi\left[\frac{1 - \dfrac{p_{vs}}{p_t}}{1 - \phi\dfrac{p_{vs}}{p_t}}\right]$$

$$\text{or} \qquad \phi - \phi\frac{p_{vs}}{p_t} = \mu - \mu\phi\frac{p_{vs}}{p_t}$$

$$\text{or} \qquad \phi\left[1 - \frac{p_{vs}}{p_t} + \mu\frac{p_{vs}}{p_t}\right] = \mu$$

$$\text{or} \qquad \phi\left[1 - (1-\mu)\frac{p_{vs}}{p_t}\right] = \mu$$

$$\therefore \qquad \phi = \frac{\mu}{1 - (1-\mu)\dfrac{p_{vs}}{p_t}} \qquad \text{...(4.12)}$$

The difference between relative humidity and degree of saturation is usually less than 2%.

4.10. DRY BULB TEMPERATURE AND WET BULB TEMPERATURE

The ***dry-bulb temperature*** (*dbt*) is the normal temperature of an air-vapour mixture as indicated or recorded by any temperature measuring device placed in the mixture. This temperature is not affected by the moisture content in the mixture.

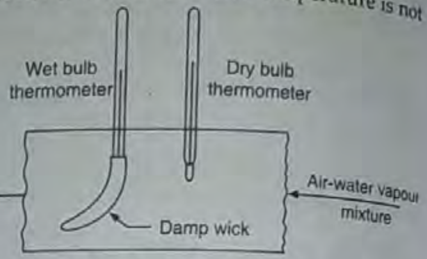


Fig. 4.11. Dry and wet bulb temperature

The ***wet-bulb temperature*** (*wbt*) of an air-vapour mixture is the temperature measured by a thermometer whose bulb is covered by a wick soaked in water. When the air passes over the wet wick, the moisture contained in the wick tends to evaporate. That produces cooling effect at the bulb and an equilibrium temperature lower than that of the air stream is recorded.

It is worthwhile to note that:

(*i*) The wet-bulb temperature is lower than the dry-bulb temperature and the difference is known as the *wet-bulb depression*.

(*ii*) The wet-bulb depression is greatest when the air is initially completely dry, *i.e.*, capable of absorbing a maximum amount of moisture.

(*iii*) When the air is initially saturated, there will be no evaporation of water and hence the two thermometers will record equal temperatures. This implies that the depression is zero with 100 percent relative humidity.

(*iv*) The dry and wet-bulb temperatures are simultaneously measured by instruments called *psychrometers*.

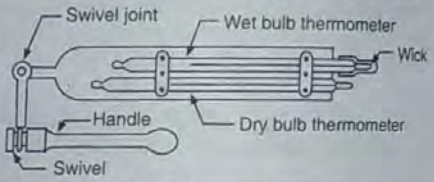


Fig. 4.12. Sling psychrometer

A sling psychrometer consists of two identical mercury-in-glass themometers mounted on a suitable frame and arranged with a swivel-mounted handle as shown in Fig. 4.12. The temperature sensing bulb of one of the thermometers is covered with a knitted or woven cotton wick which is wetted with pure clean water. For better and accurate measurements of the wet bulb temperature, a fast movement of air past the moistened wick is necessary. This is to ensure that the surrounding air does not cling to the moistened wick and that the air at the wet-bulb thermometer is always in immediate contact with the wet wick. The necessary air motion, 5 m/s to 10 m/s, is provided by rotating the psychrometer frame with the swivel mounted handle. The readings are taken after swinging the psychrometer in a smooth circular path for 15 to 20 seconds. With a too short duration, the temperature will not be depressed to its proper value. If the swinging period is too large, the wick will dry and the bulb temperature will not remain at its minimum value.

(*v*) When dry and wet bulb temperatures are known, the other psychrometric properties can be determined by calculations.

(*vi*) Many investigation have suggested different expressions to determine the partial pressure of water vapour in air from the wet and dry bulb temperature readings. Carrier's equation, as given below, is most widely used.

$$p_v = (p_{vs})_{wb} - \frac{(p_t - p_{vs})(dbt - wbt)}{1544 - 1.44\, wbt} \qquad \ldots(4.13)$$

where, p_v = partial pressure of water vapour
p_{vs} = partial pressure of water vapour when air is fully saturated
p_t = total (barometric pressure of moist air)
dbt and *wbt* = dry bulb and wet bulb temperature respectively in °C.

4.11. DEW POINT AND ADIABATIC SATURATION TEMPERATURE

Dew point refers to the temperature at which the mixture becomes saturated, *i.e.*, the moisture (water vapour) present in the mixture begins to condense consequent to continuous cooling at constant pressure.

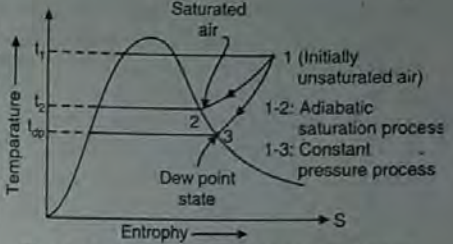


Fig. 4.13. Concept of dew point temperature

With reference to Fig. 4.13, let point 1 represent the initial state of air-water vapour mixture. The vapour is superheated, the pressure equals the partial pressure of the superheated vapour and temperature corresponds to the temperature of the mixture. When the mixture is cooled at constant pressure along the path 1-3, the cooling continues until the vapour attains the saturated state at point 3. With further cooling, the vapour condenses, *i.e.*, the moisture is released. The state point 3 represents the dew point temperature (*dpt*) of the air-water vapour mixture. The dew point temperature thus corresponds to the saturation temperature of steam at the partial pressure of water vapour in the mixture. *For saturated air, the dry bulb temperature, the wet bulb temperature and the dew point temperature is same.*

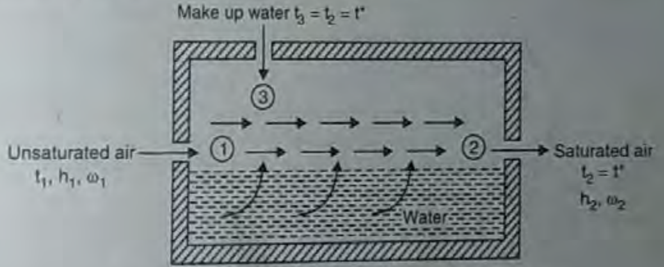


Fig. 4.14. Concept of adiabatic saturation process

The adiabatic saturation temperature (or the thermodynamic wet bulb temperature) refers to the temperatures at which the air can be brought adiabatically to saturation state by the evaporation of water into a flowing stream.

Consider a stream of unsaturated air-vapour mixture flowing over a surface of water contained in a chamber which is sufficiently long and is perfectly insulated. Due to intimate contact between the unsaturated air and liquid water, some of the water evaporates and is carried by air resulting into an increase in its humidity. The heat required for evaporation comes both from the air-vapour mixture and the liquid water in the chamber. The process continues until the energy transferred from the air to the water is equal to the energy required to vaporise the water. By the time, air reaches the exit section, it becomes saturated and an equilibrium is established. The temperature of the saturated air at the exit section is known as ***adiabatic saturation temperature*** or the ***thermodynamic wet bulb temperature***. The steady state thermal equilibrium conditions are maintained by adding make up water steadily at the rate of evaporation. This make up water has to be at the adiabatic saturation temperature, *i.e.*, the temperature of the mixture at the exit section.

With reference to Fig. 4.14, the adiabatic saturation process is represented by path 1-2. During the adiabatic saturation process, the partial pressure of vapour increases, although the total pressure of the air-vapour mixture remains constant. The unsaturated air at dry bulb temperature t_1 is cooled adiabatically to dry bulb temperature t_2 which is equal to adiabatic saturation temperature t^*. For all practical purposes, the adiabatic saturation temperature is taken equal to wet bulb temperature.

EXAMPLE 4.2

A metal beaker contains water initially at room temperature and the water is cooled by gradually adding ice water to it. When the water temperature reaches 13°C, the moisture from room air begins to condense on the beaker. Make calculations for the specific humidity and parts by mass of water vapour in the room air. Take:

room air temperature = 22°C and barometric pressure = 1.01325 bar

Solution : From steam tables, the partial pressure of water vapour at *dpt* of 12.5°C

$$p_v = 1500 \text{ N/m}^2$$

partial pressure of dry air

$$p_a = 101325 - 1500 = 99825 \text{ N/m}^2$$

(*a*) Specific humidity or humidity ratio,

$$\omega = \frac{m_v}{m_a} = 0.622\frac{p_v}{p_a} = 0.622 \times \frac{1500}{99825} = \mathbf{0.009346 \text{ kg/kg of dry air}}$$

(*b*) Parts of mass of water vapour,

$$\frac{m_v}{m} = \frac{\omega}{1+\omega} = \frac{0.009346}{1+0.00934} = \mathbf{0.00926 \text{ kg/kg of mixture}}$$

EXAMPLE 4.3

The air supplied to an air-conditioned room is noted to be at temperature 20°C and specific humidity 0.0085. Corresponding to these conditions, detetrmine the partial pressure of vapour, relative humdiity and dew point temperature.

Take barometric or total pressure = 1.0132 bar

Solution : Specific humidity

$$\omega = 0.622\frac{p_v}{p_a} = 0.622\frac{p_v}{p_t - p_v}$$

Thus : $$0.0085 = 0.622\frac{p_v}{1.0132 - p_v}$$

∴ Partial pressure of vapour

$$p_v = \frac{1.0132 \times 0.0085}{0.622 + 0.0085} = \mathbf{0.01366 \text{ bar}}$$

(*b*) The relative humidity is defined as $\phi = p_v/p_{vs}$. From steam tables, the saturation vapour pressure at 20°C = 0.0234 bar.

Then: $$\phi = \frac{0.01366}{0.0234} = 0.5837 \text{ or } \mathbf{58.38\%}$$

(*c*) The dew point temperature is the saturation temperature of water at a pressure of 0.01366 bar

DPT (from steam tables by interpolation)

$$= 11 + (12-11) \times \frac{(0.01366 - 0.01312)}{0.01401 - 0.01312} = 11 + 0.607 = \mathbf{11.607°C}$$

EXAMPLE 4.4

10 gm of water vapour was removed from a given sample of one kg of atmospheric air at 40°C and 60% relative humidity. The temperature of air after the removal of moisture reduced to 30°C. Determine the humidity ratio, partial pressure of vapour, relative humidity and dew point temperature of this air (air after removal of moisture).

Take total atmospheric pressure as 101.325 kPa.

Solution : The relative humidity is defined as $\phi = p_v/p_{vs}$. From steam tables, the saturation vapour pressure at 40°C = 7.384 kPa

That gives :

$$p_v = \phi\, p_{vs} = 0.6 \times 7.384 = 4.43 \text{ kPa}$$

Specific humidity or humidity ratio

$$\omega = 0.622\frac{p_v}{p_t - p_v}$$

$$= 0.622 \times \frac{4.43}{101.325 - 4.43}$$

$$= 0.0284 \text{ kg/kg of dry air}$$

$$= 28.4 \text{ gm/kg of dry air}$$

(*a*) Since 10 gm of water vapour per kg has been removed,

Specific humdity = 28.4 − 10 = 18.4 gm/kg
= **0.0184 kg/kg of dry air**

(*b*) At this state, the air is at 30°C with specific humidity 0.0184 kg/kg of dry air. Then

$$0.0184 = 0.622\frac{p_v}{101.325 - p_v}$$

That gives: partial pressure of water vapour,

$$p_v = \frac{101.325 \times 0.0184}{0.0184 + 0.622} = \mathbf{2.92 \text{ kPa}}$$

(*c*) At 30°C,

$$p_{vs} = 4.246 \text{ kPa} \qquad \text{(from steam tables)}$$

∴ Relative humidity

$$\phi = \frac{p_v}{p_{vs}} = \frac{2.92}{4.246} = 0.688 \text{ or } \mathbf{68.6\%}$$

(*d*) The dew point temperature is the saturation temperature at the pressure of 2.92 kPa. Then from steam tables

DPT = **24°C**

4.12. PSYCHROMETRIC CHART

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

Humidity calculations can be made by using the equations relating the dry and wet bulb temperatures to the humidity. The method, however, tends to be tedious, cumbersome and time consuming. The key to humidity calculations is then provided by the *Psychrometric* or *Hygrometric chart* which graphically describes the relationship between the properties of moist air, *i.e.*, the dry bulb, the wet bulb and dew point temperatures of the mixture and its humidity. Fig. 4.15 shows how these parameters are laid out on a typical psychrometric chart.

The psychrometic chart has the number of details and its salient aspects are:

1. The dry bulb temperature is taken as abscissa and specific humidity (*i.e.* moisture content) as ordinate.

The dry bulb temperature lines are vertical and uniformly spaced. The specific humidity lines are horizontal and also uniformly spaced. The saturation curve is drawn by plotting the various saturation points at corresponding dry bulb temperatures. The saturation curve represents 100 percent relative humidity at various dry bulb temperatures. It also indicates the wet bulb and dew point temperatures.

2. The dew point temperature lines are horizontal and non-uniformly spaced. At any point on the saturation curve, the dry and dew point temperatures are equal.

The wet bulb temperature lines run diagonally to the right and their values are read at the left where these lines meet the 100 percent relative humidity line. These lines are inclined and straight but not uniformly spaced.

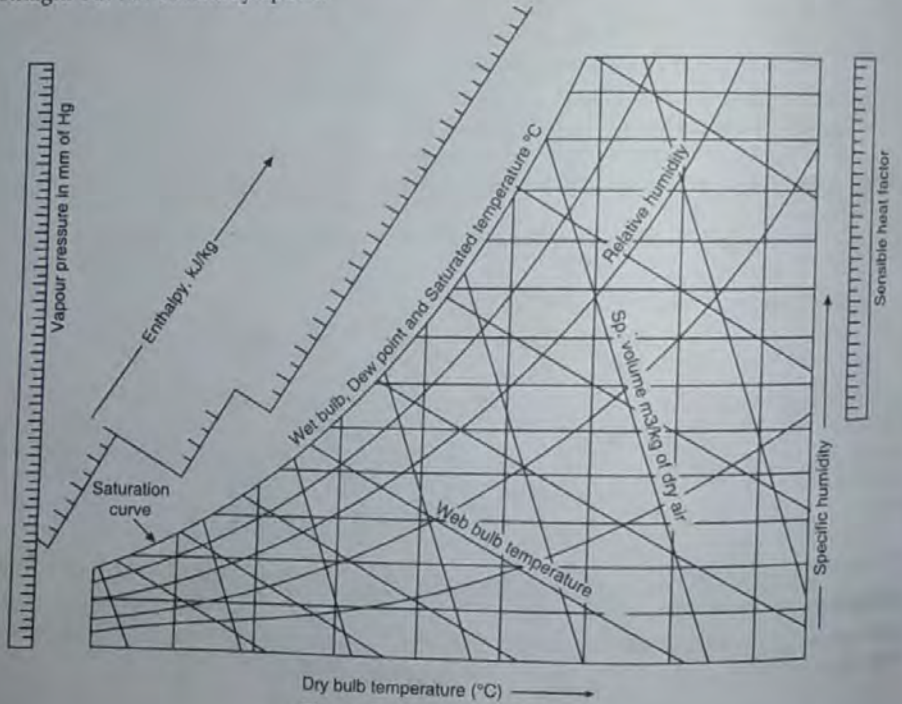


Fig. 4.15. Psychrometric chart

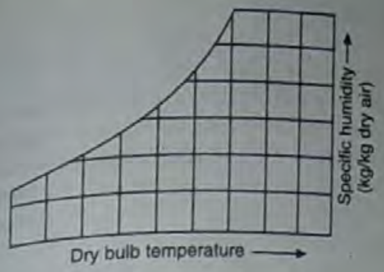


Fig. 4.16. Dry bulb and specific humidity lines

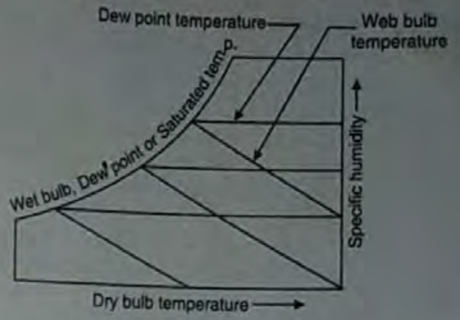


Fig. 4.17. Dew point and wet bulb temperature lines

3. The relative humidity lines curve upwards to the right with the percent values indicated on the lines themselves. The relative humidity curve depicts quantity of moisture actually present in the air as a percentage of the total amount possible at various dry bulb temperatures and masses of vapour.

The specific volume (volume of air-vapour mixture per kg of dry air) lines are indicated by obliquely inclined straight lines. These lines are uniformly spaced and are drawn upto the saturation curve.

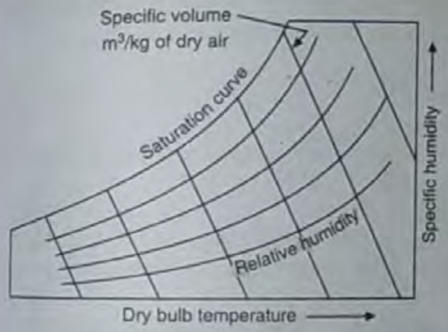


Fig. 4.18. Relative humidity and specific volume lines

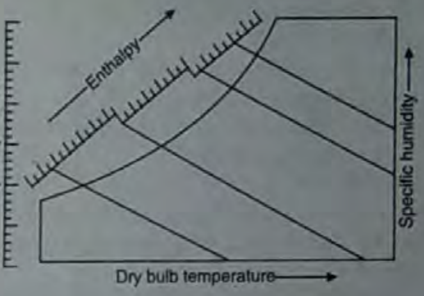


Fig. 4.19. Enthalpy and vapour pressure lines

4. The vapour pressure and enthalpy (total heat) lines are also scaled on the chart. The total heat at saturation temperature is represented by a diagonal system of co-ordinates. These inclined straight lines are uniformly spaced and are parallel to the wet bulb temperature lines. The scale on the diagonal lines is separate from the body of the chart and is indicated above the saturation line.

Pressure of water vapour is shown in the scale on left and is the absolute pressure of steam in mm of mercury.

EXAMPLE 4.5

Atmospheric air at 1 bar pressure has 15°C wet-bulb temperature and 25°C dry-bulb temperature. With the help of a psychrometric chart, determine the salient psychrometric properties of the air.

4.13.1. Sensible heating

The mixture is heated without any change in its moisture content. The process results when the mixture is made to pass over a surface whose temperature is above the dry bulb-temperature of the mixture. The heating surface may be the electric resistance heating coils or steam passed through the coils or hot water passed through the coils.

With reference to Fig. 4.22, the process of sensible heating is represented by horizontal line O-A that extends from left to right.

4.13.2. Sensible cooling

The mixture is cooled without any change in its moisture content. The process results when the mixture is made to pass over a surface whose temperature is below the dry bulb temperature of the mixture. The cooling surface may be cooled water or gas flowing through coils or the refrigerant at low temperature in the coils of the evaporator of a vapour refrigeration system.

With reference to Fig. 4.22, the process of sensible cooling is represented by horizontal line O-B that extends from right to left.

4.13.3. Humidification and dehumidification

Humidification represents the process wherein the moisture is added but its dry bulb temperature is maintained constant. In dehumidification process, the moisture is removed from air without changing its dry bulb temperature. These processes are obviously represented as vertical lines on the psychrometric chart.

With reference to Fig. 4.22, it may be noted that in humidification process O-C, there is increase both in the specific humidity and relative humidity. However, in dehumidification process O-D, both the specific humidity and relative humidity decrease.

In practice, pure humidification and dehumidification processes are not possible. These are always accompanied by heating or cooling.

4.13.4. Heating and humidification

The process is achieved when the moist air is made to pass through spray water whose temperature is maintained at a temperature higher than the dry bulb temperature of the air. The unsaturated air tends to become saturated and the heat of vaporisation is absorbed from the spray water.

With reference to Fig. 4.22, the process of heating and humidification is represented by line O-G and it is to be noted that during this process

(*i*) there is increase in specific humidity, dry and wet bulb temperatures, dew point temperature and enthalpy

(*ii*) the relative humidity may either increase or decrease.

The process of heating and humidification has practical application in winter air-conditioning.

4.13.5. Cooling and dehumidification

The process takes place when the moist air is passed through a cooling coil whose effective surface temperature is lower than the dew point temperature of the mixture.

With reference to Fig. 4.22, the process of the cooling and dehumidification is represented by line O-F and it is to be noted that during this process

(*i*) the dry bulb temperature decreases

(*ii*) the air is cooled and condensation of moisture takes place, *i.e.*, it is dehumidification

(*iii*) there is decrease in specific humidity

(*iv*) the relative humidity at outlet is generally higher than that at inlet.

The cooling and dehumidification process has practical application in summer air-conditioning.

4.13.6. Adiabatic mixing

The process takes place when two streams of moist air having different specific humidities and enthalpies are allowed to mix without the addition or rejection of either heat or moisture, *i.e.*, adiabatically and at constant total moisture content.

The state of the resultant mixture lies on the straight line that joins the state of two streams on psychrometric chart. The location of final state on the straight line depends on the masses involved, and on the enthalpy and specific heat of each stream.

4.14. AIR-CONDITIONING

Air-conditioning is an artificial process that involves cooling as well as heating coupled with ventilation, filtration and air circulation. It is essentially the process of treating air to control simultaneously its temperature, humidity, cleanliness and distribution to meet the comfort requirements of the occupants of the conditioned space. The functioning of an air-conditioning system can be conceived as depicted in Fig. 4.23.

Apart from the creation of an acceptable thermal environment (controlled temperature), control of humidity is of great importance both in humid and arid climates. Further, the air inside the conditioned space gets fouled due to absorption of pollutants from different sources and for human comfort, the indoor air has be purified.

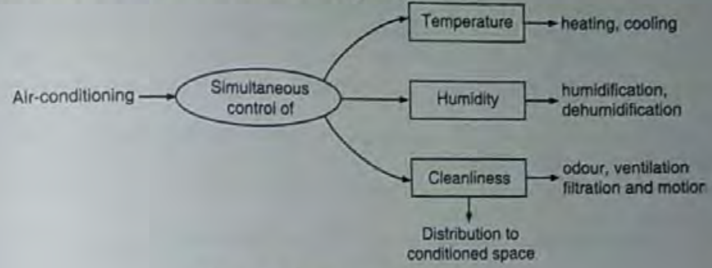


Fig. 4.23. Functioning of air-conditioning

4.15. APPLICATIONS OF AIR-CONDITIONING

Air-conditioning which was once considered as luxury, has now become a necessity in our day-to-day life. The air-conditioning has applications in diverse fields such as

(*i*) Residential and office buildings
(*ii*) Hospitals, cinema halls and departmental stores
(*iii*) Libraries, museums, computer centres and research laboratories
(*iv*) Transport vehicles :
  (*a*) cars, buses and rail coaches
  (*b*) aircrafts, space shuttles and rockets
  (*c*) submarines
(*v*) Printing, textile and photographic products
(*vi*) Food and process industries
(*vii*) Production shop laboratories, manufacture of materials and precision devices.

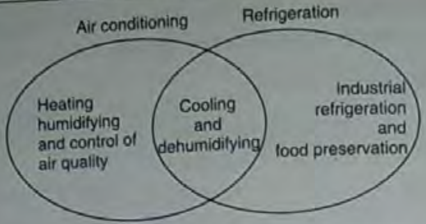


Fig. 4.24. Relationship of refrigeration and air-conditioning

Air-conditioning essentially performs three services in the manufacture of precision metal parts. These services are :

(*a*) maintenance of uniform temperatures so that the metals neither expand nor contract

(*b*) control of humidity so that the rusting of metals is prevented

(*c*) filtration of air so as to minimize dust. Cleanliness of air conditioned space is absolutely essential where electronic components are being manufactured.

The fields of refrigeration and air-conditioning are very closely inter-related as indicated in Fig. 4.24.

4.16. COMFORT AIR-CONDITIONING AND ITS TYPES

Comfort air-conditioning deals with the creation of an optimum environmental conditions conducive to human health, comfort and efficiency. Air-conditioning systems in homes, offices, stores, restaurants, theatres, schools and hospitals etc. are of this type.

The comfort air-conditioning systems are generally classified into the following three categries :

- **Summer air-conditioning :** These systems when properly designed and installed maintain the temperature and humidity of indoor air to a level at which persons feel comfortable. Essentially it involves reducing the air temperature and humidity (in humid tropics) by the process of cooling and dehumidification.
- **Winter air-conditioning :** These systems are meant for the control of environmental conditions of indoor air so as to provide comfort in winter. Essentially it involves an increase in sensible heat and water content of air by the process of heating and humidification. The heating is done by furnaces or boilers fired with solid, liquid or gaseous fuels.
- **Year-round air-conditioning :** This system manifests in the control of temperature and humidity in an enclosed space for all times of the year ; this is despite a change in the atmospheric conditions. Essentially the system comprises the heating and cooling equipment with associated components and automatic controls.

4.17. HUMAN COMFORT

Thermal comfort is a condition of mind which expresses satisfaction with thermal environment. It is the state where the person is entirely unaware of his surroundings; no consideration whether the space is too hot or too cold. Dissatisfaction with the thermal environment may be caused by the body as a whole (being too hot or cold) or by the unwanted heating or cooling of a particular part of the body (local discomfort).

Human comfort refers to the control of temperature and humidity of air and its circulation so that the resulting environment becomes human friendly; the state of environment where persons feel comfortable. Comfort is however a subjective quality; it is dependent on the preferences of an individual and varies with the age, sex, state of health and clothing etc. of a person.

4.18. WINDOW AIR-CONDITIONER

An air-conditioning system is an assembly of different components and parts used to produce a comfortable cooling/heating conditions of air within a closed space.

The closed chamber may be a living room, a conference/seminar hall or an auditorium/theatre. Further, the requirement may be industrial air-conditioning for a highly precision machine or for a research laboratory or for human comfort.

General human comfort conditions to be maintained fall in the range of :

- Temperature : 22°C to 25°C
- Relative humidity : 40% to 60%
- Air velocity : 5 m/min to 8 m/min

Besides these parameters, the standards of air purity in terms of freedom from dirt, dust, foul smell and odour, and noise is also to be ensured for the conditioned space.

The basic elements of an air-conditioning system are :

(*i*) Refrigerating plant
(*ii*) Means for humidification or dehumidification of air
(*iii*) Control system for automatic regulation of cooling or warming
(*iv*) Fans for moving the air to and from the room
(*v*) Filters for cleaning the air by removing dust and dirt particles
(*vi*) Supply and return ducts

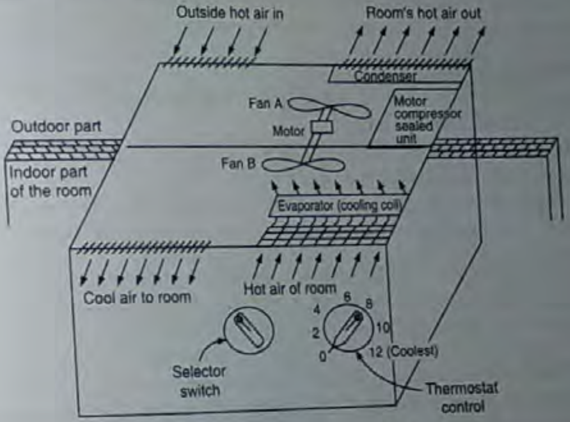


Fig. 4.25. Window air-conditioner

Figure 4.25 shows the constructional details of a window air-conditioner used for human comfort during summer. This is a self contained machine because it houses all the components including evaporator and condenser in a common enclosure. The unit is mounted either in a window or on the wall of the room to be air-conditioned. Such units are available in cooling capacity from ½ to 3½ tons of refrigeration.

The main components of the machine comprise the following sub-assemblies :

(1) System assembly consisting of compressor, condenser, capillary and evaporator units of the refrigerator system.

The hermetically sealed compressor is a compact unit containing both the compressor and motor mounted on a common shaft and encased in two-halves a dome shaped casing which are joined together by circumferential welded joint. The lubrication of the compressor parts is done by the lubricating oil contained in the lower part of the dome.

The window air-conditioners of small size generally have the condenser of the refrigerator air cooled but in large sizes the condenser may be water cooled, in which case pipe connections are needed.

The air-cooled finned type condenser is made up of copper tubes in the form of a coil and provided with aluminium fins.

The evaporator is in the form of coils made of copper and provided with aluminium fins. The capillary tubing is located between the condenser and the evaporator unit.

(2) Cabinet and grill assembly equipped with filtering unit. The filtering unit consists of oil filter or water filter and carbon filter. Oil or water filter cleans the dust particles while the carbon filter removes smell of different gases.

(3) Switch board pannel assembly consisting of selector switch and the thermostat control. The selector switch helps to run the fan/compressor at low, medium and high speeds, and the thermostat fixes the desired temperature.

(4) Outdoor and indoor fans which may be driven by the same motor or may be driven by separate motors.

The refrigerant unit employs Freon-22 or R-134 a as the refrigerant.

The compressor-motor unit, condenser and outdoor fan are kept outdoor, *i.e.*, outside the room while the remaining components are placed indoor *i.e.*, inside the room.

Specifications

A window air-conditioner is normally specified by the following parameters :

- Capacity : 1, 1.5 and 2 ton etc
- Overall dimensions : length × width × height
- Power supply : AC, 220-240 volts, 50 hertz
- Control : Site or remote

Working

When the power switch is put in the ON position the motor-compressor unit starts running. The refrigerant vapours at low temperature and low pressure coming from the evaporator enter the compressor through suction line. The vapours are compressed and there occurs an increase both in temperature and pressure. These vapours are led to condenser through discharge line. The vapours condense rejecting their heat to the atmospheric air. The condensed vapours next enter the capillary tube, are throttled to low pressure on account of friction and their temperature gets reduced to minimum operating temperature of the refrigerant cycle. The low pressure liquid refrigerant now enters the evaporator, absorbs the latent heat of vaporisation from the room air and that results in the cooling of this air. This cooled air is directed through a ducted passage in the front cover grill and that provides comfortable cooling conditions in the air.

The refrigerant vapours leave the evaporator and enter the compressor during its suction stroke and that completes the working cycle.

REVIEW QUESTIONS

A. Conceptual and conventional questions

1. Define refrigeration and air-conditioning.
2. State the difference between a refrigerator and a heat pump. How do these machines satisfy the second law of thermodynamics?
3. What is meant by COP? What value of COP is desirable, large or small and why?
4. Set up a relation for the COP of a heat pump and that of a refrigerator. Proceed to show that

$$(\mathrm{COP})_{\text{heat pump}} = 1 + (\mathrm{COP})_{\text{refrigerator}}$$

5. Define the following terms :
   (*a*) refrigerating effect
   (*b*) relative COP
   (*c*) ton of refrigeration
6. Mention the various applications of refrigeration.
7. Describe, with a neat schematic arrangement, the working of a domestic refrigerator.
8. What is moist air and saturated air?
9. Define and explain the following terms in relation to psychrometry
   (*a*) dry bulb, wet bulb and dew point temperatures.
   (*b*) relative humidity and specific humidity
10. Establish the following expression for air-vapour mixture

$$\text{specific humidity } \omega = 0.622 \frac{p_v}{p_b - p_v}$$

where p_v is the partial pressure of water vapour and p_b is the barometric pressure.

11. Define and explain the concept of dew point and adiabatic saturation temperature.
12. What is a sling psychrometer? Draw its neat sketch and explain its use.
13. What is a psychrometric chart? What information does it provide?
14. Name any five psychrometric processes and represent them on the psychrometric chart.
15. Define air-conditioning and mention some of its applications.
16. What is meant by comfort air-conditioning? Give brief description of its various types.

B. Fill in the blanks with appropriate word/words

1. A refrigeration system removes hea from a system at ________ temperature and transfers the same to a system at ________ temperature.
2. One ton of refrigeration is equivalent to ________ kW
3. The bank of tubes at the back of a domestic refrigerator of vapour compression type are the ________ tubes.
4. In a vapour compression refrigeration system, the capillary tube is located between ________ and ________
5. For psychrometric purpose, ________ is assumed to be a pure substance and not a mixture.
6. The ________ air is essentially a mixture of dry air and water vapour.
7. ________ humidity represents the amount of water vapour actually present in the air.
8. The wet bulb temperature would be zero when the relative humidity is ________ percent.
9. The ________ is a measure of the capacity of air to absorb moisture.
10. If total pressure remains constant, the ________ humidity is a function of partial pressure of water vapour only.
11. The difference between the dry bulb temperature and wet bulb temperature is known as ________
12. The dry and wet bulb temperature are measured by instruments called ________