CHAPTER

1

States of Matter

CONTENTS

INTRODUCTION

Matter normally exists in one of the three states – solid, liquid or gas. However, there is no sharp demarcation between the various states and in most cases a substance may be made to exist in any of the three states. The factors which usually determine the state in which matter exists are the intensity of intermolecular forces, the temperature and pressure. Solids have the strongest intermolecular forces and the gases have the weakest. As the temperature of a solid is increased, the molecules acquire sufficient energy to break the ordered structure and pass into the liquid form. On further increasing the temperature, the liquid changes to the gaseous state. Under certain conditions, a substance may be able to co-exist in all the three states, simultaneously. For example, solid ice, liquid water and water vapour, all co-exist at the freezing point of water.

THE GASEOUS STATE

The physical behaviour of gases is independent of chemical nature of the molecules. Therefore, almost all gases respond in an identical way to the variations in pressure, temperature and volume.

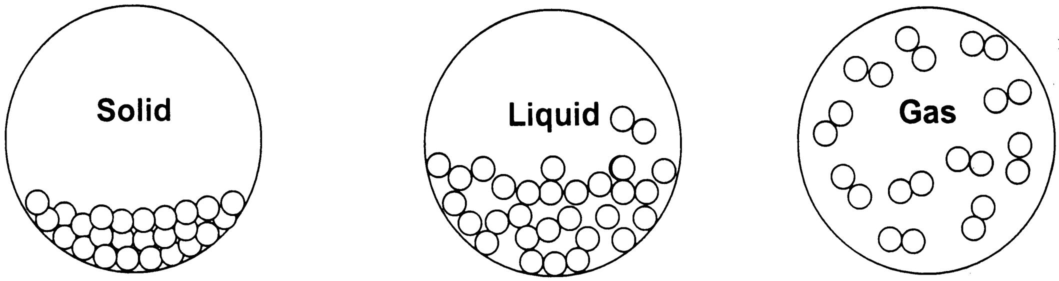

Fig. 1.1. States of Matter.

Since the molecules in a gas are always in a state of vigorous and rapid motion, these travel in random paths, collide with one another and with the wall of the container in which they are confined. These tend to occupy completely all the space (volume) available in the container and exert a pressure on the wall of the container.

Ideal and Non-ideal Gases

The general behaviour of an ideal gas with variations of pressure, volume and temperature can be given by the ideal gas equation.

$$PV = nRT \text{ for ‘n’ moles of ideal gas.}$$

where P is the pressure, V is the volume, n is the number of moles of gas, R is a gas constant and T is the absolute temperature.

The ideal gas law has been derived by combining the gas laws formulated by Gay-Lussac, Boyle, Charles and Avadardro (Fig. 1.2)

From the ideal gas law, it is clear that the volume of a gas is directly proportional to the number of moles of the gas and to the absolute temperature, and is inversely proportional to the pressure.

R (gas constant) has a value of 0.821 lit.atm.mole^{-1}deg^{-1} when P and V are expressed in atmosphere and litres respectively. The value of R is 8.3214 × 10^{7} ergs.mole^{-1}deg^{-1} when P and V are expressed in dynes/cm^{2} and cm^{3} respectively

Ideal gas molecules are assumed to exhibit no intermolecular forces of attraction. Real and

Law of Gay-Lussac $P_1/T_1 = P_2/T_2$	Boyle's Law $P_1V_1 = P_2V_2$
Charle's Law $V_1/T_1 = V_2/T_2$	Avagadro's Law $V_1/n_1 = V_2/n_2$

Fig. 1.2. Various gas laws combined for deriving the ideal gas law.

actual gases usually deviate from ideal behaviour as the molecules tend to attract one another. The deviation from the ideal behaviour becomes significant when the pressure becomes very high and the temperature very low. At ordinary temperature and pressure, these gases obey the law sufficiently accurately.

Departure of real gases from ideality can be demonstrated by means of plots such as that shown in Fig. 1.3 where PV/RT is plotted as a function of pressure for 1 mole of each gas. From the ideal gas equation, the value of PV/RT should be a constant and should yield a straight line parallel to the x-axis at a given temperature T. As can be seen from Fig. 1.3, real gases do not actually yield a straight line.

A better approximation to the real behaviour may be obtained by the use of the van der Waal's equation:

$$\left(P + \frac{an^2}{V^2}\right)(V - nb) = nRT$$

where a and b are constants for a particular gas. a/V^2 accounts for the internal pressure per mole resulting from the intermolecular forces of attraction between the molecules.

THE LIQUID STATE

The liquid state may be considered as an intermediate state as matter goes from the solid state to the gaseous state. Liquids can be considered as highly compressed gases or slightly released solids. The molecules of a gas are in a state of constant motion owing to their kinetic energy which is proportional to the absolute temperature of the gas. When the gas is cooled, its kinetic energy is gradually reduced. As the temperature is being reduced, a stage is reached where the molecules almost loose their

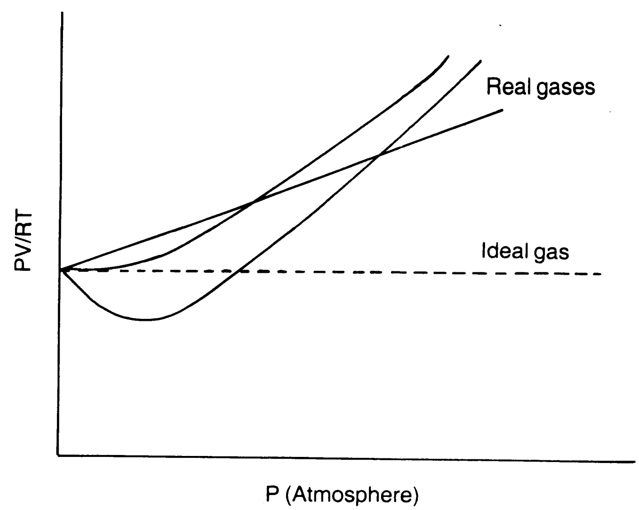

Fig. 1.3. Plot demonstrating the deviation of real gases from ideal behaviour.

kinetic energy and are not able to overcome the forces of attraction. As a result, the gas molecules come closer and ultimately the gas gets converted into the liquid state. Liquifaction of a gas can also be brought about by increasing the pressure on the gas. However pressure is effective only below a certain temperature. This temperature is called *Critical temperature* and can be defined as the temperature above which a gas cannot be liquefied even if very high pressure is applied. The *Critical pressure* is the pressure required to liquify a gas at its critical temperature. The critical temperature of water is 374°C or 647°K and its critical pressure is 218 atmospheres.

THE SOLID STATE

The most important property of the solid state is the high degree of order in which solid substances exist. Their structure may be crystalline and lattice-like or noncrystalline such as glass which are not lattice-like or only partly lattice-like. However, even the non-crystalline solids have much more order than liquids and gases. The molecules of a solid are held together by strong bonds which impart a high melting point to these substances. In order of their decreasing strengths, these include metallic bonds, ionic bonds, valence bonds and molecular bonds.

Crystalline Solids

The structural units of crystalline solids are arranged in fixed geometric patterns or lattices. Crystalline solids generally exhibit a definite shape and an orderly arrangement of units. These generally have a sharp melting point. The various crystalline solids have been divided into seven distinct forms (Fig. 1.4). These include cubic form (e.g., sodium chloride), tetragonal form (e.g., urea), hexagonal form

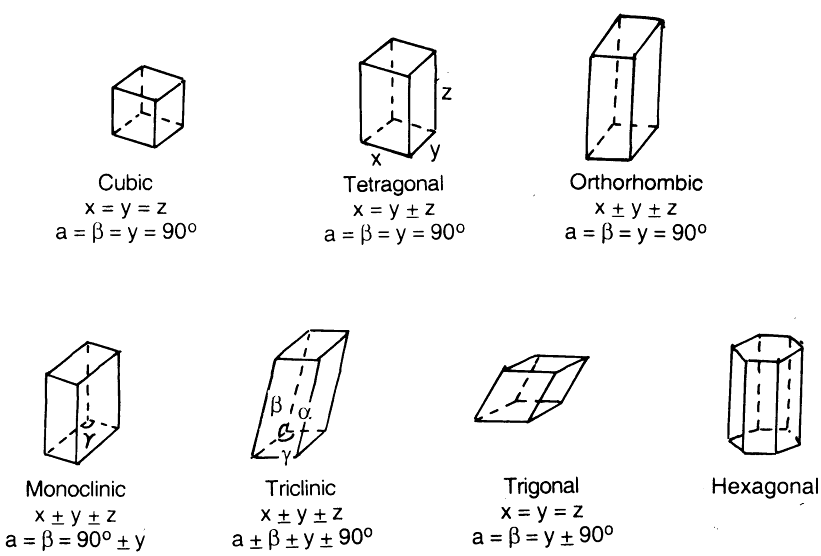

Fig. 1.4. The seven crystal systems.

(e.g., iodoform), orthorhombic form (e.g., iodine), monoclinic form (e.g., sucrose) trigonal form (e.g., calamine) and triclinic form (e.g., boric acid).

Amorphous Solids

Unlike crystalline solids, the structural units in amorphous solids are arranged in a random manner. Amorphous solids may be considered as super cooled liquids . Examples of amorphous solids include glass, woods, plastics, etc. Amorphous solids do not have a sharp melting point and melt within some narrow range of temperatures. These are in general more soluble than crystalline solids.

Polymorphism

Many substances may exist in more than one crystalline or amorphous form. *This phenomenon where compounds exist in more than one crystalline and/or amorphous forms is termed as polymorphism and the different crystalline/amorphous forms are known as polymorphs (or modifications) or polymorphic forms.* The various polymorphic forms usually arise through packing of the molecules in different arrays within the crystal or by differences in the orientation or conformation of the molecules at lattice sites.

Different polymorphic forms of a substance usually exhibit different melting points, X-ray diffraction patterns, solubilities, dissolution behaviour, stability and biological activity. A number of pharmacologically active substances such as chloramphenicol, novobiocin, furosemide, indomethacin, sulphonamides, barbiturates, steroids such as cortisone, testosterone, prednisolone, etc. have been shown to exhibit a number of polymorphic forms differing in their solubilities, stability and pharmacological activity. In general, the crystal form that has the lowest free energy is the most stable polymorph. Polymorphs that are metastable may convert to a more stable form over time.

Polymorphism can affect the mechanical properties of drug particles and can therefore affect the manufacturability and physical attributes of dosage forms like tablets. For example, different polymorphic forms of drugs like paracetamol, carbamazepine, phenobarbitone and sulfamerazine have exihibited different mechanical properties such as compressibility, flowability, hardness, bonding strength, etc. Many organic substances such as tristearin and theobroma oil also exhibit polymorphism. Theobroma oil (cocoa butter) exhibits four different polymorphic forms viz., α, β, β' and γ forms differing in their respective melting points. A change in the crystal form may also cause problems in manufacturing the product. For example, a change in crystal structure of the drug may cause cracking in a tablet or even prevent a granulation to be compressed into a tablet requiring reformulation of the product.

Polymorphism has been demonstrated to impact significantly the dissolution rate, absorption and hence, bioavailability of a number of drugs such as chloramphenicol palmitate, oxytetracycline, carbamazepine, mefenamic acid, phenylbutazone, etc. Chloramphenicol palmitate polymorph B has significantly greater absorption than polymorph A in humans. Similarly, the three polymorphic forms of terfenadine differ in the solubility and therefore bioavailability in humans.

LIQUID CRYSTALS

In addition to the three states of matter, some asymmetric molecules often exhibit a fourth state known as the liquid crystalline state or mesophase. Liquid crystals possess some of the properties of liquids and some of solids. For example, liquid crystals possess the property of mobility and rotation and thus can be considered to have the flow properties of liquids. On the other hand, these also possess the property of birefringence, a property often associated with solid crystals. In birefringence, the light passing through a material is divided into two components with different velocities and hence different refractive index.

The two main types of structure of liquid crystals are the smectic (soap or grease like) and nematic (thread like). In the smectic state, the molecules are mobile in two directions and show rotation about one axis. In the nematic state, the molecules are mobile in three dimensions. A third type known as the cholesteric crystals exist but may be considered as a special case of the nematic type (Fig. 1.5).

The liquid crystalline state is fcund widespread in nature — in nerve, brain tissue and blood vessels. Atherosclerosis is thought to result from the deposition of lipid in the liquid crystalline state on the walls of blood vessels. The three components of bile, the cholesterol, the bile salts and water when present in a definite proportion can result in the formation of smectic crystals and these may be involved in the formation of gall stones. Certain smectic crystals are believed to be involved in the stabilisation of emulsion and have been used for the solubilisation of water insoluble materials.

THE GLASSY STATE

Although glass is considered to be a nonconducting transparent solid, it is actually a type of solid matter. It can neither be considered as a typical solid nor a typical liquid. The atoms and molecules in most solids are arranged in an orderly manner whereas in glassy materials these are highly disordered. Glassy materials however, have some short-range order as in the case of polymers. Glassy materials also do not have a specific melting point but these slowly and gradually liquify on heating.

Structurally glassy materials can be considered to be made up of a random selection of polyhedral molecules linked together at their corners. Certain materials can easily be converted to a glassy state

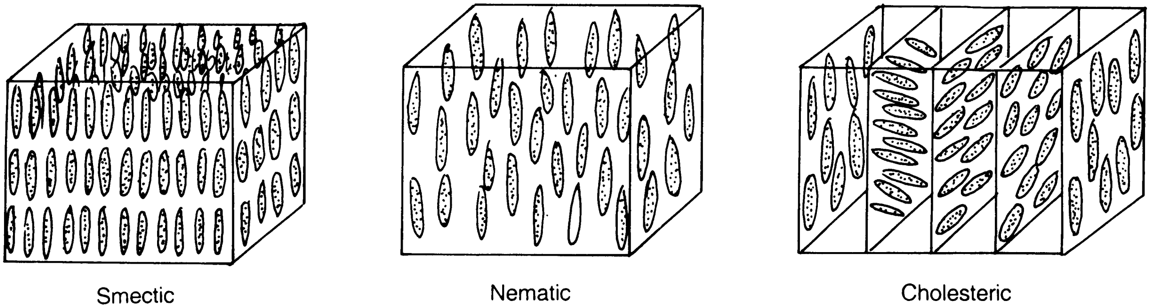

Fig. 1.5. Liquid crystalline phase.

while other pose great difficulty and certain materials cannot be converted at all. Although the theory behind this behaviour is not very clear, it has been shown that materials which can be converted to glassy state have a very high viscosity at their melting point which inhibits the formation of an ordered structure.

Although the most common materials which can be converted to glassy state are the metal oxides, even materials such as steel can be converted to the glassy state if it is cooled very quickly. This technique produces glasses since the material solidifies even before it gets a chance to develop a crystalline structure.

CHANGE IN THE STATE OF MATTER

The molecules, atoms or ions in a solid are strongly held in close proximity by intermolecular, interatomic or ionic forces respectively. The particles of the solid can oscillate only about fixed positions. As the temperature of a solid substance is raised, the particles acquire sufficient energy to disrupt the ordered arrangement and pass into the liquid state. On further increasing the temperature, the molecules pass into the gaseous state. In gaseous state, the intermolecular forces are reduced to almost negligible. Sometimes, a change of state occurs directly from solid state to the gaseous state and this is termed as sublimation.

As solid changes to a liquid state and then to gaseous state, heat is absorbed and the enthalpy (heat content) of the material increases. Thus, the enthalpy of a liquid is greater than that of a solid and the enthalpy of a gas is greater than that of the liquid. The entropy (degree of molecular randomness) of the material also increases as it goes from a solid to a liquid and to gas.

Latent Heat

When a change in the state of a material occurs, the temperature usually remains constant but heat is absorbed. This heat which results in the change of matter without increasing the temperature is called the latent heat. When this heat results in the change of state from a solid to a liquid, it is known as the *latent heat of fusion*. For example, the heat required to change ice to water at 0°C is the *latent heat of fusion*. Likewise the latent heat of vaporisation is the quantity of heat absorbed when a change of state from liquid to vapour occurs at its boiling point without changing the temperature of the material. For example, the heat required to change water to vapour at 100°C is the latent heat of vaporisation.

Vapour Pressure

When a liquid is kept in a closed evacuated container, molecules from its surface continuously leave and go into the free space above it. This is known as the process of vaporisation. Some molecules however return to the surface depending on their concentration in the vapour (the process of condensation). Eventually, a condition of equilibrium gets established when the rate of escape of molecules becomes equal to the rate of return. The vapour is then said to be saturated and the pressure exerted by the vapour at equilibrium is known as the *Vapour pressure*.

The vapour pressure of a liquid depends on the temperature and not on the amount of liquid or vapour as long as both liquid and vapour are present and equilibrium is maintained. As the temperature is raised, more of the liquid goes into the vapour state and the vapour pressure increases. As the temperature is raised further, the density of the vapour increases while that of liquid decreases. Eventually, the densities of both the phases become equal and the two phases cannot be distinguished. The temperature at which this happens is known as the *Critical temperature* and above this temperature, there is no liquid phase.

Relative Humidity

Relative Humidity may be defined as the ratio of amount of water vapor in the air at a specific temperature to the maximum amount that the air could hold at that temperature, expressed as a percentage. In other words, it is the ratio of the actual water vapour pressure to the saturation water vapour pressure at the prevailing temperature.

$$\text{Relative humidity} = \frac{\text{Actual water vapour pressure}}{\text{Saturated water vapour pressure}} \times 100\%$$

The amount of water vapour the air can hold increases with temperature. Relative humidity therefore decreases with increasing temperature if the actual amount of water vapour stays the same.

Boiling Point

When a liquid is heated in an open vessel, the vapour pressure above it increases. On further heating, its vapour pressure becomes equal to the atmospheric pressure. The temperature at which the vapour pressure of a liquid equals the external or atmospheric pressure is known as its boiling point. At the boiling point all the absorbed heat is used to change the liquid to the vapour state and there is no rise in the temperature of the liquid until it is completely vaporised. Different liquids have different boiling point.

If the external pressure above the surface of a liquid is decreased or increased, the boiling point of the liquid is also decreased or increased.

Melting point and Freezing Point

The temperature at which a solid passes into liquid state under atmospheric pressure is known as its melting point. The melting point is referred to as freezing point if the liquid passes into the solid state. The melting or freezing point of a crystalline substance is actually the temperature at which the pure liquid and solid co-exist in equilibrium. In practice, this point is taken as the temperature of the equilibrium mixture at an external pressure of 1 atm.

Vapour Pressure of a mixture of liquids

In the case of miscible liquids (solution of a liquid in liquid), the partial vapour pressure exerted by each component is proportional to its molar concentration in the mixture solution. The total vapour pressure P is given by :

$$P = P_A + P_B = P_A^o X_A + P_B^o X_B$$

where,

X_A and X_B are mole fractions of components A and B respectively.

P_A^o and P_B^o are the vapour pressures exerted by the pure components A and B respectively.

P_A and P_B are the partial vapour pressures exerted by A and B respectively in the liquid mixture.

In the case of a mixture containing two immiscible liquids each liquid exerts its own vapour pressure independently of the other. The total vapour pressure P is then given by :

$$P = P_A^o + P_B^o$$

Sublimation

Sublimation is defined as the process of transformation of solids directly into the vapour phase without passing into the intermediate liquid phase. A number of substances including camphor, menthol, naphthalene, etc., exhibit the phenomenon of sublimation. Other substances such as ice can also be forced to exhibit the phenomenon of sublimation by varying the temperature and pressure; the process being adopted during *freeze drying* of heat labile substances.

Principle

Let us consider the phase diagram for a substance as shown in Fig. 1.6.

The curve AO represents the melting point of the solid phase of the substance at different pressures. Along the curve AO, the solid exists in equilibrium with its liquid phase. To the left of the

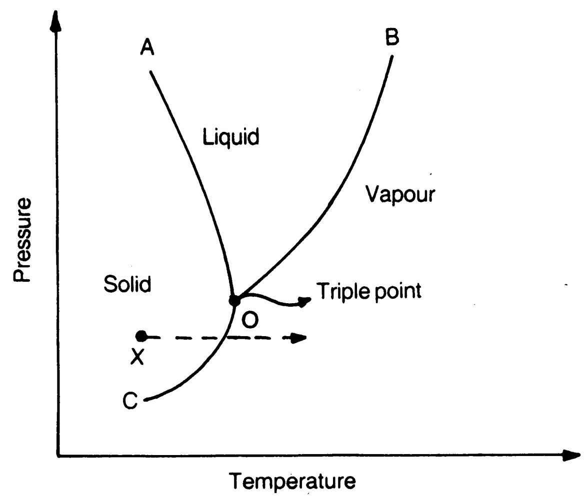

Fig. 1.6. Phase diagram illustrating the principle of sublimation.

curve, the substance exists in the solid state while to the right, it is in the liquid state. BO represents the vapour pressure of the liquid form of the substance at various temperatures. This curve is known as the vapour pressure curve of the liquid. Above this curve, the material exists in the form of liquid while below it, only the vapour form exists. The curve CO represents the vapour pressure of the solid at various temperatures and is also known as the sublimation curve. To the left of the curve, only solid exists while to the right, only the vapour form is stable. However, there exists one point (O) where all the three phases of the material are in equilibrium with each other and this is known as the Triple Point. For pure water this corresponds to a pressure of 610 N/m^2 and a temperature of 0.0075°C.

Now let us consider a point 'X' below the triple point where the substance is present in the form of a solid. If heat is applied to the substance at this point, it will pass directly into the vapour phase without passing through the liquid state. This is the process of sublimation.

Eutectic Mixtures

Certain substances such menthol, thymol, camphor, phenol, salol, etc. when mixed in a particular proportion tend to liquify due to reduction in their respective melting points. Mixtures of such substances are known as eutectic mixtures. (Greek meaning : Eutectic — Easy melting)

Principle

Let us consider two substances A and B. In Fig. 1.7, the points A and B represent the melting points of the two components. As increasing quantities of B are added to A, the freezing point of A falls along the curve AC. Similarly, as increasing quantities of A are added to B, the freezing point of B falls along the curve BC. At a particular composition C, known as the eutectic Point, the mixture of the two substances has the lowest melting point. This composition of the two substances is known as

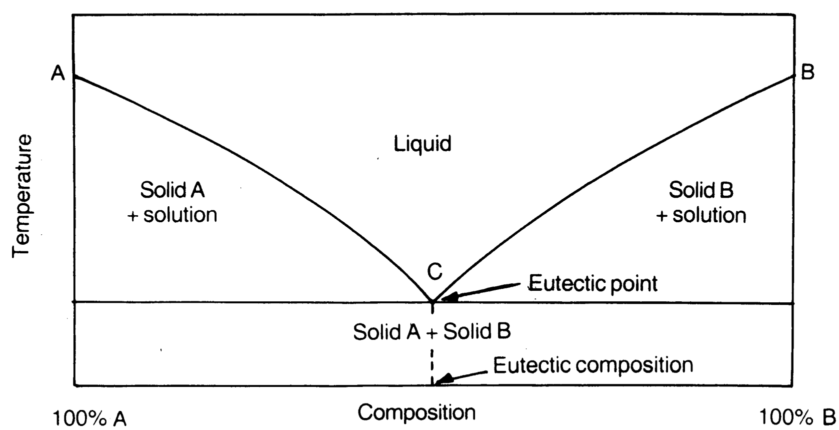

Fig. 1.7. Phase diagram showing a Eutectic System

the eutectic mixture. Below the eutectic temperature the mixture of the two substances will exist as solid while above it, the mixture will convert into a liquid.

In pharmaceutical practice, eutectic mixtures are difficult to dispense in the form of a powder. In order to incorporate such materials in a powder, it is essential to first mix each ingredient separately with an inert diluent such as light magnesium oxide, magnesium carbonate, starch, kaolin, etc., followed by gentle blending of the different portions. Alternatively, the eutectic materials can first be triturated together in order to force them to liquify. The liquid can then be adsorbed on an inert diluent.

The phenomenon of eutectic formation has also been used in pharmaceutical practice to improve the dissolution behaviour of certain drugs. For example eutectic mixture of aspirin-acetaminophen (37% and 63% respectively), urea-acetaminophen (46% and 54% respectively) and griseofulvin-succinic acid (55% and 45% respectively) dissolve more rapidly than the drugs alone or their simple mixtures.

Aerosols

Liquefaction of a gas can be achieved by applying pressure on it and keeping the temperature below the critical temperature. When the pressure is reduced, the molecules expand and the liquid reverts back to the gaseous state. Aerosols are based on this principle of reversible change of state on the application and release of pressure. In pharmaceutical aerosols, a drug is dissolved or suspended in a propellant, a material which exists as a liquid under the pressure conditions prevalent inside the container but gets converted to a gas under normal atmospheric conditions. The container is designed in such a manner that on depressing a valve, some of the drug-propellant mixture is expelled out due to the excess pressure inside the container (Fig. 1.8). The propellant used in such products are generally fluorinated hydrocarbons although gases such as nitrogen and carbon dioxide and also being used.

The aerosol containers are filled either by cooling the propellant and drug to a low temperature within the container which is then sealed with the valve. Alternatively, the drug is sealed in the container at room temperature and the required quantity of propellant is forced into the container under pressure. In both the cases, when the container is at room temperature, part of the propellant is in the gaseous state and exerts pressure necessary to extrude the drug while the remaining is in the liquid state and provides a solution or suspension vehicle for the drug.

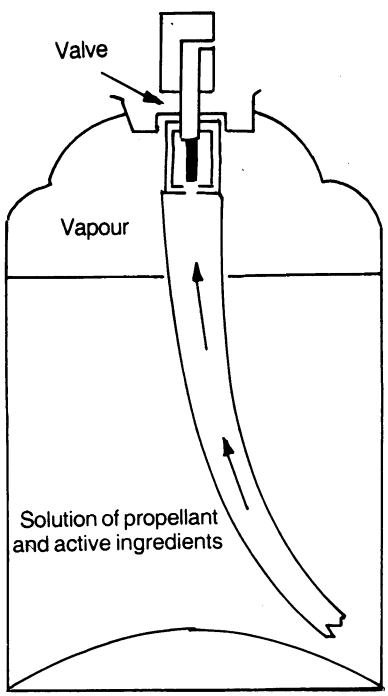

Fig. 1.8. An aerosol system.

REVISION EXERCISES

I. Long answer type questions:

1. Discuss in detail the properties of the various states of matter. How does transition take place from one state of matter to the other?
2. What do you understand by polymorphism ? Giving suitable examples give its importance in pharmacy.
3. Write notes on :
   (a) Liquid Crystals
   (b) Eutectic mixtures
   (c) Triple point
4. Define sublimation giving examples of materials which exhibit sublimation.
5. With the use of phase diagram, illustrate the principle of sublimation.
6. Discuss the principles underlying formation of aerosols.

II. Short answer type questions:

1. What is an ideal gas? Why do real gases differ in their behaviour from an ideal gas?
2. What are liquid crystals? Give examples.
3. What do you understand by latent heat of vaporisation and latent heat of fusion?
4. Define boiling point, melting point and freezing point.
5. With the help of a neat phase diagram, explain the principle of sublimation.

III. Multiple choice questions:

1. Which of the following describes the gaseous state of matter?
   a) A gas has both a definite shape and volume.
   b) A gas has a definite shape but not a definite volume.
   c) A gas has a definite volume but not a definite shape.
   d) A gas has neither a definite shape nor volume.

   Correct option: d)
2. One of the assumptions of the ideal gas law is that:
   a) Molecules have no attraction to one another
   b) Gas particles move very slowly
   c) Molecules move in curved paths
   d) None of the above

   Correct option: a)
3. The phenomenon in which a substance exists in more than one crystalline forms is known as:
   a) Polymorphism

b) Crystallinity
c) Anisotropy
d) Polycrystallinity

Correct option: a)

4. A vapor is:
   a) A very dense gas
   b) A gas with weak Vander Waal forces
   c) A gas that is normally a liquid
   d) A liquid that is normally a gas

   Correct option: c)

5. Polymorphism refers to compounds having:
   a) Different stereochemistry
   b) Different crystal structure
   c) Different composition
   d) all of the above

   Correct option: b)

6. The maximum temperature at which the two phase region exists in a mixture of two partially miscible liquids is known as:
   a) Upper consolute temperature
   b) Lower consolute temperature
   c) Critical temperature
   d) Kraft point

   Correct option: a)

7. Amorphous form of a drug dissolves __________ than the crystalline form
   a) Slower
   b) Faster
   c) Equal to
   d) Does not dissolve

   Correct option: b)

8. Which of the following are properties or examples of amorphous solids?
   a) No crystal structure
   b) No definite melting point
   c) Glassy
   d) All of the above

   Correct option: d)

9. Mesomorphic substances:
   a) Are in between solids and liquids
   b) Are nematic
   c) Are smectic
   d) Have different properties in different directions

   Correct option: a)

10. What kind of liquid crystal consists of parallel molecules in layers?
   a) Cholesteric
   b) Nematic
   c) Smectic
   d) All of the above

   Correct option: c)

11. The change of state from a solid directly to a gas is known as:
   a) Fusion
   b) Boiling
   c) Sublimation
   d) Evaporation

   Correct option: c)

12. Which of the following characteristics are NOT shared by liquids and gases?
   a) Ability to diffuse
   b) Indefinite volume
   c) Indefinite shape
   d) Fluidity

   Correct option: b)

13. The process of converting ice to water by the application of heat proceeds with:
   a) An increase in energy and a decrease in entropy
   b) An increase in energy and an increase in entropy
   c) A decrease in energy and a decrease in entropy
   d) A decrease in energy and an increase in entropy

   Correct option: b)

14. Which of the following properties are NOT shared by crystalline solids and amorphous solids?
   a) Definite shape
   b) Definite volume

c) Incompressibility
d) Definite melting point

Correct option: d)

15. When ice is melting to form water at constant pressure, which of the following hold good?
    a) The entropy of the system decreases
    b) The density decreases
    c) The temperature of the system remains constant
    d) The temperature of the system increases

Correct option: c)

16. How does vapor pressure react to increased temperature?
    a) The vapour pressure is decreased
    b) The vapour pressure is increased
    c) The vapour pressure does not change unless the atmospheric pressure changes
    d) The vapour pressure first decreases and then increases

Correct option: b)

17. The quantity of heat absorbed when a change of state from liquid to vapour occurs at its boiling point without changing the temperature of the material is known as:
    a) Latent heat of fusion
    b) Latent heat of vapourisation
    c) Latent heat of sublimation
    d) Latent heat of condensation

Correct option: b)

18. A eutectic is:
    a) A mixture of two compounds with a sharp melting point higher than those of either component
    b) A mixture of two compounds with a sharp melting point lower than those of either component
    c) A mixture of two compounds with a sharp melting point equal to that of either component
    d) A mixture of two compounds with a density lower than those of either component

Correct option: b)

19. Triple point of water corresponds to
    a) Pressure 600 N/m^2 and temperature of 0.0075°C
    b) Pressure 610 N/m^2 and temperature of 0.0075°C

c) Pressure 605 N/m^2 and temperature of 0.0075°C

d) Pressure 610 N/m^2 and temperature of 0.0070°C

Correct option: b)

20. The critical point of a pure substance is:

a) The highest temperature and pressure for which liquid and vapour can coexist

b) The point at which the saturated liquid and saturated vapour curves meet

c) The point where vapour pressure has its largest possible value

d) All of the above

Correct option: d)