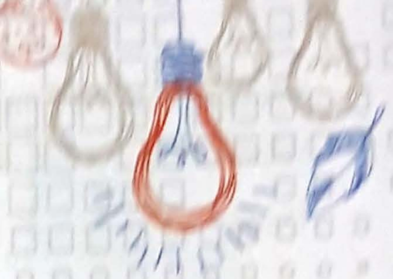


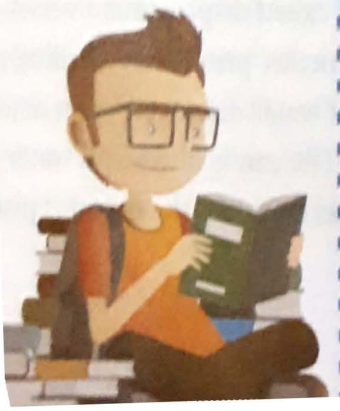
CHAPTER

2

Physical Quantities and Measurement

Learning Objectives

- Measurement of density of irregular solids using:
  - Eureka can
  - Measuring cylinder
- Measurement of density of fluids:
  - Basic concept
  - Concept of floating and sinking ability of a substance (related to density)
  - Comparison of densities in the three states of matter



Density of an object can be defined as the mass of an object in a given volume. We also know that matter is made up of tiny particles called the atoms. Different objects around us have different densities. Density is the property of an object which depicts the amount of matter in the given volume. Thus, density is defined as mass per unit volume. Density helps us understand how compact the mass of a substance is.

Density is a physical property of matter and a derived physical quantity. It helps differentiate one substance from another. Mathematically, it can be calculated by using the following equation.

$$\text{Density}\,(D) = \frac{\text{Mass}\,(M)}{\text{Volume}\,(V)}$$

From the equation we can say that density is related to how closely atoms or molecules are arranged in a material. If the volume of an object is more for a given matter, then the density shall be less. For examples, if we take two boxes (box A made from cardboard and box B made from metal), they will weigh different. Though the boxes are of the same size, but the density of metal is much higher than that of the cardboard. So, the difference in weight is because of densities of two materials.

The SI unit of density is kg/cubic meter or kg/m^3. Density of a material is said to be 1 kg m^{-3} when a mass of 1 kg is packed in a volume of 1 m^3.

Example 1: A block of metal occupies a volume of 10 cm^3 and weighs 33.5 kg. What is its density?

Solution: Mass of the metal block = 33.5 kg

Volume of the rod = 10 cm³

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{33.5}{10} = 3.35 \text{ kg cm}^3$$

Example 2: A container filled with 60 cm³ of liquid weighs 90 g. The container alone weighs 72 g. Find the density of liquid.

Solution: Mass of empty container = 72 g

Mass of container + Liquid = 90 g

$\therefore$ Mass of liquid = 90 − (mass of container)

= 90 − 72 = 18 g

Volume of liquid = 60 cm³

$$\therefore \text{Density of liquid} = \frac{\text{Mass of liquid}}{\text{Volume of liquid}}$$

$$= \frac{18 \text{ g}}{60 \text{ cm}^3} = 0.3 \text{ g/cm}^3$$

Density of liquid = 0.3 g/cm³

MEASURING DENSITY OF SOLIDS

It is comparatively easy to find density of regular solids. We first measure the mass and volume of the solid and then divide the two, to find the density. Mass of an object can be easily measured using a beam balance. To calculate the volume of regular-shaped objects, we need to find their dimensions.

In case of irregular solids, measuring density is a bit tedious work. We can measure the density of irregular solids like a stone, a block of wood, or a key by using measuring cylinder or Eureka can.

Measuring Cylinder

A measuring cylinder is an instrument used in laboratories. It is cylindrical in shape and has markings on it to measure the volume of liquids. We can measure the volume of irregular solids using a measuring cylinder.

Fig. 2.1 A graduated measuring cylinder

In this method, water is poured into the cylinder and the reading taken as the initial volume. Now, follow the given steps to measure the volume of the irregular solid.

- Tie a thread with the irregularly-shaped solid object. Immerse the object completely in the cylinder containing water. This will result in change in the level of the water.
- Note the reading of the final volume of water in the cylinder.
- To calculate the volume of the irregular object, subtract the initial volume (v_1) from the final volume (v_2), and then calculate the density of the object using the following formula:

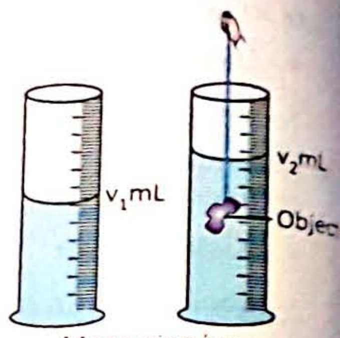


Fig. 2.2 Measuring density of irregular solid using measuring cylinder

$$\text{Density}\,(D) = \frac{\text{Mass}\,(M)}{\text{Volume}\,(V)}$$

Eureka Can

A Eureka can is a container with a spout near its top. Eureka cans are also called displacement vessels. It is based on Archimedes' principle according to which the amount of water displaced by an object is equal to its volume. The can is filled with water up to the maximum level and then the object is placed in it. The solid object displaces some water which is collected in a graduated measuring cylinder. The volume of the object is equal to the volume of the water that is forced through the spout.

The density of an irregular solid can be calculated using the equation,

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

We can find the volume of an object with a Eureka can and its mass with a balance. Then using the above formula, we can accurately calculate the density of a given object.

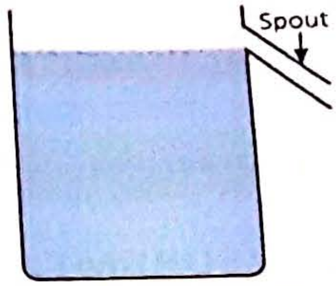


Fig. 2.3 A Eureka can

Let's Do It

Aim: To measure the density of an irregular solid using a Eureka can

Materials required: An irregular solid (such as a stone), Eureka can, water, weighing balance, string and a beaker

Procedure:

- Measure the mass of the irregular solid using weighing balance. Let the mass be m.
- Now, tie a string around the stone and immerse it in water of Eureka can.

Observation and Calculation: As the stone was lowered in Eureka can, some water got displaced which was collected in a separate beaker. The volume of the water displaced and collected in the beaker is the volume of the solid object (let it be V).

The density of the solid object is calculated by dividing the mass by volume of the object.

Therefore, density can be calculate by the formula:

$$\text{Density} = \frac{m}{V}$$

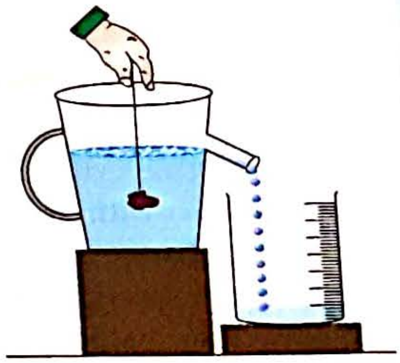


Fig. 2.4

Do, this activity in your laboratory and fill the blanks here:

Mass of the stone (m) = ________________

Volume of the displaced liquid collected in the beaker (V) = ________________

Density of the object = ________________

Skills: Experimentation, Analysis, Observation

Test Your Understanding

Write T for true and F for false statements.

1. Density of an object is defined as mass per unit volume.
2. The amount of space that an object occupies is called its mass.
3. We can measure the density of regular solids only.
4. Two objects of same size but made up of different materials will weigh different.
5. A Eureka can is used to measure the mass of a substance.
6. A matchbox is an example of irregular solids.
7. We can also use measuring cylinder to measure the volume of irregular solids.

Measuring Density of Irregular Solids

Using measuring cylinder | Using Eureka can

MEASUREMENT OF DENSITY OF FLUIDS

Liquids and gases are known as fluids. We now know, solids are denser as compared to liquids and liquids are denser as compared to gases. This is because the atoms in a solid are tightly packed, those in liquids are comparatively mobile and the ones in gases are free to move randomly. Metals, stones and wood around us are very dense. Dense materials are usually heavy or hard.

Measurement of Density of Liquids

Take a graduated glass cylinder. Let us take the mass of this cylinder with the help of the physical balance. Suppose that is m_1. Now, fill the cylinder with the liquid and measure the volume. Let V be the volume of this liquid. Again, measure the mass of the cylinder after filling the liquid whose density needs to be measured. Let it be m_2.

The mass of the liquid can be calculated by subtracting the initial mass m_1 from m_2.

Density can be determined by using the following formula:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{m_2 - m_1}{V}$$

Measurement of Density of Gases

To measure the density of a gas, take a flask whose volume is known (let it be $V\,\text{cm}^3$). Then measure the mass of this flask. Let the mass of this flask is m_1. Now, using a vacuum pump remove all air from this flask. Then fill the flask with the air whose density needs to be measured. Then measure the mass of the flask again. Let the mass be m_2.

Now, we can determine the density of the gas by using the formula

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \frac{m_2 - m_1}{V}$$

RELATIVE DENSITY

The relative density of a substance is the ratio of its density to that of water. That is:

Relative density of a substance

$$= \frac{\text{Density of the substance}}{\text{Density of water}}$$

We know that, Density $= \frac{\text{Mass}}{\text{Volume}}$, so by writing $\frac{\text{Mass}}{\text{Volume}}$ in place of the density in the above relation, we get:

Relative density of a substance

$$= \frac{\text{Mass of the substance}}{\text{Volume of the substance}} \times \frac{\text{Volume of water}}{\text{Mass of water}}$$

Now, if we take 'equal volumes of the substance and of water', then the two volume factors of the above relation cancel out, and we are left with:

Relative density of a substance

$$= \frac{\text{Mass of the substance}}{\text{Mass of an equal volume of water}}$$

This relation gives us the following definition of relative density. The relative density of a substance is the ratio of the mass of any volume of the substance to the mass of an equal volume of water. In other words, the relative density of a substance is the mass of the substance relative to the mass of an equal volume of water at 4°C. As the relative density is a ratio of two similar quantities (masses), it has no units. Thus, relative density is a pure number. The relative density values of some of the common substances are given below:

Relative Densities of Some Common Substances

Substance	Relative density (g/m^3)
1. Cork	0.24
2. Wood	0.8
3. Ice	0.92
4. Water	1
5. Glycerine	1.26
6. Glass	2.5
7. Aluminium	2.7
8. Iron	7.8
9. Mercury	13.6
10. Gold	19.3

The relative density of a substance expresses the heaviness (or density) of the substance in comparison to water. For example, the relative density of iron is 7.8. Now, by saying that the relative density of iron is 7.8 we mean that iron is 7.8 times as heavy as an equal volume of water. Thus, the relative density of a substance is a number which tells us how many times the substance is heavier than an equal volume of water. The relative density of water is 1. Another term used for relative density is specific gravity.

Example 3: The relative density of silver is 10.8. If the density of water be 1.0×10^3 kg m^{-3}, calculate the density of silver in SI units.

Solution: We know that:

Relative density of a substance

$$= \frac{\text{Density of the substance}}{\text{Density of water}}$$

Here, Relative density of silver = 10.8

Density of silver = ? (To be calculated)

And, Density of water = 1.0×10^3 kg m^{-3}

Now, putting these values of relative density of silver and density of water in the above formula, we get:

$$10.8 = \frac{\text{Density of silver}}{1.0 \times 10^3}$$

So, Density of silver = $10.8 \times 1.0 \times 10^3$ kg m^{-3}

$= 10.8 \times 10^3$ kg m^{-3}

Thus, the density of silver in SI units is 10.8×10^3 kg m^{-3}. This can also be written as 10800 kg m^{-3}.

It is obvious from the above calculations that the density of a substance can be obtained by multiplying its 'relative density' by the 'density of water'. Please note that sometimes the density of water is not given in the numerical problems. So, we should remember the density of water ourselves.

Example 4: The volume of a solid of mass 500 g is 350 cm^3.

(*a*) What will be the density of this solid?

(*b*) What will be the relative density of the solid?

Solution: (*a*) Density of solid

$$= \frac{\text{Mass of solid}}{\text{Volume of solid}}$$

$$= \frac{500 \text{ g}}{350 \text{ cm}^3}$$

$$= 1.42 \text{ g/cm}^3$$

Thus, the density of the given solid is 1.42 g/cm

(*b*) Relative density of solid

$$= \frac{\text{Density of solid}}{\text{Density of water}}$$

$$= \frac{1.42 \text{ g/cm}^3}{1 \text{ g/cm}^3}$$

$$= 1.42$$

Thus, the relative density of the solid is 1.42.

Relative density bottle

The relative density of a liquid can be determined by using a special bottle called the relative density bottle (figure 2.5). This bottle is also called the specific gravity (SG) bottle. The relative density bottle is a small glass bottle with a stopper having a fine capillary tube. It has a fixed capacity, which is generally marked on the wall of the bottle. When the bottle is completely filled with a liquid and the stopper inserted, the excess liquid rises up through the capillary tube and drains out. This ensures that the bottle always contains a fixed volume of any liquid filled in it. It can be used to determine the density of the liquids.

Fig. 2.5 Relative density bottle

Let's Do It

Aim: To determine the density of a liquid using a relative density bottle

Materials required: A relative density bottle, an unknown liquid (alcohol, kerosene or brine water), a physical balance and distilled water

Procedure:
Wash the RD bottle with distilled water. Dry it well. Insert the stopper and find its mass using the balance. Note down the mass of the empty RD bottle. Fill the bottle with distilled water. Insert the stopper. Some water will drain out through the stopper. Dry the bottle well from outside. Find the mass of the bottle filled with distilled water. Empty the bottle and dry it well. Fill it with the liquid whose relative density is to be determined and insert the stopper. Some liquid will drain out through the stopper. Dry the bottle well from outside. Find the mass of the bottle filled with liquid.

Observations and calculation:

Mass of empty bottle = m_1

Mass of bottle + distilled water = m_2

Mass of bottle + liquid = m_3

Mass of distilled water = $(m_2 - m_1)$

Mass of liquid = $(m_3 - m_1)$

As the volume of both the liquid and water are same,

$$\text{Relative density of the liquid} = \frac{m_3 - m_1}{m_2 - m_1}$$

$$\text{Density of the liquid} = \frac{m_3 - m_1}{m_2 - m_1} \times 1\ \text{g/cm}^3$$

Inference: The density of a liquid can be determined with the help of a relative density bottle.

Skills: Experimentation, Analysis, Observation

Example 5: The mass of an empty RD bottle is 24.5 g. Its mass is 74.4 g when filled with water and 87 g when filled with a liquid. Find the relative density of the liquid.

Solution: Mass of bottle when empty is

$$m_{be} = 24.5 \text{ g}$$

Mass of the bottle when filled with water is

$$m_{bw} = 74.4 \text{ g}$$

Therefore, the mass of water is

$$m_w = 74.4 \text{ g} - 24.5 \text{ g} = 49.9 \text{ g}$$

Similarly, mass of the bottle when filled with liquid is

$$m_{bl} = 87\ g$$

Therefore, the mass of liquid is

$$m_{liq} = 87 - 24.5\ g = 62.5\ g$$

The volume occupied by water is equal to the volume occupied by liquid. Now, we know that density is

$$d = \frac{\text{mass}}{\text{volume}}$$

And relative density of a liquid is

$$RD = \frac{\text{Density of liquid}}{\text{Density of water}}$$

$$\therefore \quad RD = \frac{\frac{m_{liq}}{v_{liq}}}{\frac{m_w}{v_w}} = \frac{m_{liq}}{m_w} = \frac{62.5}{49.9} = 1.25$$

Hence, the relative density of liquid is 1.25.

Do You Know?

1. Submarines are made in such a way that they can float as well as sink in the water. They are made so with the help of ballast tanks. When the submarine has to go underwater, then it fills these tanks with the sea water making the density of the submarine higher than the density of water. This allows the submarine to sink in the water and go underwater. On the other hand, when the submarine has to float, it clears the seawater from the tanks making the density of submarine lower and allowing it to rise towards the surface.
2. The average density of human body is comparable to the density of water and thus, with some efforts, the human body can float on the water. Swimming in seawater is much easier than in fresh water as the density of seawater is higher than the density of the freshwater.

Some Applications of Floatation

Icebergs float in seawater

Water shows anomalous behaviour, as it has its density maximum at 4°C. Thus, the density of ice is less than that of water. Large pieces or blocks of ice floating in seawater are called icebergs. The density of ice is about 0.9 g/cm^3, a little less than the density of seawater which is about 1.02 g/cm^3. Therefore, an iceberg floats in seawater.

Fig. 2.6 A floating iceberg

Objects made of wax float on water

The relative density of candle wax is 0.93, hence objects made of wax float on water.

It is easier to swim in sea water than in river water

Sea water has lots of salts dissolved in it.
So, sea water is denser than river water. Therefore, it is easier to swim in sea water than in river water.

A ship loaded with cargo submerges more in river water than in sea water

Because sea water has more density than river water. Ships are made of metals such as steel or aluminium alloy which are denser than water, so to make it be able to float it is hollow and filled with air making the average density lower than density of water even when it is loaded with her cargo.

Ship travels in different densities of water, sea water or fresh water, (hot or cold). So for safety loading of the ship under different sea conditions plimsol lines are provided. Plimsol lines are lines which show maximum height of the ship that should be under water. Plimsol lines are also referred as plimsol marks.

Hydrogen Balloons Rise Up in the Air

The hydrogen-filled balloons have lesser density than the components of gases present in the air. This is the only reason that the balloon rises up.

Fig. 2.7 A hydrogen balloon sails in air

Hydrometer

A hydrometer is a device based on principle of floatation to read the relative density of the liquid directly. It is usually made of glass and consists of a cylindrical stem and a bulb weighted with mercury or lead shot to make it float upright.

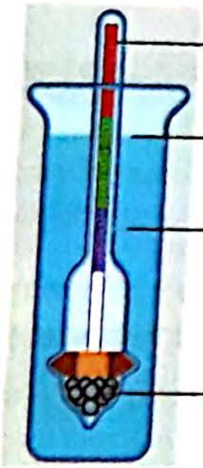


Fig. 2.8 A hydrometer

The liquid to be tested is poured into a tall jar, and the hydrometer is gently lowered into the liquid until it floats freely. Lower the density of a substance, further will the hydrometer sink. The point at which the surface of the liquid touches the stem of the hydrometer is noted. Hydrometers usually contain a paper scale inside the stem that is used to read the relative density directly. Some special hydrometers are designed to test whether a battery is fully charged (acid battery hydrometer) or whether milk is pure or not (lactometer).

COMPARISON OF DENSITIES OF SOLIDS, LIQUIDS AND GASES

The arrangement of atoms and molecules of an object gives idea about its density.

Solids

Solids are generally considered denser than liquids and gases. Although, there are some exceptions to the rule. Density is a measure of how much mass the substance contains in a given volume. The arrangement of molecules is very closely packed in solids. This arrangement gives solids fixed shape and volume. The substances found in solid state are considered to be most denser.

Liquids

The arrangement of atoms and molecules in liquids are less tightly packed as compared to solids. These molecules are more free-moving as compared to the molecules in solids. This is because of the reason that the intermolecular force of attraction is small. The molecules do not hold on so tightly to each other, hence the lower density. Liquids can flow that is why they are known as fluids. Liquids have fixed volume but no fixed shape, they can take the shape of vessel or container in which they are poured.

Gases

In case of gases the intermolecular force is the weakest. They have more intermolecular space available between them. The particles of a gas move randomly in all directions with a high speed. Therefore, gases are less dense than liquids and solids. When a gas is heated, its volume increases as well and density decreases. If we cool gases to lower temperature, their volume decrease and density increases. So, gases do not have definite shape or definite volume.

Table: Densities of some solids, liquids and gases

Substances	Density (g/cm^3)	
Wood	0.4–0.8	Solids
Ice	0.93	
Aluminium	2.7	
Lead	11.3	
Iron	7.80	
Gold	19.3	
Water	1.00	Liquids
Cooking oil	0.92	
Glycerine	1.26	
Mercury	13.5	
Air	0.0013	Gases
Hydrogen	0.00009	
Helium	0.000178	

Think & Answer ?!

Will the density of a material be always same, regardless of its size?

FACTORS AFFECTING DENSITY

Some of the factors which influence the density of a substance are discussed here.

Physical State of Matter

We know that matter is made up of atoms and molecules. On the basis of arrangement of these atoms in a substance, we classify the physical state of matter as solids, liquids and gases.

Temperature

Density of any substance depends directly on its mass and volume. If any of the two factors changes then the density of the substance also changes. As the temperature of a substance is increased, the atoms gain energy and start moving far apart. This leads to the rise in the volume of the substance, mass remaining constant.

For a substance having a fixed mass, the density will change if the volume of the substance changes. It means that if the volume of a fixed mass of a substance decreases, its density will increase whereas, if the volume increases, its density will decrease.

Solids do not undergo significant expansion or contraction with change in their temperature. As a result, there is no significant change in the volume of a solid when it is heated or cooled. So, there is almost no change in its density. However, in case of liquids and gases, there is a large change in their volumes even with small changes in temperature. As a result, when a liquid or a gas is heated, its density decreases, and when cooled, its density increases. The difference in the densities of different layers of liquids or gases set up convection currents in them.

Pressure

Solids have a tightly packed structure and hence are incompressible. Thus, the change in the pressure of a solid will not have any effect on its density. On the other hand, in case of gases, the atoms of the substance lie far apart and thus gases are highly compressible. At a constant temperature, if the pressure increases, the atoms of the gas come closer and there is a decrease in the volume. In these cases, the density of the substance will change because of the change in the volume.