

Syllabus :

Change of pressure with depth (including the formula $P = h\rho g$); Transmission of pressure in liquids; Atmospheric pressure.

Scope : Thrust and pressure and their units; pressure exerted by a liquid column $P = h\rho g$; simple daily life examples : (i) broadness of the base of a dam, (ii) Diver's suit etc., some consequences of $P = h\rho g$; transmission of pressure in liquids; Pascal's law; examples; Atmospheric pressure; common manifestation and consequences. Variation of pressure with altitude, (qualitative only); applications such as weather forecasting and altimeter. (Simple numerical problems).

(A) PRESSURE IN FLUIDS AND ITS TRANSMISSION

4.1 THRUST AND PRESSURE

Thrust : A force can be applied on a surface in any direction. If a force is applied in a direction normal (or perpendicular) to the surface, it is called the *thrust*. Thus,

Thrust is the force acting normally on a surface.

The thrust exerted by a body placed on a surface is equal to its weight. The thrust is *same* in whatsoever position the body is placed on the surface. Thus,

Thrust exerted by a body on a surface
= Weight of the body(4.1)

Thrust is a **vector** quantity.

Unit of thrust : It is measured in the units of force. The S.I. unit of thrust is newton (N) and C.G.S. unit of thrust is dyne, where $1 \text{ N} = 10^5 \text{ dyne}$.

The gravitational unit of thrust in M.K.S. system is kgf and in C.G.S. system is gf. They are related as :

$$1 \text{ kgf} = 9.8 \text{ N and } 1 \text{ gf} = 980 \text{ dyne}$$

Pressure : The effect of thrust depends on the area of the surface on which it acts. *The effect of a thrust is less on a large area, while it is more on a small area.*

Example : If you stand on loose sand, your feet sink into the sand, but if you lie on that sand, your body does not sink into the sand. In both the cases, the thrust exerted on the sand is same (equal to your weight). But when you lie on sand, the thrust acts on a larger area and when you stand, the same thrust acts on a smaller area.

The effect of thrust is expressed in terms of thrust per unit area. This quantity is called *pressure*. Thus

Pressure is the thrust per unit area of surface.

If a thrust F acts on an area A , then

$$\text{Pressure} = \frac{\text{Thrust}}{\text{Area}} \quad \text{or} \quad P = \frac{F}{A} \quad \dots(4.2)$$

Pressure is a **scalar** quantity.

Units of pressure

From relation (4.2), pressure = $\frac{\text{thrust}}{\text{area}}$

$$\therefore \text{Unit of pressure} = \frac{\text{Unit of thrust}}{\text{Unit of area}}$$

S.I. unit : The S.I. unit of thrust is newton and that of area is metre^2 , so the S.I. unit of pressure is newton per metre^2 which is abbreviated as N m^{-2} . This unit is named *pascal* (symbol Pa) after the name of the french scientist Blaise Pascal. *i.e.*,

$$1 \text{ pascal (or } 1 \text{ Pa)} = \frac{1 \text{ Newton}}{1 \text{ metre}^2}$$

$$\text{or} \quad 1 \text{ Pa} = 1 \text{ N m}^{-2}$$

Thus

One pascal is the pressure exerted on a surface of area 1 m^2 by a force of 1 N acting normally on it.

However, if thrust is measured in kgf and area in m^2 , the unit of pressure is kgf m^{-2} .

C.G.S. unit : The C.G.S. unit of pressure is dyne cm^{-2} where

$$1 \text{ dyne cm}^{-2} = 0.1 \text{ N m}^{-2} \text{ or } 1 \text{ N m}^{-2} = 10 \text{ dyne cm}^{-2}$$

unit of pressure is gf cm^{-2} .

Other units : Other units of pressure are *bar* and *millibar*, where

$$1 \text{ bar} = 10^5 \text{ N m}^{-2} \text{ and } 1 \text{ millibar} = 10^{-3} \text{ bar} = 10^2 \text{ N m}^{-2}.$$

The atmospheric pressure is generally expressed in terms of the height of mercury column in the barometre. At normal temperature and pressure, the barometric height is 0.76 m of Hg (or 76 cm of Hg or 760 mm of Hg) at sea level which is taken as one atmosphere. Thus atmospheric pressure is also expressed in a unit *atmosphere* (symbol atm) where

$$1 \text{ atmosphere (atm)} = 0.76 \text{ m of Hg} = 1.013 \times 10^5 \text{ Pa}$$

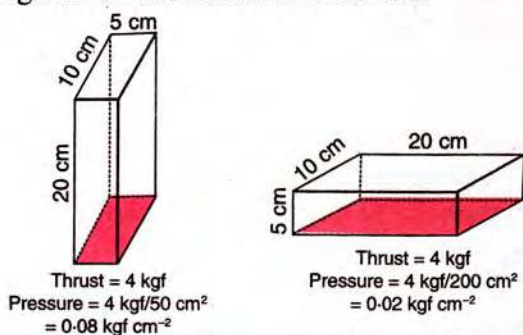
Sometimes we use *torr* as unit of atmospheric pressure after the name of the scientist Torricelli where

$$1 \text{ torr} = 1 \text{ mm of Hg}$$

$$\text{and } 1 \text{ atm} = 760 \text{ torr.}$$

Factors affecting the pressure : The pressure exerted on a surface depends on *two* factors :
(i) the area on which the thrust is applied, and
(ii) the thrust.

Examples : (1) A brick of weight 4 kgf having dimensions 20 cm $\times$ 10 cm $\times$ 5 cm exerts maximum pressure on ground when it is placed with its longest side (20 cm) vertical [Fig 4.1(a)], while it exerts minimum pressure on ground when it is placed with its shortest side (5 cm) vertical [Fig. 4.1(b)], even though the thrust is same in each case.



(a) Longest side vertical (b) Shortest side vertical

Fig. 4.1 Thrust and pressure

In Fig. 4.1(a), Thrust = 4 kgf

$$\text{Area of base} = 5 \text{ cm} \times 10 \text{ cm} = 50 \text{ cm}^2$$

$$\therefore \text{Pressure on base (or ground)} = \frac{4 \text{ kgf}}{50 \text{ cm}^2} = 0.08 \text{ kgf cm}^{-2}$$

In Fig. 4.1(b), Thrust = 4 kgf

$$\text{Area of base} = 10 \text{ cm} \times 20 \text{ cm} = 200 \text{ cm}^2$$

$$\therefore \text{Pressure on base (or ground)} = \frac{4 \text{ kgf}}{200 \text{ cm}^2} = 0.02 \text{ kgf cm}^{-2}$$

Thus pressure on ground in Fig. 4.1(b) is one-fourth of pressure in Fig. 4.1(a).

Obviously, *larger the area on which a given thrust acts, lesser is the pressure exerted by it.*

(2) In Fig. 4.1(b), if another identical brick is placed over the first brick, the thrust gets doubled (= 8 kgf) and since it acts on same area of base (= 200 cm^2), so the pressure on ground becomes = $8 \text{ kgf} / 200 \text{ cm}^2 = 0.04 \text{ kgf cm}^{-2}$ (i.e., it gets doubled).

Thus *larger the thrust acting on a given area, greater is the pressure exerted on it.*

Way of increasing pressure : For the given thrust, the pressure on a surface is increased by reducing the area of surface.

Examples : (a) The ends of nails (or pins) are made pointed so that large pressure is exerted at the pointed ends and they can be driven into, with a less effort.

(b) The cutting tools also have either sharp (or pointed) edges so that even a small thrust may cause a great pressure at the edges and cutting can be done with a less effort.

Way of decreasing pressure : For the given thrust, the pressure on a surface is reduced by increasing the area of surface.

Examples : (a) Wide wooden sleepers are placed below the railway tracks so that the pressure exerted by the iron rails on the ground becomes less.

(b) The foundations of buildings are made wider than the walls so that the pressure exerted by the building on the ground becomes less.

4.2 PRESSURE IN FLUIDS

A substance which can flow is called a *fluid*. All liquids and gases are, thus, fluids.

A solid exerts pressure on a surface due to its weight. Similarly, a fluid also exerts pressure due to its weight. A solid exerts pressure only on the surface on which it is placed i.e., at its bottom, but a fluid exerts pressure on the bottom as well as on the walls of the container due to its tendency to flow. A fluid, therefore, exerts pressure in all directions. Thus,

A fluid contained in a vessel exerts pressure at all points and in all directions.

with a liquid (say, water). Place it on a horizontal surface. Make several small holes in the wall of the vessel anywhere below the free surface of liquid. It is observed that :

- (1) The liquid spurts out through each hole. This shows that the liquid exerts pressure at each point on the wall of the vessel.
- (2) If we put our finger on any of the hole, finger feels a thrust due to liquid. This demonstrates that the liquid contained in the vessel exerts thrust at all points below its free surface. Thrust on unit area at a point gives the pressure due to liquid at that point.
- (3) If we note the distance from the bottom of the vessel to the point where the liquid from a hole strikes on the horizontal surface, it is noticed that as the depth of the hole below the free surface of liquid increases, the throw of liquid also increases i.e., the liquid reaches to a greater distance on the horizontal surface. This shows that liquid pressure at a point increases with the increase of depth of point from its free surface (Fig. 4.2).

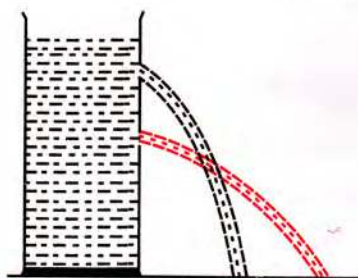


Fig. 4.2 Liquid pressure increases with increase of depth below the free surface

4.3 PRESSURE EXERTED BY A LIQUID COLUMN ($P = h\rho g$)

The pressure exerted by a liquid of density ρ at a depth h is $P = h\rho g$ where g is the acceleration due to gravity i.e.,

$$\begin{aligned} \text{Pressure } P &= h\rho g \\ &= \text{depth} \times \text{density of liquid} \\ &\quad \times \text{acceleration due to gravity} \dots (4.3) \end{aligned}$$

Proof : Consider a vessel containing a liquid of density ρ . Let the liquid be stationary. In order to calculate pressure at a depth h , consider a horizontal circular surface PQ of area A at depth h

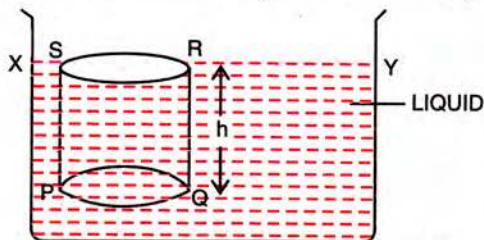


Fig. 4.3 Pressure at a depth in a liquid

The pressure on surface PQ will be due to the weight of the liquid column above the surface PQ (i.e., the liquid contained in cylinder $PQRS$ of height h with PQ as its base and top face RS lying on the free surface XY of the liquid).

$$\begin{aligned} \text{The thrust exerted on the surface } PQ & \\ &= \text{Weight of the liquid column } PQRS \\ &= \text{Volume of liquid column } PQRS \times \text{density} \times g \\ &= (\text{Area of base } PQ \times \text{height}) \times \text{density} \times g \\ &= (A \times h) \times \rho \times g = Ah\rho g \quad \dots (4.4) \end{aligned}$$

This thrust is exerted on the surface PQ of area A . Therefore, pressure

$$P = \frac{\text{Thrust on surface}}{\text{Area of surface}} = \frac{Ah\rho g}{A} = h\rho g$$

Note : Since there is atmospheric pressure above the free surface of liquid, so to find the total pressure at a depth inside a liquid, it must also be taken into consideration. If the atmospheric pressure acting on the free surface of liquid is P_0 , then.

$$\begin{aligned} \text{Total pressure in a liquid at a depth } h & \\ &= \text{Atmospheric pressure} + \text{pressure due to liquid column} \\ &= P_0 + h\rho g \quad \dots (4.5) \end{aligned}$$

Factors affecting the pressure at a point in a liquid

From eqn. (4.4), it is clear that the pressure at a point inside the liquid depends directly on the following *three* factors :

- depth of the point below the free surface (h),
- density of liquid (ρ), and
- acceleration due to gravity (g).

At a particular place on the earth surface, the acceleration due to gravity g is constant, therefore, the pressure at a point in a liquid is (i) directly proportional to the depth h of the point below the free surface of the liquid, and (ii) directly proportional to the density ρ of the liquid.

However, the pressure inside a liquid does not depend on (i) the shape and size of the vessel in which the liquid is contained, and (ii) the area of surface on which it acts.

4.4 LAWS OF LIQUID PRESSURE

Following are the *five* laws of liquid pressure :

- Inside the liquid, pressure *increases with the increase in depth* from its free surface.

points on a horizontal plane.

- (iii) Pressure is same in all directions about a point in liquid.
- (iv) Pressure at same depth is different in different liquids. It increases with the increase in density of liquid.
- (v) A liquid seeks its own level.

4.5 SOME CONSEQUENCES OF LIQUID PRESSURE $P = h\rho g$

(i) **In sea water, the pressure at a certain depth in sea water is more than that at the same depth in river water :** The reason is that the density of sea water is more than the density of river water.

(ii) **The wall of a dam is made thicker at the bottom :** Fig. 4.4 shows the side view of a dam. The thickness of its wall increases from top towards the bottom. The reason is that the pressure exerted by a liquid increases with its depth. Thus as depth increases, more and more pressure is exerted by water on the wall of dam. A thicker wall is required to withstand a greater pressure, therefore, the wall of the dam is made with thickness increasing towards the base. In Fig. 4.4, the increasing length of arrows in water shows the increasing pressure on the wall of dam towards the bottom.

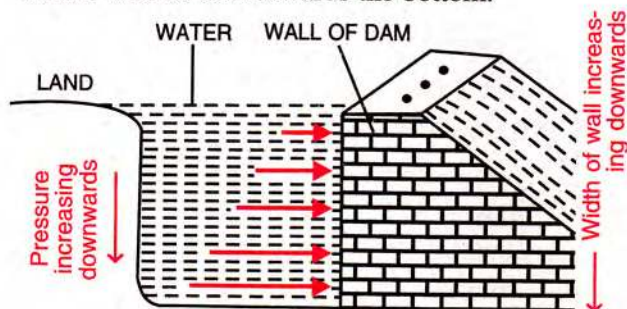


Fig. 4.4 Wall of a dam with its thickness increasing towards the bottom

(iii) **Water supply tank is placed high :** To supply water in a town (or colony), the tank to store water for supply is made at a sufficient height. The reason is that as greater is the height of tank, more will be the pressure of water in the taps of a house. Thus for a good supply of water, the height of the supply tank must always be a few metre higher than the level at which supply of water is to be made.

(iv) **Diver's suit :** The sea divers need special protective suit to wear because in deep sea, the total pressure exerted on the diver's body is much more than his blood pressure. To withstand

made from glass reinforced plastic or cast aluminium. The pressure inside the suit is maintained at one atmosphere.

(v) **Size of gas bubble inside the water :** It is noticed that as the gas bubble formed at the bottom of a lake, rises, it grows in size. The reason is that when the bubble is at the bottom of lake, total pressure exerted on it is the sum of the atmospheric pressure and the pressure due to water column. As the gas bubble rises, due to decrease in depth, the pressure due to water column decreases, so the total pressure exerted on the bubble decreases. According to Boyle's law, the volume of bubble increases due to the decrease in pressure, i.e., the bubble grows in size. When the bubble reaches the surface of liquid, total pressure exerted on it becomes just equal to the atmospheric pressure only which is minimum and so the size of bubble on surface becomes maximum.

4.6 TRANSMISSION OF PRESSURE IN LIQUIDS; PASCAL'S LAW

We have read that the pressure due to liquid at a point in a liquid of density ρ at a depth h below its free surface is $P = h\rho g$. Obviously, the pressure difference between any two points x and y in a stationary liquid will depend only on the difference in vertical height (Δh) between these points. Now if by some means, the pressure at one point x is increased, the pressure at other point y must also increase by the same amount so that the difference in pressure between the two points x and y may remain same. Thus pressure exerted at a point x is equally transmitted to the point y . This is *Pascal's law*. Thus,

Pascal's law states that the pressure exerted anywhere in a confined liquid is transmitted equally and undiminished in all directions throughout the liquid.

This can be demonstrated by the following experiment.

Experiment : Take a glass flask having narrow tubes coming out from its sides and bottom. The flask is provided with an air-tight piston at its mouth as shown in Fig. 4.5. Fill the flask with water. The water in each tube will be at the same level. The initial level of water in each tube is shown by the dotted black line. Now push the piston down into the flask gently. It is observed that jets of water rises out from each tube, reaching the same height which is shown by the upper dotted coloured line. This shows that the pressure applied to the enclosed liquid is transmitted equally in all directions every where inside the liquid.

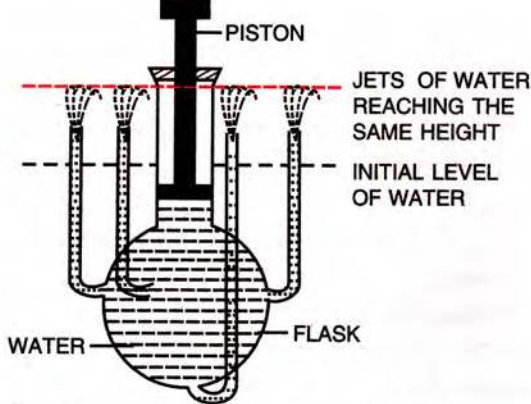


Fig. 4.5 Demonstration of Pascal's law

4.7 APPLICATION OF PASCAL'S LAW

Hydraulic machines such as *hydraulic press*, *hydraulic jack* and *hydraulic brakes* are based on Pascal's law of transmission of pressure in liquids.

Principle of a hydraulic machine

The principle of each hydraulic machine is that *a small force applied on a smaller piston is transmitted to produce a large force on the bigger piston.*

Fig. 4.6 shows two cylindrical vessels P and Q connected by a horizontal tube R . The vessels contain a liquid (or water) and they are provided with water-tight pistons A and B . The vessel P is of smaller diameter as compared to the vessel Q . Let area of cross section of the vessel P be A_1 and that of the vessel Q be A_2 . When a weight is placed on the piston A , it exerts a force F_1 on the piston A . Therefore the pressure applied on the piston A is

$$P_1 = \frac{F_1}{A_1} \quad \dots(4.6)$$

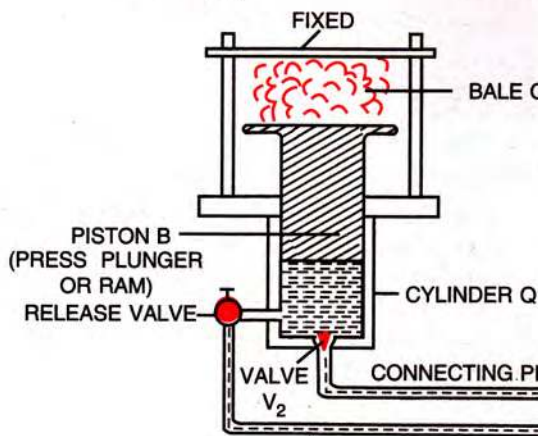


Fig. 4.7 Hydraulic press

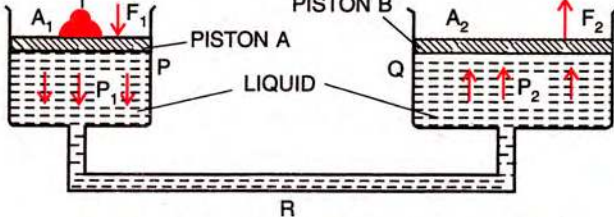


Fig. 4.6 Principle of a hydraulic machine

According to Pascal's law, the pressure exerted on piston A is transmitted through the liquid to the piston B . This exerts an upward pressure P_2 on the piston B which is equal to P_1 . Thus

$$P_2 = P_1 \quad \dots(4.7)$$

If the upward force exerted on piston B is F_2 , Then

$$\text{Pressure on piston } B \text{ is } P_2 = \frac{F_2}{A_2} \quad \dots(4.8)$$

From eqns. (4.6), (4.7) and (4.8), $\frac{F_1}{A_1} = \frac{F_2}{A_2}$

$$\text{or } \frac{F_2}{F_1} = \frac{A_2}{A_1} \quad \dots(4.9)$$

Since $A_2 > A_1$, therefore $F_2 > F_1$

Thus a small force F_1 applied on the smaller piston A can be used to produce a large force F_2 on the bigger piston B . This is the principle of a hydraulic machine which acts as a *force multiplier*.

4.8 EXAMPLES OF HYDRAULIC MACHINES

(i) Hydraulic press (or Bramah press)

A hydraulic press works on the principle of Pascal's law.

Construction : Fig. 4.7 shows a hydraulic press. It consists of two hollow cylinders P and Q

bottom. The cylinder P has a tank (or reservoir) at the bottom connected through the valve V_1 . The area of cross section of cylinder Q is larger than that of P . Water-tight pistons A and B are fitted in these cylinders. Let the area of cross sections of pistons A and B be A_1 and A_2 respectively. The two cylinders are connected by a pipe R . The piston A of the smaller cylinder is called the *pump plunger* and piston B of the larger cylinder is called the *ram* (or *press plunger*). To press down or raise up the pump plunger A , a lever arrangement provided with a handle H is used. The cylinder Q at its bottom is provided with a *release valve* which joins it to the reservoir.

Principle : When a force F_1 is applied on the piston A , it exerts a pressure on liquid contained in the cylinder P . According to Pascal's law, this pressure is transmitted through liquid in tube R to the piston B of the other cylinder Q due to which the piston B tends to move upwards. Since the area of cross section of cylinder P is less than that of the cylinder Q , therefore by applying a small force on the piston A , we can lift a large weight kept on the piston B .

When no weight is placed on the piston B , it rises up against a fixed roof with a force F_2 ($F_2 > F_1$). If a bale of cotton is kept on the press plunger B , it gets compressed.

Working : When the pump plunger A is raised by raising the handle H , the pressure in cylinder P decreases and the valve V_1 opens upwards. As a result, water from the reservoir tank is pushed up into the cylinder P by the atmospheric pressure acting on the free surface of water in the supply tank. When pump plunger A is pushed downwards by lowering the handle H , the valve V_1 closes due to an increase in pressure in cylinder P . Now pressure from cylinder P is transmitted to the connecting pipe R . As the pressure in pipe R becomes greater than in cylinder Q , the valve V_2 opens, so water from cylinder P is forced into the cylinder Q , due to which the press plunger B is raised against the fixed roof and the bale of cotton placed on the press plunger B gets compressed.

release valve is opened so that the ram (or press) plunger B gets lowered and water of the cylinder Q runs out into the reservoir.

Uses of hydraulic press : A hydraulic press is used mainly for the following purposes :

1. For pressing cotton bales and goods like quilts, books, etc.
2. For extracting the juice from sugarcane, sugar beet, etc.
3. For squeezing oil out of linseed and cotton seeds.
4. For engraving monograms on goods.

(ii) Hydraulic jack (or Hydraulic lift)

A hydraulic jack is used for lifting heavy vehicles such as cars, trucks etc., in service stations for their repairing. It works on the Pascal's principle (or the principle of a hydraulic machine).

Construction : A simple form of a hydraulic jack is shown in Fig. 4.8. It consists of two cylindrical vessels P and Q connected to each other by a tube R having a valve V . The piston A in the narrow cylinder P is attached to a lever and the piston B of the wider cylinder Q has a platform for lifting the vehicle. The vessels are filled with a liquid (say, water).

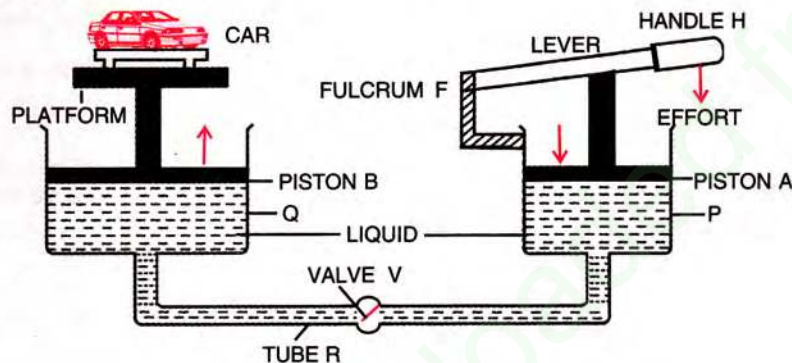


Fig. 4.8 Hydraulic jack

Working : When handle H of lever is pressed down by applying an effort, the valve V opens because of increase in pressure in the cylinder P . The liquid runs out from the cylinder P to the cylinder Q . As a result, the piston B rises up and it raises the car placed on the platform. When the car reaches the desired height, the handle H of lever is no longer pressed. The valve V gets closed (since

same) so that the liquid may not run back from the cylinder Q to the cylinder P .

(iii) Hydraulic brakes

The hydraulic brakes used in cars etc., are also based on Pascal's principle.

Construction : Fig. 4.9 shows the hydraulic brake arrangement of a vehicle. It consists of a pipe line R containing a liquid (oil), one end of which is connected to the master cylinder P fitted with a piston A attached to the foot pedal. The other end of pipe R is connected to the brake arrangement of different wheels of the vehicle. Fig. 4.9 shows only one wheel connected with the pipe line. For each wheel, there is a wheel cylinder Q having two pistons B_1 and B_2 , attached to the brake shoes. The area of cross section of the wheel cylinder Q is greater than the area of cross section of the master cylinder P . The brake shoes press against the rim of wheel.

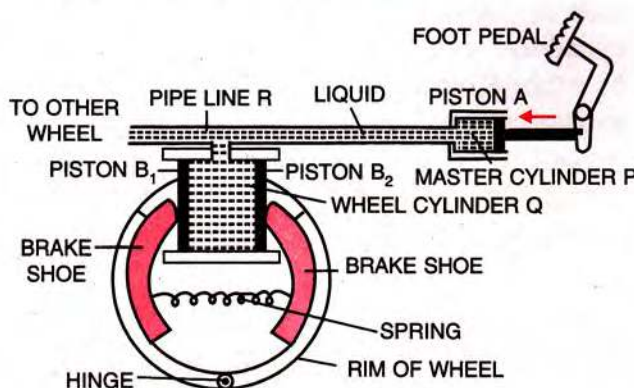


Fig. 4.9 Hydraulic brake

Working : To apply brakes, the foot pedal is pressed due to which pressure is exerted on the liquid in the master cylinder P , so liquid runs out from the master cylinder P to the wheel cylinder Q . As a result, the pressure is transmitted equally and

and B_2 of the wheel cylinder Q . Therefore the pistons B_1 and B_2 get pushed outwards and brake shoes get pressed against the rim of the wheel due to which the motion of vehicle retards. Since the area of cross section of piston A in the master cylinder P is less than that in the wheel cylinder Q , a small force applied at the foot pedal produces a large force on the pistons B_1 and B_2 of the wheel cylinder Q . This is the force responsible for retarding the motion of the vehicle. It should be noted that due to transmission of pressure through liquid, equal pressure is exerted on all wheels of the vehicle connected to the pipe line R .

On releasing the pressure on the pedal, the liquid runs back from the wheel cylinder Q to the master cylinder P and the spring pulls the brake shoes to their original position and forces the pistons B_1 and B_2 to return back into the wheel cylinder Q . Thus the brakes get released.

Note : In all hydraulic machines, effort is less than load while the distance moved by effort is more than the distance moved by load such that the product of effort and the distance moved by effort is equal to the product of load and the distance moved by load (in ideal situation when there is no energy loss). i.e.,

work done by effort = work done by load.

Thus, mechanical advantage (M.A.)

$$= \frac{\text{Load}}{\text{Effort}} > 1$$

and velocity ratio (V.R.)

$$= \frac{\text{distance moved by effort}}{\text{distance moved by load}} > 1$$

Hence a hydraulic machine acts like a *force multiplier*.

EXAMPLES

1. A boy weighing 60 kgf is wearing shoes with heel of area of cross section 20 cm^2 , while a girl weighing 45 kgf is wearing sandals with heel of area of cross section 1.5 cm^2 . Compare the pressure exerted on ground by their heels when they stand on the heel of one foot.

Thrust on heel of boy, $F_1 = 60 \text{ kgf}$

Area of cross section of heel of boy, $A_1 = 20 \text{ cm}^2$

$$\therefore \text{Pressure exerted by boy, } P_1 = \frac{F_1}{A_1} = \frac{60 \text{ kgf}}{20 \text{ cm}^2} = 3 \text{ kgf cm}^{-2} \quad \dots(i)$$

Now thrust on heel of girl, $F_2 = 45 \text{ kgf}$

Area of cross section of heel of girl, $A_2 = 1.5 \text{ cm}^2$

$$\therefore \text{Pressure exerted by girl, } P_2 = \frac{F_2}{A_2} = \frac{45 \text{ kgf}}{1.5 \text{ cm}^2} = 30 \text{ kgf cm}^{-2} \quad \dots(ii)$$

$$\frac{P_2}{P_1} = \frac{30}{3} = \frac{10}{1} = 10 : 1$$

Thus the girl's heel exerts pressure 10 times more than that of the boy's heel.

2. Calculate the pressure due to a water column of height 100 m. (Take $g = 10 \text{ m s}^{-2}$ and density of water $= 10^3 \text{ kg m}^{-3}$).

Given, $h = 100 \text{ m}$, $\rho = 10^3 \text{ kg m}^{-3}$, $g = 10 \text{ m s}^{-2}$

Pressure $= h\rho g$

$$= 100 \times 10^3 \times 10 = 10^6 \text{ N m}^{-2}.$$

3. At what depth below the surface of water will pressure be equal to twice the atmospheric pressure? The atmospheric pressure is 10 N cm^{-2} , density of water is 10^3 kg m^{-3} and $g = 9.8 \text{ m s}^{-2}$.

Given, atmospheric pressure $P_0 = 10 \text{ N cm}^{-2}$

$$= \frac{10 \text{ N}}{(10^{-2} \text{ m})^2} = 10^5 \text{ N m}^{-2}$$

$\rho = 10^3 \text{ kg m}^{-3}$ and $g = 9.8 \text{ m s}^{-2}$

Pressure at a depth h below the surface of water
= atmospheric pressure

+ pressure due to water column of height h .

$$\text{or } 2P_0 = P_0 + h\rho g \quad \text{or } h\rho g = P_0$$

$$\text{Hence } h = \frac{P_0}{\rho g} = \frac{10^5}{10^3 \times 9.8} = 10.2 \text{ m}$$

Thus a water column of height 10.2 m exerts a pressure equal to the atmospheric pressure and therefore at depth 10.2 m below the surface of water, the total pressure will be equal to twice the atmospheric pressure.

4. A cube of each side 5 cm is placed inside a liquid. The pressure at the centre of one face of cube is 10 Pa. Calculate the thrust exerted by the liquid on this face.

Given, pressure $P = 10 \text{ Pa}$,

$$\begin{aligned} \text{Area of face } A &= 5 \text{ cm} \times 5 \text{ cm} = \frac{5}{100} \text{ m} \times \frac{5}{100} \text{ m} \\ &= 25 \times 10^{-4} \text{ m}^2. \end{aligned}$$

The thrust exerted by the liquid on the face

$$F = P \times A = 10 \text{ Pa} \times (25 \times 10^{-4}) \text{ m}^2 = 2.5 \times 10^{-2} \text{ N}.$$

5. A square plate of side 10 m is placed horizontally 1 m below the surface of water. The atmospheric pressure is $1.013 \times 10^5 \text{ N m}^{-2}$. Calculate the total thrust on the plate.

(Density of water $\rho = 10^3 \text{ kg m}^{-3}$, $g = 9.8 \text{ m s}^{-2}$)

Given, $h = 1 \text{ m}$, $\rho = 10^3 \text{ kg m}^{-3}$, $g = 9.8 \text{ m s}^{-2}$

Atmospheric pressure $P_0 = 1.013 \times 10^5 \text{ N m}^{-2}$,

area of plate $= 10 \text{ m} \times 10 \text{ m} = 10^2 \text{ m}^2$.

= atmospheric pressure + pressure due to the column of water

$$= P_0 + h\rho g$$

$$= (1.013 \times 10^5) + (1 \times 10^3 \times 9.8)$$

$$= 1.111 \times 10^5 \text{ N m}^{-2}$$

$$\begin{aligned} \therefore \text{Total thrust on the plate} &= \text{Pressure} \times \text{Area of plate} \\ &= (1.111 \times 10^5) \times 10^2 \\ &= 1.111 \times 10^7 \text{ N}. \end{aligned}$$

6. A vessel of base area $100 \text{ cm} \times 60 \text{ cm}$ and height 200 cm is completely filled with a liquid of density $1.1 \times 10^3 \text{ kg m}^{-3}$.

(a) Ignoring the atmospheric pressure, find :

- the thrust at the bottom of the vessel,
- the pressure at the bottom of the vessel,
- the pressure at a depth of 5 cm from the free surface,
- the net force experienced by a metal foil of area 10 cm^2 placed at a depth of 5 cm from the free surface,

(b) The thrust at the bottom of the vessel if the atmospheric pressure equal to $1 \times 10^5 \text{ N m}^{-2}$ is taken into account.

Take $g = 9.8 \text{ m s}^{-2}$.

(a) Given, area of base of vessel $= 100 \text{ cm} \times 60 \text{ cm}$,

$$= \frac{100}{100} \text{ m} \times \frac{60}{100} \text{ m} = 0.6 \text{ m}^2$$

height $= 200 \text{ cm}$, $\rho = 1.1 \times 10^3 \text{ kg m}^{-3}$, $g = 9.8 \text{ m s}^{-2}$

Volume of the vessel $= 100 \text{ cm} \times 60 \text{ cm} \times 200 \text{ cm}$

$$\begin{aligned} &= \frac{100}{100} \text{ m} \times \frac{60}{100} \text{ m} \times \frac{200}{100} \text{ m} \\ &= 1.2 \text{ m}^3 \end{aligned}$$

(i) Thrust at the bottom of the vessel

= Weight of liquid in the vessel

= Volume $\times$ density $\rho \times g$

$$= 1.2 \times (1.1 \times 10^3) \times 9.8$$

$$= 1.294 \times 10^4 \text{ N}$$

$$\begin{aligned} \text{(ii) Pressure at the bottom of the vessel} &= \frac{\text{Thrust}}{\text{Area}} \\ &= \frac{1.294 \times 10^4 \text{ N}}{0.6 \text{ m}^2} = 2.16 \times 10^4 \text{ N m}^{-2} \end{aligned}$$

(iii) Pressure at a depth of 5 cm ($= 0.05 \text{ m}$) from the free surface

$$= h\rho g = 0.05 \times (1.1 \times 10^3) \times 9.8 = 539 \text{ N m}^{-2}$$

(iv) Net force on the metal foil will be **zero** because the force exerted by the liquid on each of the two faces (upper and lower) of foil, will be equal and opposite.

(b) Total pressure at the bottom of vessel = Atmospheric pressure + pressure at the bottom due to liquid column

$$\begin{aligned} &= (1.0 \times 10^5) + (2.16 \times 10^4) \\ &= (1.0 \times 10^5) + (0.216 \times 10^5) \\ &= 1.216 \times 10^5 \text{ N m}^{-2} \end{aligned}$$

$$= (1.216 \times 10^5) \times 0.6 = 7.296 \times 10^4 \text{ N}.$$

7. In Fig. 4.10, a tube of length 200 cm filled with a liquid of density $0.90 \times 10^3 \text{ kg m}^{-3}$ is placed inclined with the vertical such that the level A of liquid in the tube is at a vertical height 100 cm from its lowest point C. There is a point B in the tube below the point A at a vertical depth 60 cm.

(a) Calculate the pressure at points

(i) A, (ii) B and (iii) C.

(b) What will be the pressure at point C when the tube is made vertical?

Take atmospheric pressure = $1.013 \times 10^5 \text{ N m}^{-2}$.

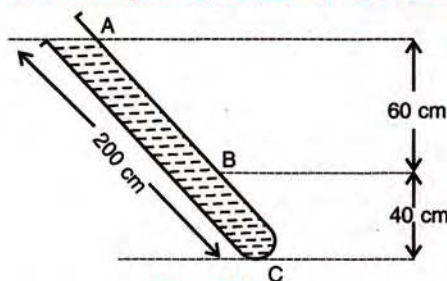


Fig. 4.10

Given, $\rho = 0.9 \times 10^3 \text{ kg m}^{-3}$, $P_0 = 1.013 \times 10^5 \text{ N m}^{-2}$, $g = 9.8 \text{ m s}^{-2}$

(a) (i) At the point A,

$$\begin{aligned} \text{Pressure} &= \text{Atmospheric pressure } (P_0) \\ &= 1.013 \times 10^5 \text{ N m}^{-2} \end{aligned}$$

(ii) At the point B,

$$\begin{aligned} \text{Pressure} &= \text{Atmospheric pressure} + \text{pressure due to liquid column of vertical height 60 cm } (h = 0.6 \text{ m}) \\ &= P_0 + h\rho g \\ &= (1.013 \times 10^5) + [0.6 \times (0.9 \times 10^3) \times 9.8] \\ &= (1.013 \times 10^5) + (0.053 \times 10^5) \\ &= 1.066 \times 10^5 \text{ N m}^{-2} \end{aligned}$$

(iii) At the point C,

$$\begin{aligned} \text{Pressure} &= \text{Atmospheric pressure} + \text{pressure due to liquid column of vertical height 100 cm } (h = 1 \text{ m}) \\ &= (1.013 \times 10^5) + [1 \times (0.9 \times 10^3) \times 9.8] \\ &= (1.013 \times 10^5) + (0.0882 \times 10^5) \\ &= 1.101 \times 10^5 \text{ N m}^{-2}. \end{aligned}$$

(b) On making the tube vertical, at the point C,

$$\begin{aligned} \text{Pressure} &= \text{Atmospheric pressure} + \text{pressure due to liquid column of height 200 cm } (h = 2 \text{ m}), \\ &= (1.013 \times 10^5) + [2 \times (0.9 \times 10^3) \times 9.8] \\ &= (1.013 \times 10^5) + (0.1764 \times 10^5) \\ &= 1.189 \times 10^5 \text{ N m}^{-2}. \end{aligned}$$

8. A U tube is first partially filled with mercury. Then water is added in one arm and an oil is

and oil columns so that mercury level is same in both the arms of U tube. Given : density of water = 10^3 kg m^{-3} , density of oil = 900 kg m^{-3} .

Since level of mercury is same in both the arms of the U tube, therefore

Pressure of water column on the surface of mercury in one arm = Pressure of oil column on the surface of mercury in the other arm. i.e.,

$$h_1 \rho_1 g = h_2 \rho_2 g$$

where h_1 = height of water column,

ρ_1 = density of water = 10^3 kg m^{-3} ,

h_2 = height of oil column, and

ρ_2 = density of oil = 900 kg m^{-3} .

$$\therefore \frac{h_1}{h_2} = \frac{\rho_2}{\rho_1} = \frac{900}{10^3} = \frac{9}{10}$$

9. Fig. 4.11 shows a cube of each side 15 cm immersed in a tub containing water of density 10^3 kg m^{-3} such that its top surface is 20 cm below the free surface of water.

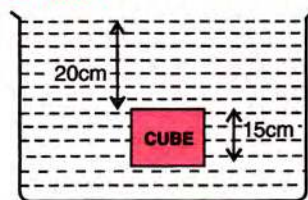


Fig. 4.11

Calculate :

- the pressure at the top of cube,
- the pressure at the bottom of cube,
- the resultant pressure on cube.
- the resultant thrust on cube.

Take atmospheric pressure = 10^5 Pa and $g = 9.8 \text{ N kg}^{-1}$.

Given, atmospheric pressure $P_0 = 10^5 \text{ Pa}$, $g = 9.8 \text{ N kg}^{-1}$, depth of top of the cube from the free surface of water $h_1 = 20 \text{ cm} = 0.2 \text{ m}$, depth of bottom of cube from the free surface of water $h_2 = (20 + 15) \text{ cm} = 35 \text{ cm} = 0.35 \text{ m}$

(i) Pressure at the top surface of cube

$$\begin{aligned} P_1 &= P_0 + h_1 \rho g \\ &= 10^5 + (0.20 \times 10^3 \times 9.8) \\ &= 1.0196 \times 10^5 \text{ Pa} \end{aligned}$$

(ii) Pressure at the bottom surface of cube

$$\begin{aligned} P_2 &= P_0 + h_2 \rho g \\ &= 10^5 + (0.35 \times 10^3 \times 9.8) \\ &= 1.0343 \times 10^5 \text{ Pa} \end{aligned}$$

(iii) Resultant pressure on cube

$$\begin{aligned} &= P_2 - P_1 = 1.0343 \times 10^5 - 1.0196 \times 10^5 \\ &= 0.0147 \times 10^5 \text{ Pa (or } 1.47 \times 10^3 \text{ Pa)}. \end{aligned}$$

(iv) Area of base of cube

$$\begin{aligned} &= 15 \text{ cm} \times 15 \text{ cm} \\ &= \frac{15}{100} \text{ m} \times \frac{15}{100} \text{ m} = 225 \times 10^{-4} \text{ m}^2 \end{aligned}$$

$$\begin{aligned}
 &= \text{Resultant pressure} \times \text{area of base} \\
 &= (1.47 \times 10^3) \times (225 \times 10^{-4}) \\
 &= 33.074 \text{ N (upwards)}
 \end{aligned}$$

Note: The resultant pressure on cube will be upwards. The resultant thrust acting on cube in upward direction is called upthrust. Obviously this upthrust depends on the immersed volume (= area of base $\times$ height) of the cube and not on its depth inside water. Here we can note that if cube is replaced by a lamina which has negligible thickness ($h \rightarrow 0$), pressure on the two sides of lamina will be equal, hence upthrust on it will be zero.

10. An air bubble rises from the bottom of a lake of depth 10.34 m to its surface. Compare the pressure on bubble at the bottom to that on surface. (Atmospheric pressure = 0.76 m of Hg, density of Hg = $13.6 \times 10^3 \text{ kg m}^{-3}$ and density of water = 10^3 kg m^{-3}).

$$\begin{aligned}
 \text{Given, Atmospheric pressure } P_0 &= 0.76 \text{ of Hg} \\
 &= 0.76 \times (13.6 \times 10^3) \times 9.8 = 1.013 \times 10^5 \text{ N m}^{-2} \\
 h &= 10.34 \text{ m}, \rho = 10^3 \text{ kg m}^{-3}, g = 9.8 \text{ m s}^{-2}
 \end{aligned}$$

Pressure on bubble at the bottom of lake

$$\begin{aligned}
 P_1 &= \text{Atmospheric pressure} + \text{pressure due to water column} \\
 &= P_0 + h\rho g \\
 &= (1.013 \times 10^5) + (10.34 \times 10^3 \times 9.8) \\
 &= 2.026 \times 10^5 \text{ N m}^{-2} \quad \dots(i)
 \end{aligned}$$

Pressure on bubble at the surface of lake

$$\begin{aligned}
 P_2 &= \text{Atmospheric pressure } P_0 \\
 &= 1.013 \times 10^5 \text{ N m}^{-2} \quad \dots(ii)
 \end{aligned}$$

From eqns. (i) and (ii)

$$\frac{P_1}{P_2} = \frac{2.026 \times 10^5}{1.013 \times 10^5} = \frac{2}{1}$$

area of cross section in the ratio 1 : 10. What force is needed on the narrow piston to overcome a force of 100 N on the wider piston ?

$$\text{Given, } A_1 : A_2 = 1 : 10, F_1 = ?, F_2 = 100 \text{ N}$$

By the principle of hydraulic machine

Pressure on narrow piston = Pressure on wider piston

$$\text{or} \quad \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$\therefore F_1 = F_2 \times \frac{A_1}{A_2} = 100 \times \frac{1}{10} = 10 \text{ N.}$$

12. The area of cross section of press plunger of a hydraulic press is 4 m^2 . It is required to overcome a resistive load of 400 kgf on it. Calculate the force required on the pump plunger if the area of cross section of the pump plunger is 0.01 m^2 .

Let F be the force required on the pump plunger.

$$\text{Given, for pump plunger } F_1 = F, A_1 = 0.01 \text{ m}^2, \text{ for press plunger } F_2 = 400 \text{ kgf}, A_2 = 4 \text{ m}^2.$$

By Pascal's law,

Pressure on pump plunger

= Pressure on press plunger.

$$\text{or} \quad \frac{F_1}{A_1} = \frac{F_2}{A_2}$$

$$\text{i.e.,} \quad \frac{F}{0.01} = \frac{400}{4}$$

$$\therefore F = 100 \times 0.01 = 1 \text{ kgf.}$$

i.e., Force required on pump plunger = 1 kgf.

EXERCISE 4 (A)

- Define the term thrust. State its S.I. unit.
- What is meant by pressure ? State its S.I. unit.
- (a) What physical quantity is measured in bar ?
(b) How is the unit bar related to the S.I. unit pascal ?

Ans. (a) Pressure, (b) 1 bar = 10^5 pascal

- Define one pascal (Pa), the S.I. unit of pressure.

- State whether thrust is a scalar or vector ?

Ans. Vector

- State whether pressure is a scalar or vector ?

Ans. Scalar

- Differentiate between thrust and pressure.
- How does the pressure exerted by a thrust depend on the area of surface on which it acts ? Explain with a suitable example.
- Why is the tip of an allpin made sharp ?
- Explain the following :
(a) It is easier to cut with a sharp knife than with a blunt one.
(b) Sleepers are laid below the rails.
- What is a fluid ?
- What do you mean by the term fluid pressure ?

fluid differ ?

Ans. A solid exerts pressure only on its base downwards while a fluid exerts pressure at all points in all directions.

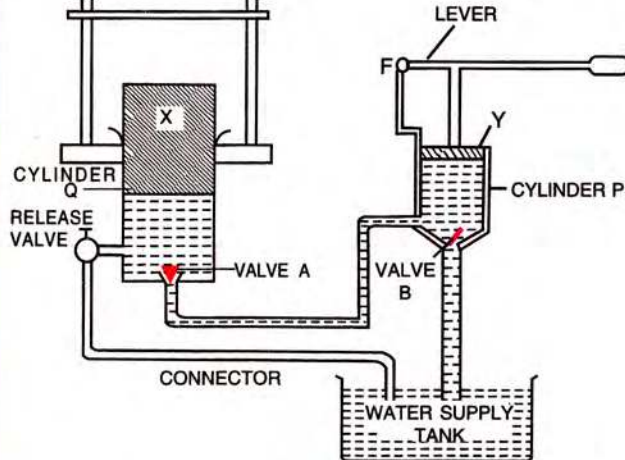


Fig. 4.12

- (i) Name the parts labelled by the letters X and Y.
 - (ii) Describe what happens to the valves A and B and to the quantity of water in the two cylinders when the lever arm is moved down.
 - (iii) Give reasons for what happens to the valves A and B in part (ii).
 - (iv) What happens when the release valve is opened ?
 - (v) What happens to the valve B in cylinder P when the lever arm is moved up ?
 - (vi) Give a reason for your answer in part (v).
 - (vii) State one use of the above device.
31. Draw a simple diagram of a hydraulic jack and explain its working.
 32. Explain the working of a hydraulic brake with a simple labelled diagram.
 33. Complete the following sentences :
 - (a) Pressure at a depth h in a liquid of density ρ is
 - (b) Pressure is..... in all directions about a point in a liquid.
 - (c) Pressure at all points at the same depth is.....
 - (d) Pressure at a point inside a liquid is to its depth.
 - (e) Pressure of a liquid at a given depth is to the density of liquid.
- Ans.** (a) $h\rho g$ (b) same (c) same (d) directly proportional (e) directly proportional.

Multiple Choice Type :

1. The S.I. unit of pressure is :
 - (a) N cm^{-2}
 - (b) Pa
 - (c) N
 - (d) N m^2

Ans. (b) Pa

14. Describe a simple experiment to demonstrate that a liquid enclosed in a vessel exerts pressure in all directions.
15. State three factors on which the pressure at a point in a liquid depends.
16. Write an expression for the pressure at a point inside a liquid. Explain the meaning of the symbols used.
17. Deduce an expression for the pressure at a depth inside a liquid.
18. How does the pressure at a certain depth in sea water differ from that at the same depth in river water ? Explain your answer.
19. Pressure at free surface of a water lake is P_1 , while at a point at depth h below its free surface is P_2 . (a) How are P_1 and P_2 related ? (b) Which is more P_1 or P_2 ?

Ans. (a) $P_2 = P_1 + h\rho g$, (b) $P_2 > P_1$
20. Explain why a gas bubble released at the bottom of a lake grows in size as it rises to the surface of lake.
21. A dam has broader walls at the bottom than at the top. Explain.
22. Why do sea divers need special protective suit ?
23. State the laws of liquid pressure.
24. A tall vertical cylinder filled with water is kept on a horizontal table top. Two small holes A and B are made on the wall of the cylinder, A near the middle and B just below the free surface of water. State and explain your observation.
25. How does the liquid pressure on a diver change if :
 - (i) the diver moves to the greater depth, and
 - (ii) the diver moves horizontally ?

Ans. (i) Pressure increases, (ii) Pressure remains unchanged
26. State Pascal's law of transmission of pressure.
27. Name two applications of Pascal's law.
28. Explain the principle of a hydraulic machine. Name two devices which work on this principle.
29. Name and state the principle on which a hydraulic press works. Write one use of the hydraulic press.
30. The diagram in Fig. 4.12 shows a device which makes use of the principle of transmission of pressure.

2. The pressure inside a liquid of density ρ at a depth h is :

- (a) $h\rho g$ (b) $\frac{h}{\rho g}$
(c) $\frac{h\rho}{g}$ (d) $h\rho$

Ans. (a) $h\rho g$

3. The pressure P_1 at a certain depth in river water and P_2 at the same depth in sea water are related as :

- (a) $P_1 > P_2$ (b) $P_1 = P_2$
(c) $P_1 < P_2$ (d) $P_1 - P_2 = \text{atmospheric pressure}$

Ans. (c) $P_1 < P_2$

4. The pressure P_1 at the top of a dam and P_2 at a depth h from the top inside water (density ρ) are related as :

- (a) $P_1 > P_2$ (b) $P_1 = P_2$
(c) $P_1 - P_2 = h\rho g$ (d) $P_2 - P_1 = h\rho g$

Ans. (d) $P_2 - P_1 = h\rho g$

Numericals :

1. A hammer exerts a force of 1.5 N on each of the two nails A and B. The area of cross section of tip of nail A is 2 mm² while that of nail B is 6 mm². Calculate pressure on each nail in pascal.

Ans. On A : 7.5×10^5 pascal, On B : 2.5×10^5 pascal.

2. A block of iron of mass 7.5 kg and of dimensions 12 cm $\times$ 8 cm $\times$ 10 cm is kept on a table top on its base of side 12 cm $\times$ 8 cm. Calculate : (a) thrust and (b) pressure exerted on the table top. Take 1 kgf = 10 N.

Ans. (a) 75 N (b) 7812.5 Pa

3. A vessel contains water up to a height of 1.5 m. Taking the density of water 10^3 kg m⁻³, acceleration due to gravity 9.8 m s⁻² and area of base of vessel 100 cm², calculate : (a) the pressure and (b) the thrust, at the base of vessel.

Ans. (a) 1.47×10^4 N m⁻² (b) 147 N

4. The area of base of a cylindrical vessel is 300 cm². Water (density = 1000 kg m⁻³) is poured into it up to a depth of 6 cm. Calculate : (a) the pressure and (b) the thrust of water on the base. ($g = 10$ m s⁻²).

Ans. (a) 600 Pa, (b) 18 N

5. (a) Calculate the height of a water column which will exert on its base the same pressure as the 70 cm column of mercury. Density of mercury is 13.6 g cm⁻³.

(b) Will the height of the water column in part (a) change if the cross section of the water column is made wider ?

Ans. (a) 9.52 m (b) No

6. The pressure of water on the ground floor is 40,000 Pa and on the first floor is 10,000 Pa. Find the height of the first floor.

(Take : density of water = 1000 kg m⁻³, $g = 10$ m s⁻²)

Ans. 3 m

7. A simple U tube contains mercury to the same level in both of its arms. If water is poured to a height of 13.6 cm in one arm, how much will be the rise in mercury level in the other arm ?

Given : density of mercury = 13.6×10^3 kg m⁻³ and density of water = 10^3 kg m⁻³.

Ans. 1 cm

8. In a hydraulic machine, a force of 2 N is applied on the piston of area of cross section 10 cm². What force is obtained on its piston of area of cross section 100 cm²?

Ans. 20 N

9. What should be the ratio of area of cross section of the master cylinder and wheel cylinder of a hydraulic brake so that a force of 15 N can be obtained at each of its brake shoe by exerting a force of 0.5 N on the pedal ?

Ans. 1 : 30

10. The areas of pistons in a hydraulic machine are 5 cm² and 625 cm². What force on the smaller piston will support a load of 1250 N on the larger piston ? State any assumption which you make in your calculation.

Ans. 10 N

Assumption : There is no friction and no leakage of liquid.

11. (a) The diameter of neck and bottom of a bottle are 2 cm and 10 cm respectively. The bottle is completely filled with oil. If the cork in the neck is pressed in with a force of 1.2 kgf, what force is exerted on the bottom of the bottle ?

(b) Name the law/principle you have used to find the force in part (a)

Ans. (a) 30 kgf (b) Pascal's law

12. A force of 50 kgf is applied to the smaller piston of a hydraulic machine. Neglecting friction, find the force exerted on the large piston, if the diameters of the pistons are 5 cm and 25 cm respectively.

Ans. 1250 kgf

13. Two cylindrical vessels fitted with pistons A and B of area of cross section 8 cm² and 320 cm² respectively, are joined at their bottom by a tube and they are completely filled with water. When a mass of 4 kg is placed on piston A, find : (i) the pressure on piston A, (ii) the pressure on piston B, and (iii) the thrust on piston B.

Ans. (i) 0.5 kgf cm⁻², (ii) 0.5 kgf cm⁻² (iii) 160 kgf

14. What force is applied on a piston of area of cross section 2 cm² to obtain a force 150 N on the piston of area of cross section 12 cm² in a hydraulic machine ?

Ans. 25 N

4.9 ATMOSPHERIC PRESSURE

The earth is surrounded by air up to a height of about 300 km from its surface. This envelope of air around the earth is called **atmosphere**. The weight of air column exerts a thrust on the earth surface. The thrust exerted on unit area of the earth surface is called the atmospheric pressure. Thus

The thrust exerted per unit area on the earth surface due to column of air, is called the atmospheric pressure on the surface of earth.

Note : The weight of air column over 1 cm^2 area on the earth surface is nearly 1 kgf, so the atmospheric pressure on the earth surface is about 1 kgf per cm^2 ($= 1 \text{ kgf}/1 \text{ cm}^2 = 10 \text{ N}/10^{-4} \text{ m}^2 = 10^5 \text{ N m}^{-2}$). This implies that a thrust of about 100,000 N acts on every 1 m^2 of the surface of objects on the earth. The average surface area of a human body is about 2 m^2 , therefore the atmosphere exerts a total thrust of about $2 \times 10^5 \text{ N}$ on our body. However, we are not aware of this enormous thrust (or load) on us because the pressure of our blood (*i.e.*, **blood pressure**), balances it. The blood pressure is slightly more than the atmospheric pressure. However, at high altitude, the atmospheric pressure becomes less because the height of air column above that altitude is less than at the earth surface. As a result, at high altitudes the blood pressure becomes much more than the atmospheric pressure and nose bleeding may occur due to excess blood pressure.

4.10 DEMONSTRATION OF ATMOSPHERIC PRESSURE

The existence of atmospheric pressure can be easily demonstrated in laboratory by the following simple experiment.

Collapsing tin can experiment

Take a thin tin can fitted with an airtight stopper. The stopper is removed and a small quantity of water is boiled in the can. Gradually the steam occupies the entire space of can by expelling the air from it [Fig. 4.13(a)]. The stopper is then tightly replaced and simultaneously the flame beneath the can is removed. Cold water is then poured over the can. It is observed that the can collapses inwards as

shown in Fig 4.13(b). The reason is that initially the pressure due to steam inside the heated can is same as the air pressure outside the can [Fig. 4.13(a)]. But on pouring cold water over the can, fitted with a stopper [Fig. 4.13(b)], the steam inside the can condenses, producing water and water vapours at a very low pressure. Now the air pressure outside the can exceeds the vapour pressure inside the closed can. Consequently, the excess atmospheric pressure outside the can causes it to collapse inwards. This demonstrates that the atmosphere outside the can exerts a pressure which is the atmospheric pressure.

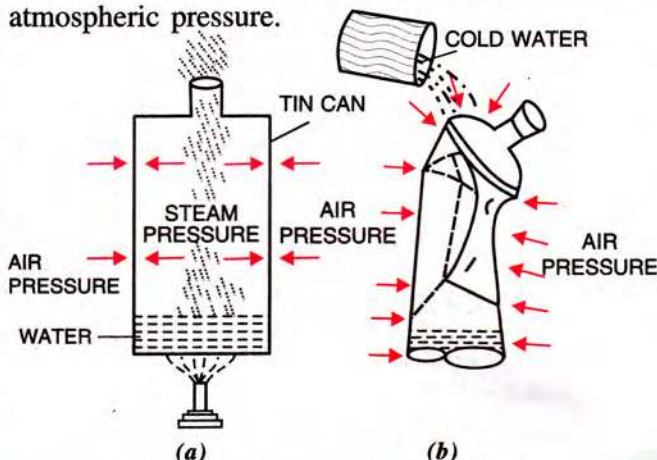


Fig. 4.13 Collapsing can experiment

4.11 COMMON CONSEQUENCES OF THE ATMOSPHERIC PRESSURE

- (i) **Sucking a drink with a straw :** When a drink is sucked with a straw (Fig 4.14), first the air in straw goes into our lungs due to which the air pressure inside the straw decreases. The atmospheric pressure acting on the surface of drink being more than the pressure inside the straw, forces the drink to move up into the straw which then reaches into our mouth.



Fig. 4.14 Sucking a drink with a straw

- (ii) **Filling a syringe with a liquid :** When syringe is kept with its opening just inside a liquid and its plunger is pulled up in the barrel (Fig. 4.15), the pressure of air inside the barrel below the plunger becomes much less than the atmospheric pressure acting on the liquid. As a result, the atmospheric pressure forces the liquid to rise up in the syringe.

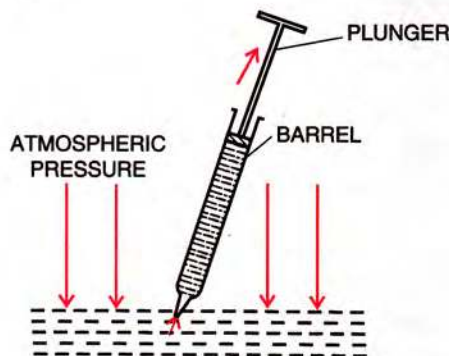


Fig. 4.15 Action of syringe

In a similar manner, in a water pump, water is drawn up from a well on pulling the piston up.

- (iii) **Filling of ink into a fountain pen :** As a syringe is filled with a liquid due to the atmospheric pressure, ink also gets filled into a fountain pen. The pen is kept with its nib inside ink. When the rubber tube of fountain pen is pressed, almost all the air of rubber tube expels out in form of bubbles through the ink. When the rubber tube is released, the pressure inside the rubber tube is much less than the atmospheric pressure acting on the ink. As a result, the ink rises into the tube through the capillary below the nib of the pen.

- (iv) **Action of rubber suckers :** Rubber suckers are often used as hooks in the kitchen and bathroom. For this, rubber sucker is pressed hard against the wall (Fig. 4.16) so that the air between the sucker and the wall is forced out, creating a vacuum in between. The atmospheric pressure acting on it from outside then holds the sucker along with the hook on it firmly against the wall. For firm grip, the wall must be smooth.

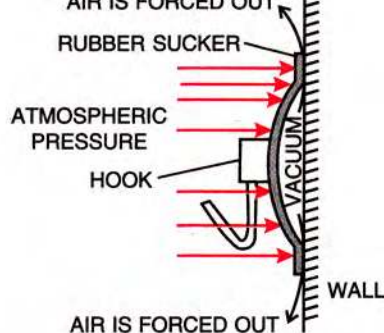


Fig. 4.16 Action of rubber sucker

- (v) **Action of a siphon system :** Water is supplied from a higher level to a lower level using a siphon system. Fig. 4.17 shows the siphon system in which there are two vessels P and Q . Vessel P is at a higher level than the vessel Q . Water contained in the vessel P is passed to the vessel Q by means of a glass (or rubber) tube AB with one end A kept immersed inside water in vessel P , while the other end B is kept open in vessel Q . To transfer water from vessel P to vessel Q , first air is sucked out from the tube at the lower end B of it, so that pressure inside the tube decreases. It becomes less than the atmospheric pressure acting above the water surface in vessel P . Due to excess pressure at A , water rises in the tube through the end A , so as to reach up to the level C . Then water flows down through the tube from the higher level C to the lower level B in the vessel Q due to the difference in pressure of water at the levels C and B .

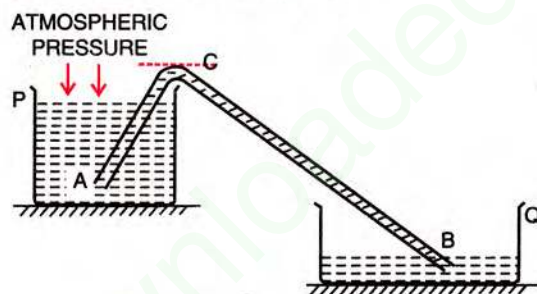


Fig. 4.17 Siphon system

- (vi) **Taking out oil from a sealed oil can :** It is difficult to take out oil from a *completely filled and sealed can* by making a single hole in it. The reason is that there is no air inside a completely filled and sealed oil can. When the can is tilted, the pressure due to the column of oil (inside the can) at the hole is much less than

the atmospheric pressure outside the can, so the oil does not flow out of the hole. But if one more hole is made at the opposite end on the top cover of the can, air outside the can will enter in through this hole and will exert atmospheric pressure on the oil from inside along with the pressure due to oil column. This results in the increase in pressure on oil, and so it easily flows out through the hole of the can.

4.12 MEASUREMENT OF ATMOSPHERIC PRESSURE

Atmospheric pressure at a place is measured by a *barometer*. Thus

A barometer is an instrument which is used to measure the atmospheric pressure.

The following *three* types of barometers are commonly used :

- (i) Simple barometer
- (ii) Fortin's barometer
- (iii) Aneroid barometer

(i) Simple barometer

In 1643, Torricelli first designed a *simple barometer* using mercury as the barometric liquid.

Construction : A simple barometer has a hard glass tube of about 1 m length closed at one end. The tube is completely filled with pure mercury such that no air bubble remains inside the tube. The open end of tube is closed with thumb and the tube is then made upside down several times so as to force out any air bubble which might have entered in it. The completely filled tube with its open end closed by thumb is then inverted into a trough of mercury in such a way that the open end of tube is well immersed in mercury and the tube stands vertical as shown in Fig. 4.18. Now the thumb is removed. Care is taken that no air enters in the glass tube.

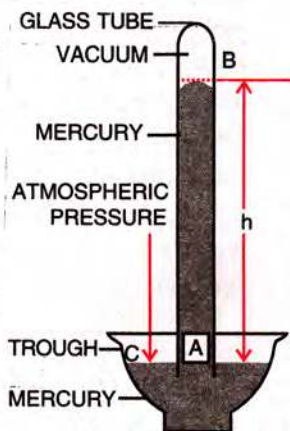


Fig. 4.18 Simple barometer

It is seen that the mercury level in tube falls till its height above the mercury level in the trough becomes h ($\approx$ nearly 76 cm) as shown in Fig. 4.18.

Explanation : In Fig 4.18, the atmospheric pressure acts at all points (such as C) on the surface of mercury in the trough. The pressure at point A is due to the weight (or thrust) of the mercury column AB above it. When mercury level in the tube becomes stationary, the pressure inside tube at the point A which is at the level of the point C, must be same as that at the point C. Thus the vertical height of mercury column in it (i.e., $AB = h$) is called the *barometric height*. The space left empty above the mercury column in the tube is called the *torricellian vacuum*. Ideally there should be no air in this space.

Working : If the atmospheric pressure increases, the pressure at point C increases and mercury from trough flows into the tube thereby increasing the vertical height of mercury column in the tube so as to equalise pressures at the points A and C. On the other hand, when the atmospheric pressure decreases, the vertical height of the column in tube decreases to balance it. Thus, *the vertical height of mercury column from the mercury surface in trough to the level in tube, is a measure of the atmospheric pressure.*

Barometric height at normal temperature and pressure : The barometric height at normal temperature and pressure at sea level is 0.76 m (or 76 cm or 760 mm) of mercury.

Factors affecting the barometric height : The barometric height at a place changes only when the atmospheric pressure at that place changes.

Note : (1) The barometric height remains *same* even when the shape of tube is changed or the length of tube submerged inside mercury in the trough is changed or tube is tilted from its vertical position as shown in Fig 4.19.

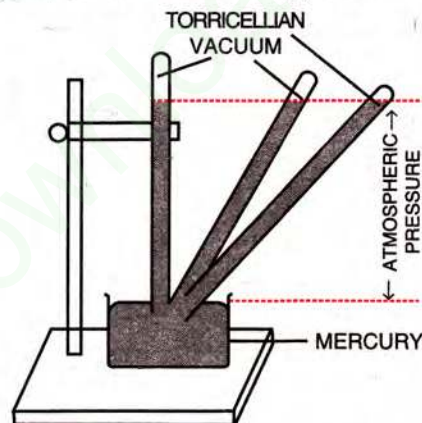


Fig. 4.19 Tilting of the barometer tube

empty space above the mercury column in tube is perfect *vacuum*. If somehow air enters the empty space or a drop of water (or liquid) gets into the tube, it will immediately change into vapour in the vacuum space and the air (or the vapours of liquid) will exert pressure on the mercury column due to which the barometric height will decrease. Such a barometer is a *faulty barometer*. The barometric height of a faulty barometer will be less than the actual atmospheric pressure.

Advantages of using mercury as a barometric liquid

A barometre can be made by using any liquid, but the use of mercury as a barometric liquid is preferred for the following reasons :

1. The density of mercury ($= 13.6 \times 10^3 \text{ kg m}^{-3}$) is greater than that of any other liquid, so only 0.76 m height of mercury column is needed to balance the normal atmospheric pressure. Use of other liquids require much longer tube.
2. The vapour pressure of mercury is negligible, so the vapours in the torricellian vacuum does not affect the barometric height.
3. The mercury neither wets nor sticks to the glass tube therefore it gives the accurate reading.
4. The surface of mercury is shining and opaque. Therefore, it is easily seen while taking the observation.
5. It can easily be obtained in a pure state.

Disadvantages of using water as a barometric liquid

If water is used in a barometer, it has the following disadvantages :

1. The density of water is low ($= 10^3 \text{ kg m}^{-3}$), so nearly 10.4 m height of water column is needed to balance the normal atmospheric pressure. But it is highly inconvenient to take a tube of height 10.4 m for a barometer.
2. The vapour pressure of water is high, so its vapours in the vacuum space will make the reading inaccurate.
3. Water sticks with the glass tube and wets it, so the reading becomes inaccurate.

seen while taking the observation.

Demerits of a simple barometer

- (i) There is no protection for the glass tube.
- (ii) The surface of mercury in the trough is open therefore there are chances that the impurities may fall in and get mixed with the mercury of the trough.
- (iii) It is inconvenient to move the barometer from one place to another *i.e.* it is not portable.
- (iv) A scale can not be fixed with the tube (or it can not be marked on the tube) to measure the atmospheric pressure. The reason is that when the atmospheric pressure changes, the height of mercury column in the tube changes. As a result, the level of free surface of mercury in the trough changes due to the flow of mercury in or out of the tube. Therefore, the free surface of mercury in trough will not remain coinciding with the zero mark of scale if a scale is fixed with it to measure the barometric height.

The above demerits have been removed in the *Fortin barometer*.

(ii) Fortin barometer

The Fortin barometer is a modified form of a simple barometer. It is used in laboratory to measure the atmospheric pressure. It also uses mercury as the barometric liquid.

Construction : The Fortin barometer shown in Fig. 4.20 consists of a narrow glass tube of length about 85 cm to 90 cm. This tube is closed at one end and has a opening at the other end. It is completely filled with pure mercury and is kept inverted in a glass vessel having a leather cup at the bottom. The cup contains mercury and behaves like a trough. The open end of tube is dipped into mercury of the cup. The glass tube is protected by enclosing it in a brass case. At the bottom of the brass case, there is a screw *S*, the end of which supports the leather cup of the glass vessel. The leather cup can be raised up or lowered down with the help of the screw *S* to adjust the mercury level in the glass vessel. The mercury level in the glass vessel is adjusted to coincide with the zero mark of the main scale graduated in mm attached with the brass tube. The zero mark of the fixed scale is

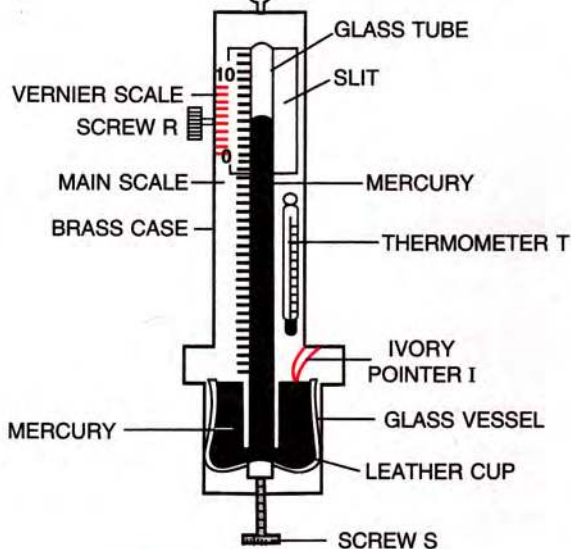


Fig. 4.20 Fortin barometer

at the tip of an ivory pointer I which is distinctly visible from outside. The upper part of the brass tube has a slit in it so as to note the mercury level in the glass tube. For accurate measurement, a vernier scale is provided which slides over the main scale by using the screw R . A thermometer T is also mounted on the case which records the room temperature.

Measurement : To measure the atmospheric pressure, first the level of mercury in the leather cup is raised up or lowered down with the help of the screw S so that the mercury level in the glass vessel just touches the ivory point I . The position of mercury level in the barometer tube is noted with the help of the main scale and the vernier scale. The sum of vernier scale reading and the main scale reading gives the barometric height.

(iii) Aneroid barometer

This barometer has no liquid. It is light and portable and therefore, it can easily be carried from one place to another. It is calibrated to read directly the atmospheric pressure. It needs no prior adjustment like Fortin barometer.

Construction : Fig. 4.21 (a) shows the main parts of an aneroid barometer. It consists of a metallic box B which is partially evacuated. The top D of box is springy and is corrugated in form of a diaphragm as shown in Fig. 4.21 (b). At the middle of diaphragm, there is a thin rod L toothed

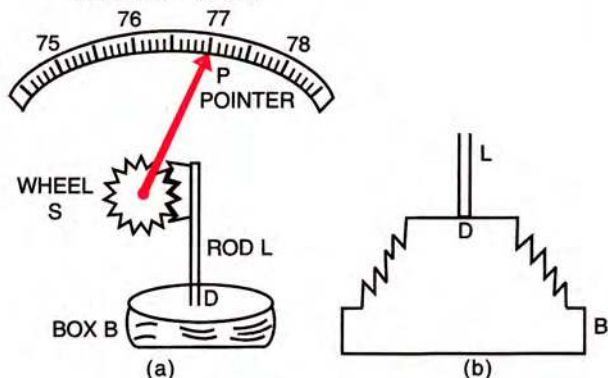


Fig. 4.21 Aneroid barometer

at its upper end. The teeth of rod fit well into the teeth of a wheel S attached with a pointer P which can slide over a circular scale. The circular scale is graduated and is *initially calibrated* with a standard barometer so as to read the atmospheric pressure directly in terms of the barometric height.

Working : When atmospheric pressure increases, it presses the diaphragm D and the rod L gets depressed. The wheel S rotates clockwise and pointer P moves to the right on the circular scale. On the other hand, when atmospheric pressure decreases, the diaphragm D bulges out due to which the rod L moves up and the wheel S rotates anti-clockwise. Consequently, the pointer moves to the left.

Uses of a barometer

A barometer is used for the following *three* purposes:

1. To measure the atmospheric pressure at a place.
2. For weather forecasting.
3. As an altimeter to measure the height.

4.13 VARIATION OF ATMOSPHERIC PRESSURE WITH ALTITUDE

The atmospheric pressure decreases with altitude mainly due to the following *two* factors:

- (i) decrease in height of air column which causes a *linear* decrease in the atmospheric pressure,
- (ii) decrease in density of air which causes a *non-linear** decrease in atmospheric pressure.

* The decrease in density of air with altitude is not linear. It is rapid at low altitude but slow at high altitude.

of a number of parallel air layers. Each layer experiences a pressure on it due to the thrust (or weight) of the air column above it. Therefore, as we go up, the height of air column above us decreases and so thrust exerted by the air column also decreases, which results in the decrease of atmospheric pressure with increase in altitude.

(ii) Since the lower air layers get compressed due to the weight (or thrust) of the upper layers, therefore, the density of air layers is more near the earth surface and it decreases as we go higher and higher. The decrease in density with altitude is *not linear*. It is rapid at low altitude (near the sea level) and is slow at higher altitude. Due to decrease in density of air with altitude, the atmospheric pressure also decreases with altitude in a non-linear way.

Fig. 4.22 shows the variation of atmospheric pressure with height above the sea level. At Mount Everest, the atmospheric pressure is only 30% of the atmospheric pressure at sea level.

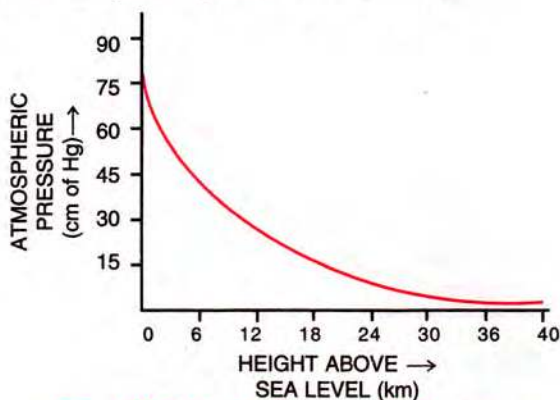


Fig. 4.22 Variation in atmospheric pressure with altitude

Consequences : (1) At high altitudes, since the atmospheric pressure is less, breathing becomes difficult and nose bleeding may occur due to excess of pressure of blood over the atmospheric pressure. Therefore blood pressure patients are not advised to go to hill stations or higher altitudes.

(2) At high altitude, a fountain pen leaks. The reason is that the fountain pen filled with ink contains some air at a pressure equal to the atmospheric pressure on the earth surface. When pen is taken to an altitude, atmospheric pressure at altitude is low so the excess pressure inside the rubber tube forces the ink to leak out.

The atmospheric pressure at a place is affected by the change in temperature and the amount of water vapours present in air at that place. The reason is that the density of air changes with the change in temperature and with the change of water vapours present in it. The density of air decreases with the increase in temperature and also with the increase in the amount of moisture present in it (*i.e.*, the density of moist or humid air is less than the density of dry air). Consequently, the atmospheric pressure (or the barometric height) gradually decreases as the temperature or the presence of moisture increases. Thus, the change in the atmospheric pressure helps us to know about the weather in advance. By seeing the barometric height, the weather forecast can be made as follows:

- (i) If the barometric height at a place *suddenly falls*, it means that the pressure at that place has suddenly decreased which indicates the *coming of a storm or cyclone*.
- (ii) If the barometric height *gradually falls*, it indicates that the moisture is increasing *i.e.*, there is a *possibility of rain*.
- (iii) A *gradual increase* in the barometric height means that the moisture in air is decreasing. This indicates the coming of a *dry weather*.
- (iv) A *sudden rise* in the barometric height means the flow of air from that place to other surrounding low pressure areas. This indicates the coming of an *extremely dry weather*.
- (v) If there is *no abrupt change* in barometric height, it indicates that the atmospheric pressure is normal *i.e.*, the weather will remain unchanged.

4.15 ALTIMETER

An altimeter is an aneroid barometer, but it is used in aircraft to measure its altitude. Since atmospheric pressure decreases with the increase in height above the sea level, therefore a barometer which measures the atmospheric pressure, can be used to determine the altitude of a place above the sea level. Its scale is calibrated in terms of height of ascent *with height increasing towards left because the atmospheric pressure decreases with increase of height above the sea level*.

1. 'The atmospheric pressure at a place is 75 cm of Hg'. What does it mean? Express it in N m^{-2} .

Use : density of Hg = 13.6 g cm^{-3} , $g = 9.8 \text{ m s}^{-2}$.

The atmospheric pressure at a place is 75 cm of Hg. It means that the atmospheric pressure at that place is equal to the pressure due to mercury column of height 75 cm.

Given : $h = 75 \text{ cm} = 0.75 \text{ m}$, $g = 9.8 \text{ m s}^{-2}$,

$\rho = 13.6 \text{ g cm}^{-3} = 13.6 \times 10^3 \text{ kg m}^{-3}$.

$$\begin{aligned}\text{Atmospheric pressure } P &= h\rho g \\ &= 0.75 \times (13.6 \times 10^3) \times 9.8 \\ &= 9.996 \times 10^4 \text{ N m}^{-2}.\end{aligned}$$

2. The upper blood pressure of a patient is 160 cm of Hg whereas the normal blood pressure should be 120 cm of Hg. Calculate the extra pressure generated by the heart in S.I. unit. Take density of Hg = 13600 kg m^{-3} and $g = 9.8 \text{ m s}^{-2}$.

Given, $\rho = 13600 \text{ kg m}^{-3}$, $g = 9.8 \text{ m s}^{-2}$

Extra pressure = $160 - 120 = 40 \text{ cm} = 0.4 \text{ m}$ of Hg

From relation $P = h\rho g$

$$\begin{aligned}\text{Extra pressure } P &= 0.4 \times 13600 \times 9.8 \\ &= 5.3312 \times 10^4 \text{ Pa}.\end{aligned}$$

3. (a) What length of water column is equivalent to 0.76 m of mercury column? State the assumption made in your calculation.

(b) Can water be used as barometric liquid? Give a reason.

(a) Given : height of mercury column $h_1 = 0.76 \text{ m}$
Let h_2 be the height of water column which will

produce same pressure as height $h_1 (= 0.76 \text{ m})$ of mercury column.

$$\text{Then } h_1\rho_1g = h_2\rho_2g$$

$$\therefore h_2 = \frac{h_1\rho_1}{\rho_2} = 0.76 \times 13.6 = 10.34 \text{ m}.$$

Assumption : The density of mercury is 13.6 times the density of water i.e., $\rho_1 = 13.6 \rho_2$

(b) Water cannot be used as the barometric liquid because it will then require the barometer tube of length more than 10.34 m which will be highly inconvenient.

4. A mercury barometer reads 75 cm. Now 3 cm^3 of atmospheric air is introduced into the tube. The mercury falls to a height of 65 cm and the length of air column above the mercury is found to be 15 cm. Calculate the cross sectional area of the barometer tube.

Initial volume of air $V_1 = 3 \text{ cm}^3$ at a pressure $P_1 = \text{atmospheric pressure} = 75 \text{ cm of mercury}$.

The level of mercury falls to 65 cm because the air in the tube exerts pressure on it. Therefore, pressure of air inside the tube, $P_2 = 75 - 65 = 10 \text{ cm of Hg}$.

Given, length of air column = 15 cm. If $A \text{ cm}^2$ is the area of cross section of the tube, then volume of the trapped air $V_2 = 15 \times A \text{ cm}^3$.

$$\begin{aligned}\text{By Boyle's law, } P_1V_1 &= P_2V_2 \\ 75 \times 3 &= 10 \times (15 \times A)\end{aligned}$$

$$\therefore A = \frac{75 \times 3}{10 \times 15} = 1.5 \text{ cm}^2.$$

EXERCISE 4 (B)

1. What do you understand by atmospheric pressure?
2. Write the numerical value of the atmospheric pressure on the surface of the earth in pascal.

Ans. 1.013×10^5 pascal

3. What physical quantity is measured in torr? How is it related to the S.I. unit of the quantity?

Ans. Atmospheric pressure, $1 \text{ torr} = 133.28 \text{ Pa}$

4. Name the physical quantity which is expressed in the unit 'atm'. State its value in pascal.

5. We do not feel uneasy even under the enormous pressure of atmosphere above as well as around us. Give a reason.

6. Describe an experiment to demonstrate that air exerts pressure.

7. Explain the following :

- (i) A balloon collapses when air is removed from it.
(ii) Water does not run out of a dropper unless its rubber bulb is pressed.

- (iii) Two holes are made in a sealed tin can to take out oil from it.

8. Why does the liquid rise in a syringe when its piston is pulled up?

9. How is water drawn up from a well by a water pump?

10. A bell jar connected to a vacuum pump contains a partially inflated balloon. On creating vacuum inside the bell jar, balloon gets more inflated. How does the pressure change : increase, decrease or remains same, inside the (a) bell jar and (b) balloon?

Ans. (a) decrease, (b) decrease

11. What is the purpose of a barometer?

Ans. To measure the atmospheric pressure

12. What is a barometer? How is a simple barometer constructed?

13. Explain how is the height of mercury column in

atmospheric pressure.

14. Illustrate with the help of a labelled diagram of a simple barometer that the atmospheric pressure at a place is 76 cm of Hg.
15. Why is the barometric height used as a unit to express the atmospheric pressure ?
16. What is meant by the statement 'the atmospheric pressure at a place is 76 cm of Hg'? State its value in Pa. **Ans.** 1.013×10^5 Pa
17. How will you show that there is vacuum above the surface of mercury in a barometer ? What name is given to this vacuum ?
18. How is the barometric height of a simple barometer affected if
- (a) its tube is pushed down into the trough of mercury?
 - (b) its tube is slightly tilted from vertical ?
 - (c) a drop of liquid is inserted inside the tube ?
- Ans.** (a) remains unaffected (b) remains unaffected (c) decreases
19. State *two* uses of a barometer.
20. Give *two* reasons for the use of mercury as a barometric liquid.
21. Give *two* reasons why water is not a suitable barometric liquid.
22. Mention *two* demerits of a simple barometer and state how they are removed in a Fortin barometer.
23. Draw a simple labelled diagram of a Fortin barometer and state how it is used to measure the atmospheric pressure.
24. What is an aneroid barometer ? Draw a neat and labelled diagram to explain its construction and working.
25. State *two* advantages of an aneroid barometer over a simple barometer.
26. How is the reading of a barometer affected when it is taken to (i) a mine, and (ii) a hill ?
- Ans.** (i) increases (ii) decreases.
27. How does the atmospheric pressure change with altitude ? Draw an approximate graph to show this variation.
28. State *two* factors which affect the atmospheric pressure as we go up.
29. Why does a fountain pen leak at a high altitude ?
30. Why does nose start bleeding on high mountains ?
31. What is an altimeter ? State its principle. How is its scale calibrated ?

regarding weather :

- (a) gradual fall in the mercury level,
- (b) sudden fall in the mercury level,
- (c) gradual rise in the mercury level ?

Multiple choice type :

1. The unit torr is related to the barometric height as :
- (a) 1 torr = 1 cm of Hg (b) 1 torr = 0.76 m of Hg
 - (c) 1 torr = 1 mm of Hg (d) 1 torr = 1 m of Hg
- Ans.** (c) 1 torr = 1 mm of Hg
2. The normal atmospheric pressure is :
- (a) 76 m of Hg (b) 76 cm of Hg
 - (c) 76 Pa (d) 76 N m^{-2}
- Ans.** (b) 76 cm of Hg
3. The atmospheric pressure at earth surface is P_1 and inside mine is P_2 . They are related as :
- (a) $P_1 = P_2$ (b) $P_1 > P_2$
 - (c) $P_1 < P_2$ (d) $P_2 = 0$
- Ans.** (c) $P_1 < P_2$

Numericals :

1. Convert 1 mm of Hg into pascal. Take density of Hg = $13.6 \times 10^3 \text{ kg m}^{-3}$ and $g = 9.8 \text{ m s}^{-2}$.
- Ans.** 133.28 Pa
2. At a given place, a mercury barometer records a pressure of 0.70 m of Hg. What would be the height of water column if mercury in barometer is replaced by water ? Take density of mercury to be $13.6 \times 10^3 \text{ kg m}^{-3}$.
- Ans.** 9.52 m
3. At sea level, the atmospheric pressure is 76 cm of Hg. If air pressure falls by 10 mm of Hg per 120 m of ascent, what is the height of a hill where the barometer reads 70 cm Hg. State the assumption made by you.
- Ans.** 720 m
- Assumption :** Atmospheric pressure falls linearly with ascent.
4. At sea level, the atmospheric pressure is 1.04×10^5 Pa. Assuming $g = 10 \text{ m s}^{-2}$ and density of air to be uniform and equal to 1.3 kg m^{-3} , find the height of the atmosphere. **Ans.** 8000 m
5. Assuming the density of air to be 1.295 kg m^{-3} , find the fall in barometric height in mm of Hg at a height of 107 m above the sea level. Take density of mercury = $13.6 \times 10^3 \text{ kg m}^{-3}$.
- Ans.** 10 mm of Hg