

Module 1 Pressure

This module is designed to help you to:

- explain the concept of pressure;
- describe that pressure exists at all points within a fluid;
- explain that pressure in a fluid at rest is the same at all points at the same depth (or height) from a reference level;
- perform activities to explain the concepts of pressure;
- analyze how the concepts of pressure can be applied in daily life e.g. manometer, hydraulic lift.

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10.1.1 Introduction

In this module, we discuss mechanical properties of fluids at rest. We also discuss why pressure is regarded as a scalar. Pressure exists at every point inside a fluid and increases with increase in depth. According to Pascal's law: for an enclosed fluid, pressure exerted at any point is transmitted equally in all directions. We also discuss the application of the principle to hydraulic mechanics.

A fluid is a substance that can flow. All liquids and gases are fluids. They have no definite shape of their own. They take the shape of the container in which they are stored. Incompressible liquids have a fixed volume but no definite shape. In contrast, gases have neither a fixed volume nor any definite shape.

For a fluid at rest, the force exerted by it must be normal to its surface irrespective of the orientation of the surface. A force in any other direction will necessarily have a component parallel to the liquid surface, causing it to move.

10.1.2 Pressure

Pressure of a fluid at a point is defined as the force acting per unit area. It is a scalar quantity.

$$\therefore P = \frac{\text{Normal Force}}{\text{Area}} = \frac{\text{Thrust}}{\text{Area}}$$

As the direction of force is always normal to the area at every point, hence pressure is considered a scalar quantity (Fig.10.1.1).

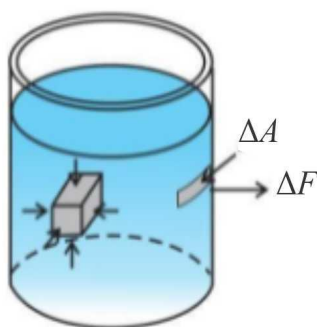


Fig.10.1.1: *The force exerted by the liquid in the beaker on the submerged object or on the walls is normal (perpendicular) to the surface at all points*

For an elementary area ΔA of a surface around a point, the pressure at that point

$$P = \lim_{\Delta A \rightarrow 0} \left(\frac{\Delta F}{\Delta A} \right)$$

As ΔA does not have any specific orientation, the pressure does not depend on the orientation of the surface element.

10.1.3 Pressure exists at all points within a fluid

The pressure exists at all points in a fluid at rest, irrespective of whether a solid surface is in contact with it or not. Let us consider a very small prismatic element (ABCDEF) of a fluid in its interior (Fig. 10.1.2). The surrounding fluid exerts pressure on each surface of this element. The element is small so that the effect of gravity can be ignored, but it has been enlarged for the sake of clarity.

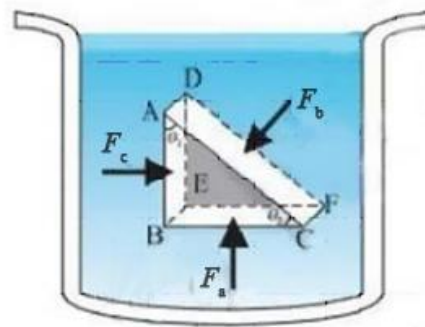


Fig.10.1.2: Forces on a prismatic element in the interior of a fluid at rest

10.1.4 Pressure, exerted at a point is the same in all directions in a fluid

In Fig. 10.1.2, ABCDEF is a small right angled prismatic element, in the interior of a fluid at rest. As this element is very small, every part of it can be considered at the same depth from the liquid surface. Hence the effect of gravity is the same at all points of this element. The forces on this element are due to the rest of the fluid. These forces have to be normal to the surfaces of the element.

Let the fluid exert pressure P_a , P_b and P_c on the faces BEFC, ADFC and ADEB (with areas A_a , A_b and A_c) of this prismatic element due to the normal forces, F_a , F_b and F_c respectively, acting on the surfaces.

For equilibrium of this fluid element, we have

$$F_b \sin \theta = F_c \quad F_b \cos \theta = F_a$$

$$\text{Also } A_b \sin \theta = A_c \quad A_b \cos \theta = A_a \quad (\text{by geometry})$$

$$\therefore \frac{F_c}{A_c} = \frac{F_a}{A_a} = \frac{F_b}{A_b}$$

$$\text{Hence } P_c = P_a = P_b$$

It follows that the pressure exerted is the same along all directions, for a fluid at rest. This is known as Pascal's law.

Instead of the prismatic element, we could have taken a very small cylindrical element as shown in Fig.10.1.3.

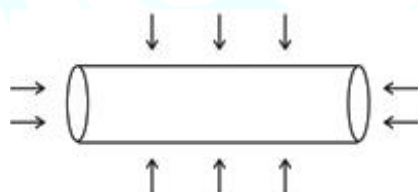


Fig.10.1.3: Forces on a cylindrical element in the interior of a fluid at rest

We can again show that the pressure exerted on this cylindrical element is equal on all sides of this element. To reinforce that pressure exerted at a point is the same in all directions in a fluid, let the students observe the flow of water from a plastic bottle with holes near its bottom. This activity may be carried out as under:

Activity 10.1.1

- Take an empty plastic bottle. Drill four small holes, symmetrically, near the bottom of the bottle, as shown in Fig.10.1.4. Make sure that the holes are at the same height from the bottom and have the same size.
- Fill the bottle with water. Observe the flow of water, through the holes.
- Note down the distance of the points from the bottle where the water stream falls.
- Draw your conclusions.



Fig.10.1.4: *Illustration of Pascal's law*

Discussion questions

- (i) What do you observe?
- (ii) Do different streams of water, coming out of the different holes, fall at the same distance from the bottle? What does this indicate?
- (iii) Does it indicate that, for points at the same depth, liquids exert equal pressure in all directions?
- (iv) What changes will there be, if we replace water by any other liquid?
- (v) What will happen if the shape of the container for the same liquid and same height is changed?

Answers

- (i) We will observe that water from each hole falls at the same distance from the bottle.
- (ii) Yes. This indicates that the pressure exerted by the liquid remains the same at the same height in all the directions.
- (iii) Yes.
- (iv) The distance covered by the liquid from the holes is the same in all the directions for all liquids.
- (v) The distance covered by the liquid from the holes is the same in all directions for the same height; it doesn't depend on the shape of the container.

Precautions

- (i) If the holes are not drilled properly, the water may drip from the rough edges. This may lead to different ranges for different water streams.
- (ii) If the holes are not drilled at equal heights, a similar problem can occur.

Repeat the above activity by changing

1. shape of the container
2. taking different liquids

You will observe the same results as above.

10.1.5 Pressure in a fluid at rest is the same at all points at the same depth (or height) from a reference level

The choice of 'reference level' from which the height/depth is measured, in general, depends on the system under consideration.

For example,

1. To measure pressure at different levels in the atmosphere, the reference level is taken as the sea level and heights (altitudes) are measured from this reference level.
2. If a liquid has a free surface, this is a convenient level from which distance may be measured. Thus, for pressure at a point inside a liquid, the reference level is taken as the upper surface of the liquid. Similarly, to express pressure at a point inside the sea, the sea level is taken as a reference level and depths are measured from there.

In Fig.10.1.2, we considered an infinitesimally small element ABCDEF so that every part of it could be considered at the same depth from the liquid surface(taken to be reference level). It was shown that the pressure is the same at all points that are at the same depth.

Consider a homogeneous fluid of density ρ at rest in a container (Fig.10.1.5). Let us consider two points; point 1 at a height h above point 2. Let us take an imaginary cylinder of the liquid between the points considered. Let A be the area of cross-section of the cylinder. Further, let pressures at points 1 and 2 be P_1 and P_2 respectively.

As liquid in the cylinder is in equilibrium, we have,

$$P_1 A + Ah\rho g = P_2 A$$

$$\therefore P_2 = P_1 + h\rho g$$

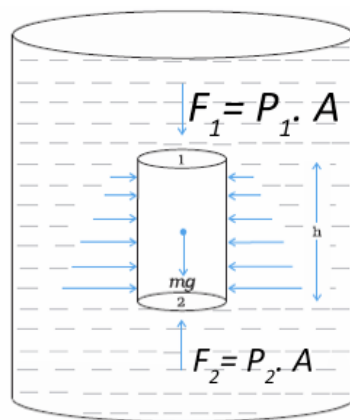


Fig.10.1.5: Pressure difference between two points in a liquid

The above relation leads us to the conclusion that the deeper one goes in the fluid, higher is the pressure one has to encounter. This increase in pressure, with depth, helps one to understand the need of special suits which deep sea divers have to wear while diving. The enormous pressure, in deep waters, would become unbearable for the human body in the absence of such special suits.

10.1.6 Condition for validity of expression for pressure

The pressure P , at depth h , below the liquid-air interface, is greater than the atmospheric pressure by an amount of ρgh Thus

$$P = P_a + \rho gh \quad (10.1.1)$$

Eq(10.1.1) holds true if ρ and g are constants.

ρ is constant for incompressible liquids and g is constant at a height h above the surface of earth for $h \ll R$ (radius of the earth)

As gasses are compressible; Eq(10.1.1) in general does not hold.

In the atmosphere, ρ varies with altitude. This is because unlike liquids, gasses cannot be treated as incompressible.

Compressibility of a substance is the reciprocal of its bulk modulus. A representative Table (Table 10.1.1) of bulk moduli of solids, liquids and gasses is given below for comparison.

Table 10.1.1: Bulk moduli of solids, liquids and gasses

State of Matter	Sample Material	Bulk Modulus ($\times 10^9 \text{ Nm}^{-2}$)
Solid	Steel	160
Liquid	Water	2.2
Gas	Air(at STP)	0.0001



Let Us Reflect

Q.10.1.1 For liquid in a container, the pressure at a given depth depends on

- (A) density of the liquid only
- (B) depth below the surface only
- (C) acceleration due to gravity only
- (D) all of the above.

Q. 10.1.2 For a given liquid at a certain point inside a container, the liquid pressure is

- (A) more on moon than on earth
- (B) less on moon than on earth
- (C) same on moon and earth
- (D) same everywhere in the universe.



Answers

A.10.1.1 (D)

A.10.1.2 (B)

10.1.7 Open tube manometer

The open tube manometer, an instrument to measure pressure differences, consists of a U-tube containing a suitable liquid (Fig.10.1.6).

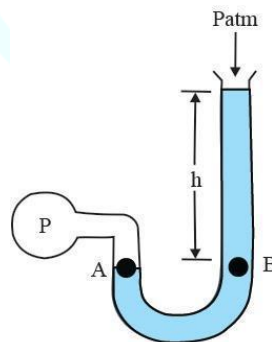


Fig. 10.1.6: *The open tube manometer*

One end of the tube is open to the atmosphere and the other end is connected to the system whose pressure we wish to measure.

In (Fig.10.1.6), the unknown pressure P at point A is to be measured. The pressure at B, is equal to the pressure at A as A and B are at the same level i.e. $P_A = P_B = P$. The pressure, on top of the open arm, is the atmospheric pressure P_{atm} . As h is the depth of point B, from the open surface of liquid, we have;

$$P = P_A = P_B = P_{atm} + \rho gh$$

$$\text{and } P - P_{atm} = \rho gh$$

The manometer measures this difference in pressure (ρgh) known as the gauge pressure. The gauge pressure

is the difference between the actual pressure (P) and the atmospheric pressure. Most pressure-measuring devices measure the gauge pressure.

For measuring small pressure differences, a low density liquid (such as oil) can be used. For large pressure differences, a high density liquid (such as mercury) has to be used.

We know from section 10.2.4, that pressure difference depends on the vertical distance h , mass density (ρ)

of the fluid and acceleration due to gravity (g). It does not depend upon the shape of the vessel containing the fluid.

Consider a U-tube filled with a liquid (Fig.10.1.7). A and B are two points, a vertical distance h apart as shown.

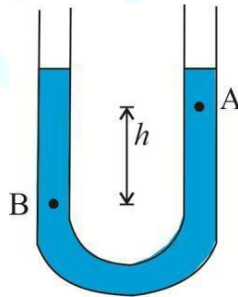


Fig.10.1.7: A U-tube manometer

Pressure difference between two points (A and B), is given by

$$P_B - P_A = \rho gh$$

Since both arms are open to the atmosphere, the pressure on top of the liquid in both arms is the same. Also, the level of liquid in both arms is the same. In this case, pressure is the same at the same level on both sides of the U-tube containing a fluid.

Let us now consider a U- tube, filled with two immiscible liquids of different densities (Fig.10.1.8). Now the pressure can be different at the same level in the two arms.

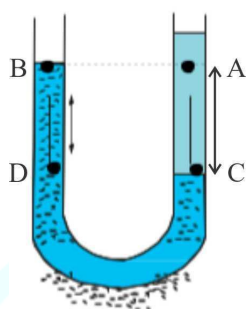


Fig. 10.1.8: A U-tube filled with two immiscible liquids

Suppose the density of liquid filled in the left arm is more than the density of liquid in the right arm. Here, points A and B are at the same level, but the pressure at A is higher than the pressure at B. The pressure at points C in the right limb and D in the left limb in both the arms will have the same value. But the heights of liquid columns above C and D in the two arms are different. We may note the height of the liquid column above C which balances the height of the liquid. Columns above D are greater because of its lower density.



Let Us Reflect

Q.10.1.3 What is the difference between gauge pressure and actual pressure?

Q.10.1.4 What is the difference between barometer and manomet



Answers

A.10.1.3 Absolute pressure is the actual pressure at a point. Gauge pressure, on the other hand, uses atmospheric pressure as its reference point. Gauge pressure is the measure of pressure difference between a system and the surrounding atmosphere.

A.10.1.4 A barometer measures atmospheric pressure with reference to the zero pressure of a vacuum enclosed in it. A manometer, on the other hand, measures the difference in the pressure of the gas inside the container and the atmospheric pressure.

Activity 10.1.2**Effect of change of pressure on a fluid**

Let us now try to find out what happens when we change the pressure on a fluid contained in a vessel by doing some activities.

- Take an aluminium tube about 15 cm long and 1 to 1.5 cm in diameter (Fig.10.1.9).
- Cut out a slice, about 2 cm thick, from a medium-sized potato.
- Insert the tube in the slice, press it, and rotate it 2–3 times. Remove the tube. You will find a piece of potato, fixed in the tube, somewhat like a piston head.
- Repeat the same process with the other end of the tube. Now you have the tube, with both ends closed by potato pieces, with an air column in between.

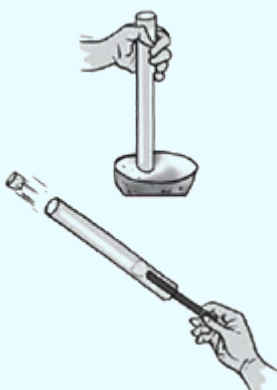


Fig.10.1.9: *An Illustration of the effect of pressure applied on fluid*

Take a pencil with one end unsharpened. Place this unsharpened end over one of the pieces of potato. Press it suddenly to push the potato piece in the tube. Observe how the potato piece, at the other end, flies out. This activity shows rather dramatically how increased air pressure can push objects.

Caution: When you perform this activity, make sure that nobody is standing in front of the tube to prevent any mishap.

Questions for discussion

- What will happen if in the above activity the diameter of the tube is increased?

- (ii) What happens if the force applied is decreased?
- (iii) What change will be observed if the length of the tube is increased?

Teachers can facilitate the students to arrive at the following conclusions.

- (i) When the diameter of the tube is increased (area increases) keeping the force constant, the pressure decreases [$\because P = \frac{F}{A}$]. Therefore the potato blows off with less velocity.
- (ii) When the applied force is decreased pressure also decreases [$\because P = \frac{F}{A}$]. Therefore the potato blows off with less velocity.
- (iii) Change in a potato's blow-off velocity depends upon the amount of compression of air due to increase in the length of the tube.

Activity 10.1.3

- Inflate a balloon and tie its mouth tightly.
- Now squeeze the balloon as shown in (Fig. 10.1.10) and observe.

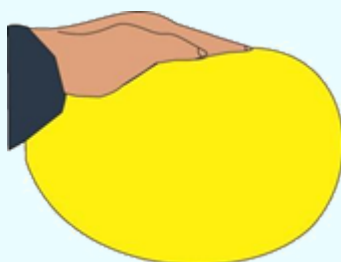


Fig.10.1.10: Pressure applied on an inflated balloon

Note: You may find an uneven bulge in some regions of the balloon. This may be due to non-uniform wall thickness of the balloon or due to application of greater pressure on one side of the balloon.

Questions for discussion

1. Does the balloon bulge uniformly in all directions?
2. What does the above observation indicate?
3. What happens if a smaller balloon is squeezed with the same force?
4. What changes will be observed if the same balloon is squeezed with a greater force?

The teacher can facilitate the students to the following conclusions-

- (1) The balloon bulges uniformly in all directions that are normal to the 'direction of squeeze' i.e. the direction of the applied force.
- (2) The flexible walls of the container (balloon) show how the increase in pressure, caused by squeezing, is transmitted equally throughout the balloon.
- (3) When a smaller balloon is squeezed with the same force, more bulging is observed due to increased pressure.
- (4) When the same balloon is squeezed with greater force, more bulging is observed because of increased pressure.

Activity 10.1.4

- Take a horizontal cylinder having a piston and three vertical tubes (at different points) as shown in (Fig. 10.1.11) Fill up water in tubes. (The level will be the same in all tubes)

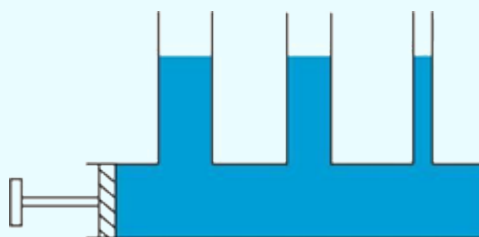


Fig.10.1.11: *Transmission of pressure applied on horizontal piston*

- Make students appreciate that the pressure in the horizontal cylinder is indicated by the height of the liquid column in the vertical tubes. The height of the liquid column is necessarily the same in all the (interconnected) vertical tubes.
- Now push the piston. Draw their attention to the fact that the fluid rises to the same level in all the tubes.
- Facilitate the learners to conclude that any increase in pressure on the piston is transmitted uniformly throughout the liquid.

Conclusion

Whenever external pressure is applied, at any part of an incompressible fluid, contained in a vessel, it is transmitted undiminished and equally in all directions. This is Pascal's law for transmission of fluid pressure.

Activity 10.1.5

To understand Pascal's law, let us perform another activity. Fig.10.1.12 shows a homogeneous and incompressible liquid in a container fitted with a piston. As we have learnt in the previous section, the pressure difference, between two points C and D (as shown), depends only on the vertical height h separating the two points. A force F , applied on the piston (as shown), will increase pressure at points below the piston by F/A , where A is the area of cross-section of the piston.

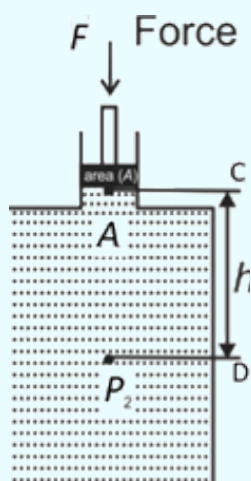


Fig. 10.1.12: *Transmission of pressure applied on vertical piston*

As the pressure difference between the bottom of the piston, and at a point D, at a depth h below the piston, is $h\rho g$, the additional pressure F/A , developed by the force, should also be transmitted undiminished to point D. Hence the pressure at D also increases by the same amount F/A . This is essential to ensure that the pressure difference between two points separated by height h remains $h\rho g$.

Activity 10.1.6



Fig10.1.13: *Application of Pascal's Law- Interconnected syringes*

- Take two syringes of different cross sections without needles.

- Connect the syringes with a tightly fitting rubber/plastic tube as shown in Fig.10.1.13. A drip tube may be used for this purpose. Seal the tube to the syringe. While sealing, take care that the piston of one syringe is pulled out and that of the other is pushed in.
- Push the piston of the smaller syringe. Observe the piston of the larger syringe. Does the larger piston move out?
- Notice that according to Pascal's law, the pressure transmitted must be the same. Since the two tubes have different areas of cross-section the forces on the pistons will be different. It would be more on the piston having a larger cross-section.
- You can test it by placing a suitable object (such as a paper weight) on the larger piston and try to lift it by pushing in the smaller piston.
- You can test it by placing a suitable object (such as a paper weight) on the larger piston and try to lift it by pushing in the smaller piston.

10.1.8 Applications of Pascal's law

Pascal's law has many applications in daily life. Perhaps the best-known applications of Pascal's law are the hydraulic lift and the hydraulic brakes. These are devices which convert a small force into a larger one. In a hydraulic lift, as shown in Fig. 10.1.14, two pistons are separated by a space filled with a fluid. (Piston can be pushed down or pulled up without allowing fluid to escape). The cross-section of one piston is larger than the cross-section of another piston. The idea is that a small force applied to the smaller piston will result in a much larger force on the larger piston. If the smaller piston is pressed down, the pressure, on the fluid, increases. This increase in pressure will be transmitted undiminished and equally in all directions throughout the liquid. The pressure that the smaller piston exerts against the fluid, will be exactly equal to the pressure that the fluid exerts against the bigger piston.

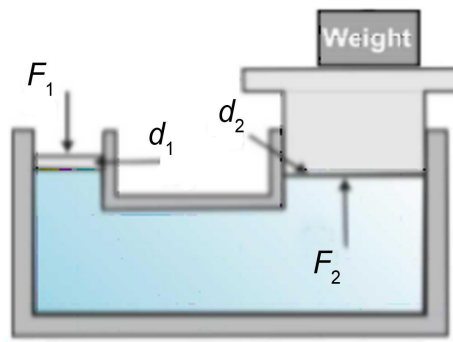


Fig. 10.1.14: Hydraulic lift

Suppose the cross-section of the smaller piston is A_1 and the larger piston is A_2 . When a force F_1 is exerted on the smaller piston, the piston applies F_1 on the fluid. So, the pressure applied by the smaller piston, on the fluid, is

$$P = \frac{F_1}{A_1}$$

Same pressure is applied by the fluid on the larger piston. Hence the upward force F_2 , on the larger piston

$$\text{is } F_2 = PA_2 = \frac{F_1}{A_1} \cdot A_2$$

Thus, the applied force gets multiplied by a factor $\frac{A_2}{A_1}$.

This factor is the mechanical advantage of the device. By increasing the area A_2 , of the larger piston, or reducing the area A_1 , of the smaller piston, the force on the larger piston can be increased quite significantly. Thus a suitably designed hydraulic lift can be used to raise heavy loads (like a car or a truck) placed on the platform of the larger cross-section by applying a small force on the piston of the smaller cross-section.

The hydraulic lift does not violate the law of energy conservation. Energy, in the form of work done, is conserved in this case also. Work is associated with the force applied over a distance. Though the force exerted on the larger piston is more, the distance through which it moves is very much smaller. If d_1 is the distance through which the smaller piston moves and d_2 is the distance through which the larger piston moves, then the conservation of energy implies

$$F_1 d_1 = F_2 d_2$$

$$d_2 = \frac{F_1}{F_2} d_1$$

Since $F_1 \ll F_2$, $d_2 \ll d_1$, Thus, the distance moved by the larger piston is much smaller than the distance through which the smaller piston moves.



Let Us Reflect

Q.10.1.5 In a hydraulic lift, (p, P) and (f, F) denote the pressures and forces on the smaller and the larger pistons respectively. We have

- (A) $P > p$ and $F > f$
- (B) $P < p$ and $F < f$
- (C) $P = p$ and $F > f$
- (D) $P = p$ and $F = f$

Q.10.1.6 In a hydraulic lift, a 2500 kg car is to be slowly raised through 20 cm by applying a force on the smaller piston. The area of the cross section of the smaller piston is one-tenth of the larger piston.

The distance moved by the smaller piston and the force applied on it are

- (A) 2 m and 250 kg wt
- (B) 0.2 m and 250 kg wt
- (C) 2 m and 25 kg wt
- (D) 20 m and 250 kg wt



Answers

A.10.1.5 (C)

A.10.1.6 (A)

Extended learning possibilities

The students may be asked to find out about applications of Pascal's law. They may visit automobile service stations to observe the functioning of (i) hydraulic lifts for automobiles and (ii) hydraulic brakes fitted in automobiles. They may also visit a construction site where hydraulic pistons are fitted in almost all construction machines involved/ associated with heavy loads. The students may also be encouraged to search some websites giving animated versions of applications of Pascal's law.

10.1.9 Summary

- Pressure can be treated like a scalar quantity because the force on the surface of a liquid is always normal to the surface.
- Pressure exists at all points inside a fluid. At a given point, the fluid pressure is the same in all directions.
- The absolute pressure exceeds the gauge pressure by atmospheric pressure.
- Inside an enclosed fluid, the pressure exerted is transmitted equally in all directions. This is known as Pascal's law.
- Pascal's law has been used in designing hydraulic machines which can lift very heavy loads by exerting much smaller effort.

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