Faculty of Science

General physics
(101 PhY)

PART (1) properties of matter

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Chapter One

PHYSICAL QUANTITIES

Quantitative versus Qualitative

A physical quantity is one that can be measured and consists of a magnitude and unit. Are classified into two types: Base quantities and Derived quantities

- **Base quantity** Fundamental units are those units that can express themselves without the assistance of any other units. For example: Kilogram (kg) is a fundamental unit because it is independently expressed and cannot be broken down to multiple units.

- **Derived quantity** Derived units are those units which cannot be expressed in the absence of fundamental units. For example: Newton (N) is a derived unit because it cannot be expressed in the absence of fundamental unit (meter) and can be broken down to multiple units (Newton equals to **kg.m /s^2**).

The international systems of units

In earlier time scientists of different countries were using different systems of units for measurement. Three such systems, the CGS, the FPS (or British) system and the MKS system were in use extensively till recently. The base units for length, mass and time in these systems were as follows:

- In **CGS** system they were centimetre, gram and second respectively.
- In **FPS** system they were foot, pound and second respectively.
- In **MKS** system they were metre, kilogram and second respectively.

	MKS system (SI system)	CGS system	FPS system
Length	m(meter)	cm(centimeter)	ft (foot)
Mass	kg(kilogram)	g(gram)	lb(pound)
Time	s(second)	s(second)	s(second)

Quantity	**Name**	**Symbol**
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	a
Temperature	Kelvin	k
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

Derived Quantity	Relation with Base and Derived Quantities	Special Name
area	length × width	
volume	length × width × height	
density	mass ÷ volume	
speed	distance ÷ time	
acceleration	change in velocity ÷ time	
force	mass × acceleration	newton (N)
pressure	force ÷ area	pascal (Pa)
work	force × distance	joule (J)
power	work ÷ time	watt (W)

Prefixes

Prefixes simplify the writing of very large or very small quantities

Prefix	Abbreviation	Power
nano	n	10^{-9}
micro	μ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}

Dimensional Analysis

Engineering and science, dimensional analysis is the analysis of the relationships between different physical quantities by identifying their base quantities (such as length, mass, time, electric charge) and units of measure (such as miles vs. kilometers, or pounds vs. kilo-grams) tracking these dimensions as calculations or comparisons are performed.

The importance of dimensional analysis

- To check the correctness of the form of the equation
- To derive a relation between the physical quantities but it can't have the values of the constants.
- To determine the proper units for some particular terms in an equation.
-

Dimension of basic and derived units

Basic Units	
Length	[L]
Time	[T]
Mass	[M]
Temperature	[K]

Derived Units	
Velocity	$[L][T^{-1}]$
Acceleration	$[L][T^{-2}]$
Force	$[M][L][T^{-2}]$
Frequency	$[T^{-1}]$
Density	$[M][L^{-3}]$
Volume	$[L^{3}]$
Pressure	$[M][L^{-1}][T^{-2}]$
Work	$[M][L^{2}][T^{-1}]$

Example (1-1):

Show that the following equation is dimensionally correct:

$$X = v_o t + \frac{1}{2} a t^2$$

Where (v_o) is velocity and (a) is acceleration

Solution:

$$Dim[LHS] = [L]$$

$$Dim[RHS] = \left[\frac{L}{T}\right][T] + \frac{1}{2}\left[\frac{L}{T^2}\right][T]^2$$

$$= [L] + \frac{1}{2}[L] = \frac{3}{2}[L]$$

$$Dim[LHS] = Dim[RHS]$$

The equation is dimensionally correct (ignore constants)

Example (1-2):

Show that the following equation is dimensionally correct:

$$v = vo + \text{at}$$

where (v_o) is velocity and (a) is acceleration

Solution:

$$Dim[LHS] = \left[\frac{L}{T}\right]$$

$$Dim[RHS] = \left[\frac{L}{T}\right] + \left[\frac{L}{T^2}\right][T]$$

$$= \left[\frac{L}{T}\right] + \left[\frac{L}{T}\right] = 2\left[\frac{L}{T}\right]$$

$$Dim[LHS] = Dim[RHS]$$

The equation is dimensionally correct (ignore constants)

Example (1-3):

The period (p) of a simple pendulum is the time for one complete swing. How does (p) depend on mass (m) of the bob, the length (L) of the string, and the acceleration due to gravity (g)?

Solution:

Let $p \propto m^a L^b g^c$

$$p = km^a L^b g^c$$

$$Dim[LHS] = Dim[RHS]$$

$$[T] = [M]^a [L]^b \left[\frac{L}{T^2}\right]^c$$

$$[T] = [M]^a [L]^{b+C} [T]^{-2c}$$

$$\therefore \; a = 0$$

$$\therefore \; -2c = 1 \Rightarrow c = -0.5$$

$$\therefore \; b + c = 0 \Rightarrow b = 0.5$$

$$p = kL^{0.5} g^{-0.5} = k\sqrt{\frac{L}{g}}$$

Example (1-4):

Newton's second law states that acceleration is proportional to the force acting on an object and is inversely proportional to th object mass. What are the dimensions of force?

Solution:

The acceleration $\rightarrow [a] = \frac{[L]}{T^2}$,

The mass $m \rightarrow [m] = [M]$

$$a \propto Fm^{-1} \Rightarrow a = \frac{kF}{m}$$

$$\therefore F = \frac{ma}{k} \Rightarrow [F] = [m][a] = [M][L][T]^{-2}$$

Example (1-5):

The wave length λ of a wave depends on the speed (v) of the wave and its frequency (f). Decide which of the following equations is correct: $\lambda = vf$ or $\lambda = v/f$.

Solution:

$$\lambda = v^a f^b$$

$$Dim[LHS] = Dim[RHS]$$

$$[L] = \left[\frac{L}{T}\right]^a \left[\frac{1}{T}\right]^b$$

$$[L] = [L]^a [T]^{-a-b}$$

$$\therefore\ a = 1$$

$$-a - b = 0 \Rightarrow\ \therefore b = -1$$

$$\lambda = v^1 f^{-1} = \frac{v}{f}$$

$\therefore$ The correct relation is $\lambda = {}^{v}/_{f}$

$$Dim[RHS] = [L]$$

From equation (1):

$$Dim[RHS] = \left[\frac{L}{T}\right]\left[\frac{1}{T}\right] = \left[\frac{L}{T^2}\right] \neq Dim[LHS] \Rightarrow Uncorrect$$

From equation (2):

$$Dim[RHS] = {\left[\frac{L}{T}\right]}\Big/{\left[\frac{1}{T}\right]} = [L] = Dim[LHS] \Rightarrow Correct$$

$\therefore$ The correct relation is $\lambda = {}^{v}/_{f}$

Example (1-6):

Suppose a sphere of Radius (R) is pulled at constant speed (v) through a fluid viscosity η. The force (F) that is required to pull the sphere through the fluid depends on v, R and η, $(F = (const))$. Find the dimensions of η.

Solution:

$$Dim[LHS] = Dim[RHS]$$

$$[v] = \left[\frac{L}{T}\right] \ ,$$

$$[F] = \frac{[M][L]}{T^2}, \qquad [\eta] = ???$$

$$F = (const)vR\eta$$

$$\therefore \ \eta = \frac{F}{(const)vR} \Rightarrow [\eta] = \frac{[F]}{[v][R]}$$

$$[\eta] = \frac{[M][L]}{[T^2]} \frac{1}{\left[\frac{L}{T}\right][L]}$$

$$\therefore \ [\eta] = \frac{[M]}{[L][T]}$$

Chapter TWO

Properties of Matter

Introduction to matter

Matter is anything, such as a solid, liquid or gas, that has weight (mass) and occupies space. For anything to occupy space, it must have volume. Thinking about it, everything on earth has weight and takes up space, and that means everything on earth is matter.

Properties of Matter

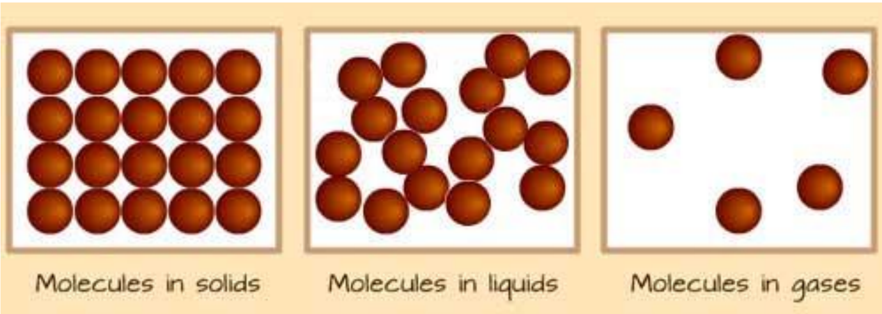
The basic properties of matter are it is made up of mass and it has a volume occupying space. The properties of matter can be divided into two categories:

- **Extensive properties** – It is that property which depends on the quantity of matter in a body. For example **mass**, **volume**, **calories** etc.
- **Intrinsic properties** – It is that property which is independent of the quantity of matter present in the body. It rather depends on the type of matter the substance is made up of. For example **density**, **hardness**, **melting point**, **boiling point**, color etc.

States of Matter

There are mainly three states of matter-Solid, Liquid and Gas. Solids, liquids and gases are all made up of very tiny stuff that the naked eye cannot see, called atoms, molecules and/or ions.

The illustration below is an idea of how atoms, molecules and ions in matter look like under a microscope.



In this lesson, we shall look at Solids, Liquids and Gases, which are known as the three states of matter.

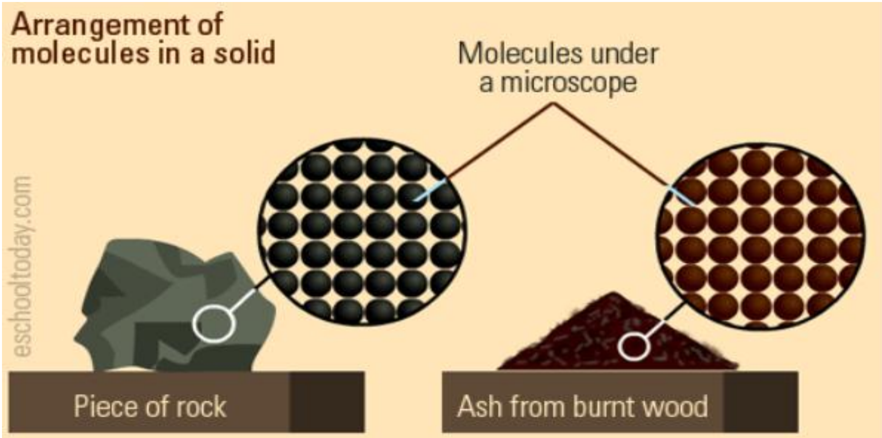
NOTE

Plasma is considered to be the fourth state of matter. It is hot ionized gas having almost an equal number of negatively charged electrons and positively charged ions. It is highly affected by both electrical and magnetic field. For example, noble gases are used as glowing tubes my ionizing it with the help of electricity.

Solids

Solids are simply hard substances, and they are hard because of how their molecules are packed together. Examples include rock, chalk, sugar, a piece of wood, plastic, steel or nail. They are all solids at room temperature. They can come in all sizes, shapes and forms. Think of ice cubes as an example. They are solids when frozen. They change into liquid at room temperature. What about ashes? Is that solid too? Yes, ashes are tiny solid particles that fall off when something burns— like wood ash in the fireplace.

In the diagram below, see how similar the arrangement of molecules are in the piece of rock and wood ash.



Characteristic of particles (molecules) in a solid.

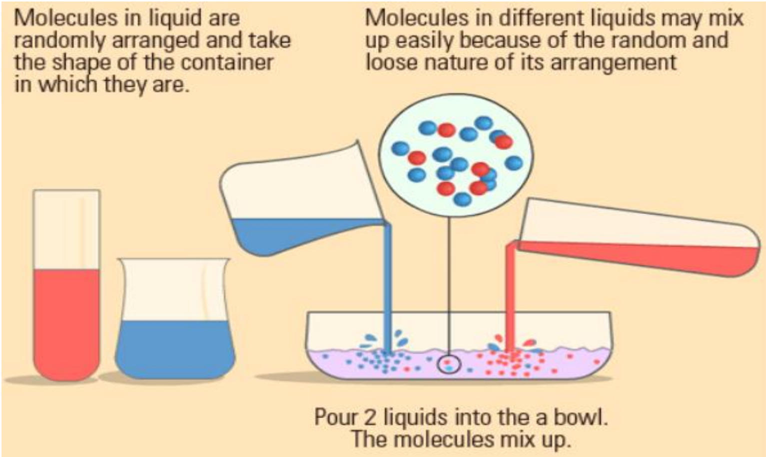
- The particles are close together (that's why they cannot be squashed or compressed.
- The particles cannot move freely from place to place (this is why they have a fixed shape). The particles are arranged in a regular, distinct pattern.
- The particles are held together by strong forces called bonds (This is why solids do ***not*** flow like water. Their particles are only able to vibrate in their position and cannot move from place to place.)
- The particles can vibrate in a fixed position

Different solids behave slightly differently because they have different properties such as 'STRENGTH'. This makes solids useful for different things. Look at a pencil eraser—it is solid, but can slightly change shape because the strength of its bonds is slightly weaker than that in a piece of diamond.

Liquid

The particles in liquids are not as closely bonded, arranged and fixed in place as in solids. The particles in liquid can flow freely and can mix with particles from other liquids. Liquids have their atoms close together, so they are not very easy to ***compress***.

Liquids, unlike gases are pulled by gravity to the bottom of the container holding it. They take the shape of the container holding it. You can pour a volume of liquid from one container to the other — it can change shape but the volume will be the same.



Characteristic of particles in liquids:

The particles are:

— Close together, but not as packed as in solids. (They cannot be compressed or squashed)

— Arranged in a random way.

— move around each other (They flow and take the shape of their container because their particles can move over each other)

— The bonds in a liquid are strong enough to keep the particles close together, but weak enough to let them move around each other.

Gases

Gas is everywhere, and it surrounds us. The air around us is a kind of gas. The atmosphere surrounding the earth is a gas too. Helium, Oxygen, Carbon dioxide and water vapour are all gases. The particles in gases are very different from that of solids and liquids. In gases, the particles are far apart from each other and arranged in a random way.

The particles also move quickly in all directions. Gases can fill up any container of any shape and size. Gases can be compressed or squashed because the molecules are far from each other. When gas is compressed, the gas molecules move from an area of high pressure to low pressure.

Vapour is also a gas. Gases that are liquid at room temperature, like water, can be classified as vapour. This means they are usually liquid, but can vaporize (turn into gas) under certain conditions.

Comparisons between the three State of Matter

Properties	Solid	Liquid	Gas
Shape	Solids have a definite shape	Liquids do not have a definite shape. It takes up the shape of the container in which it is	Gas does not have a definite shape. It takes up the shape of the entire space kept in

Properties	Solid	Liquid	Gas
		kept	
Volume	Solids have a definite Volume	Liquids have a definite volume	Gas do not have a definite volume
Effect of rise in temperature	With the rise in temperature there is small expansion. On reaching the melting point solids change into liquids and at sublimation directly changes from solid to gas	With the rise in temperature there is small expansion. On reaching the vaporization point liquid changes to gas and at freezing point liquid changes to solid state	With the rise in temperature there is large expansion. On reaching the deposition point gas changes to solids and at condensation point gas changes to liquid state
Kinetic energy	Low	More kinetic energy compared to solids	Highest
Malleability	Malleable	Non malleable	Non malleable
Ductility	Ductile	Non ductile	Non ductile
Compressible	Cannot be compressed into smaller volume with	Cannot be compressed into smaller volume with	Can be compressed into smaller volume

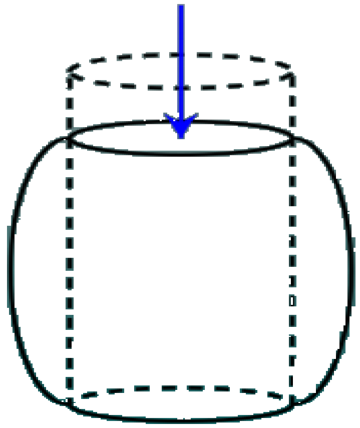
Properties	Solid	Liquid	Gas
	increase in pressure	increase in pressure	with increase in pressure
Inter-molecular space	The molecules are closely packed having very less intermolecular space	The intermolecular space is larger in liquids compared to that of solids	The intermolecular space is largest in gas compared to that of solids
Inter-molecular attraction	Strong intermolecular forces of attraction holding the molecules firmly in position	Weak intermolecular forces of attraction as a result of which the molecules freely slide over each other, hence making it viscous in nature	Weakest intermolecular forces of attraction as a result of which the molecules are free to move in any direction
Example	Gold, silver etc	Water, oil etc	Oxygen, hydrogen etc

ELASTICITY

Deformation

Deformation refers to any changes in the shape or size of an object due to:

- An applied force (the deformation energy in this case is transferred through work)
- A change in temperature (the deformation energy in this case is transferred through heat).



Compressive stress results in deformation which shortens the object but also expands it outwards.

Elastic Deformation versus Plastic Deformation

Elastic Deformation	Plastic Deformation
Elastic deformation is the deformation that disappears upon the removal of the external forces, causing the alteration and the stress associated with it	Plastic deformation is the permanent deformation or change in shape of a solid body without fracture under the action of a sustained force
Reversible	Irreversible
Non- permanent; the substance can resume the initial state back	Permanent; the substance stays unchanged after removing the stress
Causes the chemical bonds of the substance to undergo stretching and bending	Causes some of the chemical bonds of the substance to undergo breakage
Atoms do not slip pass on each other	Atoms slip pass on each other

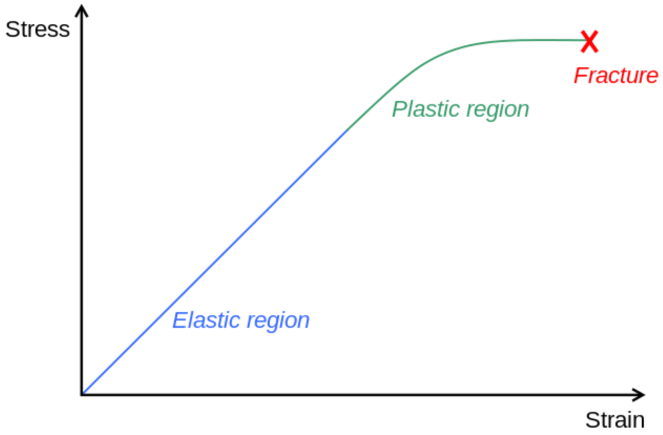


Diagram of a stress–strain curve, showing the relationship between stress (force applied) and strain (deformation) of a ductile metal.

Elastic Properties of Matter

An **elastic body** is one that returns to its original shape after a deformation.

- Golf Ball
- Rubber Band
- Soccer Ball

An **inelastic body** is one that does **not** return to its original shape after a deformation.

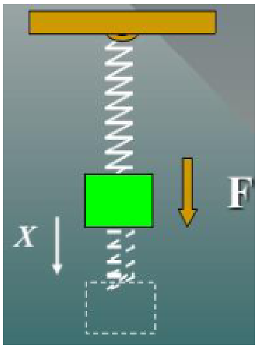
- Dough or Bread
- Clay
- Inelastic Ball

Elastic or Inelastic?

An elastic collision loses no energy. The deformation on collision is fully restored.

In an inelastic collision, energy is lost and the deformation may be permanent.

An Elastic Spring

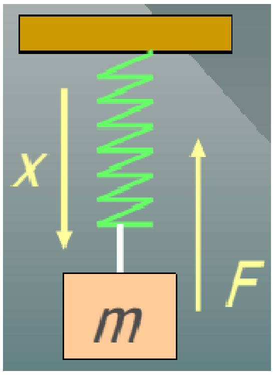


A spring is an example of an elastic body that can be deformed by stretching.

A **restoring force**, ***F***, acts in the direction opposite the displacement of the oscillating body.

$$F = -kx$$

Hooke's Law



When a spring is stretched, there is a restoring force that is proportional to the displacement.

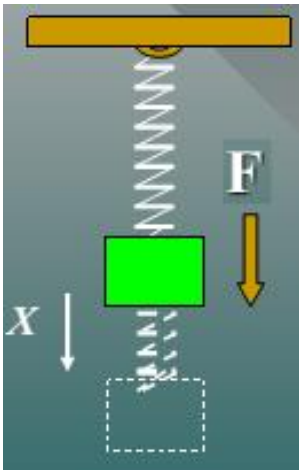
$$F = -kx$$

The spring constant k is a property of the spring given by:

$$k = \frac{\Delta F}{\Delta x}$$

The spring constant k is a measure of the elasticity of the spring.

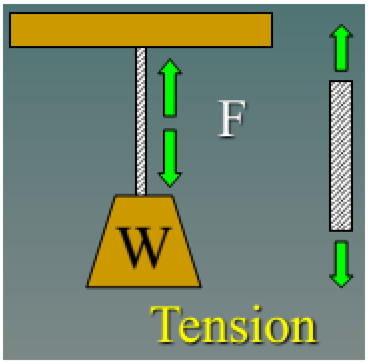
Stress and Strain



Stress refers to the cause of a deformation, and strain refers to the effect of the deformation.

The downward force F causes the displacement x. Thus, the stress is the force; the strain is the elongation.

Types of Stress

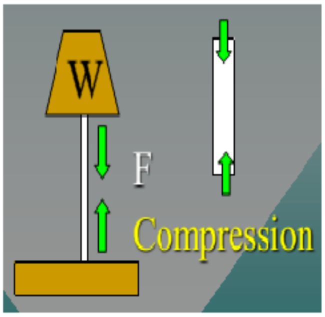


A tensile stress occurs when equal and opposite forces is directed away from each other.

A compressive stress occurs when equal and opposite forces is directed toward each other.

Summary of Definitions

Stress is the ratio of an applied force F to the area A over which it acts:



$$Stress = \frac{F}{A}$$

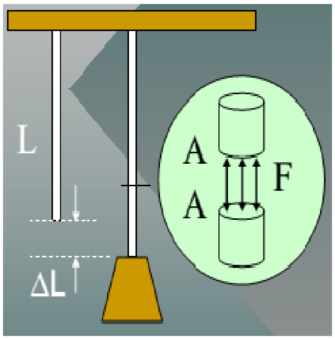
$$Unite: Pa = \frac{N}{m^2} \quad or \quad \frac{1b}{in^2}$$

Strain is the relative change in the dimensions or shape of a body as the result of an applied stress:

Examples: Change in length per unit length; change in volume per unit volume.

Longitudinal Stress and Strain

For wires, rods, and bars, there is a longitudinal stress F/A that produces a change in length per unit length. In such cases:



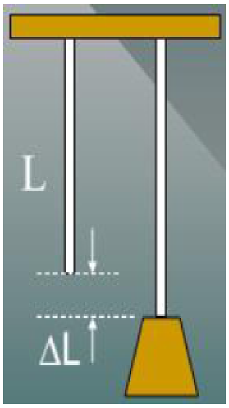
$$Stress = \frac{F}{A}$$

$$Strain = \frac{\Delta L}{L}$$

Example 1.

A steel wire 10 m long and 2 mm in diameter is attached to the ceiling and a 200-N weight is attached to the end. What is the applied stress?

First find area of wire:



$$A = \frac{\pi D^2}{4} = \frac{\pi(0.002m)^2}{4}$$

$$= 3.14x10^{-6}m^2$$

$$Stress = \frac{F}{A} = \frac{200\ N}{3.14 \times 10^{-6}m^2}$$

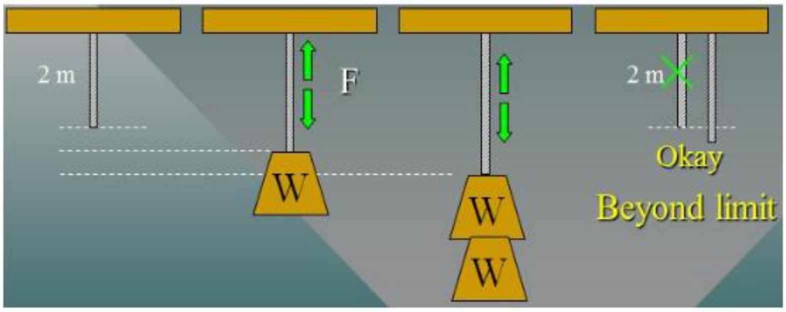
$$= 6.37 \times 10^{7} Pa$$

Example 1 (Cont.)

A 10 m steel wire stretches 3.08 mm due to the 200 N load. What is the longitudinal strain? Given: L = 10 m; ΔL = 3.08 mm

The Elastic Limit

The elastic limit is the maximum stress a body can experience without becoming permanently deformed.

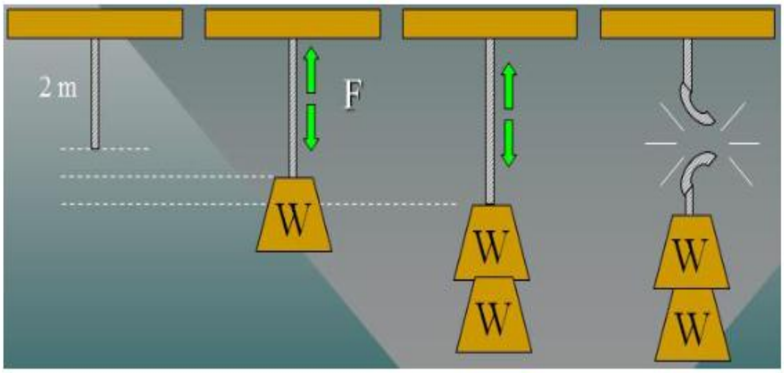


If the stress exceeds the elastic limit, the final length will be longer than the original 2 m.

Elastic Limit Definition

Elastic limit is the maximum stress within which the body regains its original condition when the deforming force is removed.

The ultimate strength is the greatest stress a body can experience without breaking or rupturing.

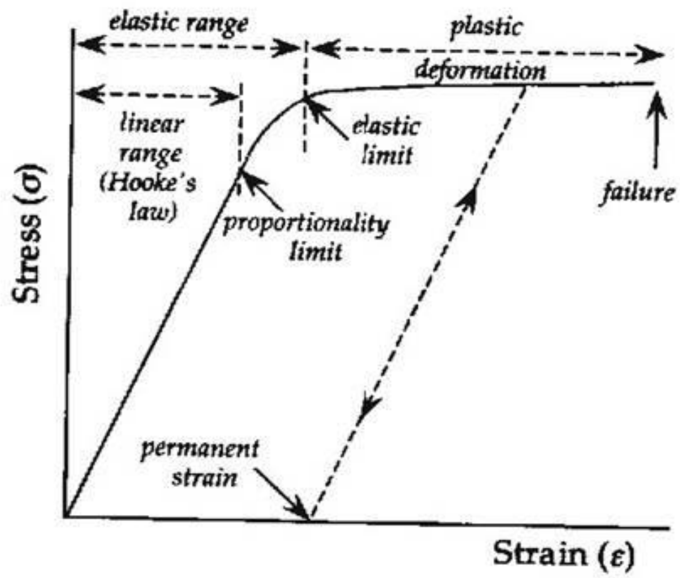


If the stress exceeds the ultimate strength, the string breaks!

The stress strain curve

In the case of crystalline material or metals the stress-strain curve will be linear for small deformations. The relationship between stress and strain is given by Hooke's law.

The stress beyond the elastic limit the relation is not linear. Beyond the elastic limit the materials undergo plastic deformation.



Example 2.

The elastic limit for steel is 2.48×10^8 Pa. What is the maximum weight that can be supported without exceeding the elastic limit?

$$\text{Recall: } A = 3.14 \times 10^{-6}\, m^2$$

$$Stress = \frac{F}{A} = 2.48 \times 10^8 \; Pa$$

$$F = (2.48 \times 10^8\, Pa)\, A$$

$$F = (2.48 \times 10^8\, Pa)(3.14 \times 10^{-6}\, m^2) = 779\, N$$

Example 2(Cont.)

The ultimate strength for steel is 4089 x 108 Pa. What is the maxi- mum weight that can be supported without breaking the wire?

$$\text{Recall: } A = 3.14 \times 10^{-6}\, m^2$$

$$Stress = \frac{F}{A} = 4.89 \times 10^8 \; Pa$$

$$F = (4.89 \times 10^8\, Pa)\, A$$

$$F = (4.89 \times 10^8\, Pa)(3.14 \times 10^{-6}\, m^2) = 1536\, N$$

The Modulus of Elasticity

Provided that the elastic limit is not exceeded, an elastic deformation (strain) is directly proportional to the magnitude of the applied force per unit area (stress).

$$Modulus\ of\ Elasticity = \frac{stress}{strain}$$

Example 3.

In our previous example, the stress applied to the steel wire was 6.37×10^7 Pa and the strain was 3.08×10^{-4}. Find the modulus of elasticity for steel.

$$Modulus = \frac{stress}{strain} = \frac{6.37 \times 10^7}{3.08 \times 10^{-4}} = 207 \times 10^9 Pa$$

This longitudinal modulus of elasticity is called Young's Modulus and is denoted by the symbol Y

Young's Modulus

For materials whose length is much greater than the width or thickness, we are concerned with the longitudinal modulus of elasticity, or Young's Modulus (Y).

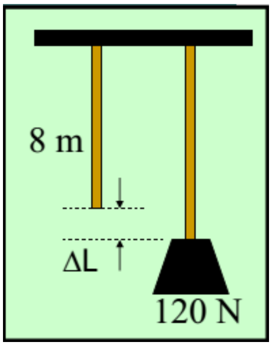
$$Young's\ Modulus = \frac{longitudinal\ stress}{longitudinal\ strain}$$

$$Y = \frac{F/A}{\Delta L/L} = \frac{FL}{A\Delta L}$$

$$Unite: Pa \quad or \quad \frac{1b}{in^2}$$

Example 4:

Young's modulus for brass is 8.96 x 10^{11} Pa. A 120 N weight is attached to an 8 m length of brass wire; find the increase in length. The diameter is 1.5 mm.



First find area of wire:

$$A = \frac{\pi D^2}{4} = \frac{\pi(0.0015\, m)^2}{4}$$

$$= 1.77 \times 10^{-6}\, m^2$$

Y = 8.96 x 10^{11} Pa; F = 120 N; L = 8 m; A = 1.77 x 10^{-6} m^2; F = 120 N; ΔL = ???

$$Y = \frac{FL}{A\Delta L} \Rightarrow \Delta L = \frac{FL}{AY}$$

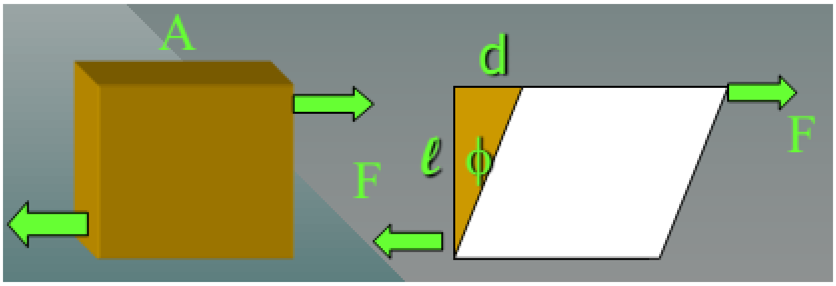
$$\Delta L = \frac{FL}{AY} = \frac{(120\, N)(8.00\, m)}{(1.77 \times 10^{-6} m^2)(8.96 \times 10^{11} Pa)}$$

Increase in length:

$$\Delta L = 0.605 \text{ mm}$$

Shear Modulus

A shearing stress alters only the shape of the body, leaving the volume unchanged. For example, consider equal and opposite shearing forces F acting on the cube below:



The shearing force F produces a shearing angle ϕ. The angle ϕ is the strain and the stress is given by F/A as before.

Calculating Shear Modulus

Stress is force per unit area:

$$Stress = \frac{F}{A}$$

The strain is the angle expressed in radians:

$$Strain = \phi = \frac{d}{l}$$

The shear modulus S is defined as the ratio of the shearing stress F/A to the shearing strain ϕ:

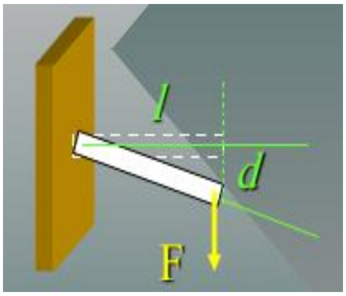
$$S = \frac{F/A}{\phi}$$

The shear modulus Units are in Pascals.

Example 5.

A steel stud (S = 8.27 x 10^{10} Pa) 1 cm in diameter projects 4 cm from the wall. A 36,000 N shearing force is applied to the end. What is the defection d of the stud?

First find area of wire:



$$A = \frac{\pi D^2}{4} = \frac{\pi (0.01\, m)^2}{4} = 7.85 \times 10^{-5}\, m^2$$

F = 36000 N; l = 0.04 m; A = 7.85 x 10^{-5} m^2; d = ???

$$S = \frac{F/A}{\phi} = \frac{F/A}{d/l} = \frac{Fl}{Ad} \Rightarrow d = \frac{Fl}{AS}$$

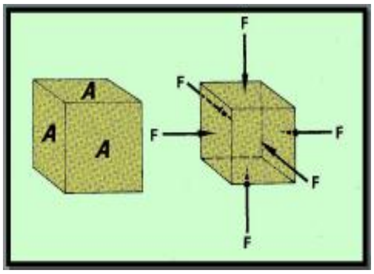
$$d = \frac{Fl}{AY} = \frac{(36000\,N)(0.04\,m)}{(7.85 \times 10^{-5} m^2)(8.27 \times 10^{10} Pa)}$$

$$= 0.222\,mm$$

Volume Elasticity

Not all deformations are linear. Sometimes an applied stress F/A results in a decrease of volume. In such cases, there is

$$B = \frac{Volume\ stress}{Volume\ strain} = \frac{-F/A}{\Delta V/V}$$



a bulk modulus B of elasticity.

The bulk modulus is negative because of decrease in V.

The Bulk Modulus

$$B = \frac{-F/_{A}}{\Delta V/_{V}}$$

Since F/A is generally pressure P, we may write:

$$B = \frac{-P}{\Delta V/_{V}} = \frac{PV}{\Delta V}$$

Units remain in Pascals (Pa); since the strain is unitless.

Example 7.

A hydrostatic press contains 5 liters of oil. Find the decrease in volume of the oil if it is subjected to a pressure of 3000 kPa. (Assume that B = 1700 MPa.)

$$B = \frac{-P}{\Delta V/_{V}} = \frac{PV}{\Delta V}$$

$$B = \frac{-P}{\Delta V/_{V}} = \frac{-PV}{\Delta V}$$

$$\Delta V = \frac{-PV}{\mathrm{B}} = \frac{-(3 \times 10^{6} Pa)(5\ L)}{(1.70 \times 10^{9} Pa)}$$

Decrease in V in milliliters (mL);

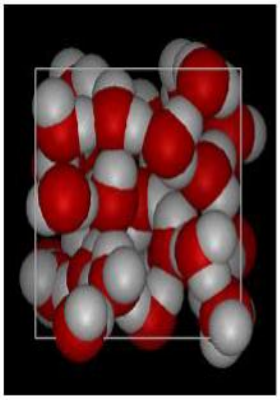
$$\Delta V = -8.82\ mL$$

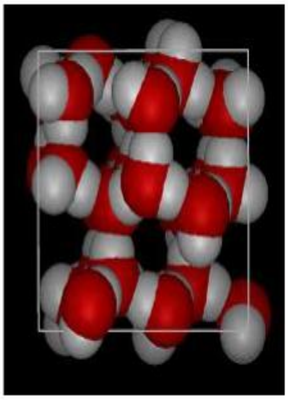
Chapter THREE

Fluid Statics

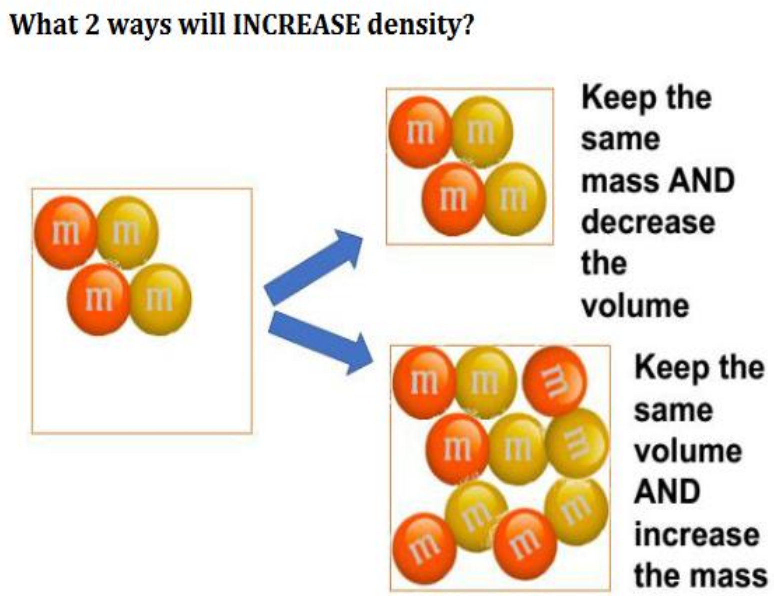
Density and pressure

Density is defined as mass per unit volume. It is a measure of how tightly packed and how heavy the molecules are in an object. Density is the amount of matter within a certain volume.





To find the density Divide $Density = \frac{Mass\ g}{Volume\ c^3}$



Pressure

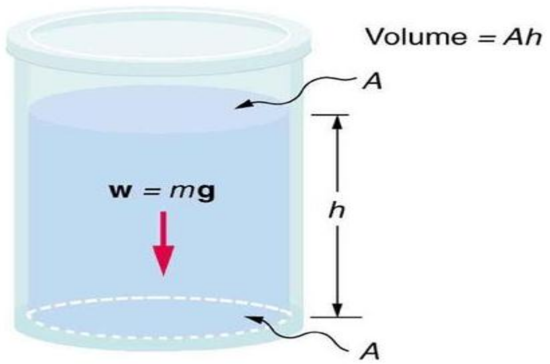
Pressure is an important physical quantity—it plays an essential role in topics ranging from thermodynamics to solid and fluid mechanics. As a scalar physical quantity (having magnitude but no direction), pressure is defined as the force per unit area applied perpendicular to the surface to which it is applied. Pressure can be expressed in a number of units depending on the context of use.

Units, Equations and Representations

In SI units, the unit of pressure is the Pascal (Pa), which is equal to a Newton / meter^2 (N/m^2). Other important units of pressure include the pound per square inch (psi) and the standard atmosphere (atm). The elementary mathematical expression for pressure is given by:

$$\text{Pressure} = \frac{Force}{Area} = \frac{F}{A}$$

where p is pressure, F is the force acting perpendicular to the surface to which this force is applied, and A is the area of the surface. Any object that possesses weight, whether at rest or not, exerts a pressure upon the surface with which it is in contact. The magnitude of the pressure exerted by an object on a given surface is equal to its weight acting in the direction perpendicular to that surface, divided by the total surface area of contact between the object and the surface



Pressure is the weight of the fluid *mg* divided by the area *A* supporting it (the area of the bottom of the container):

$$P = \frac{mg}{A}.$$

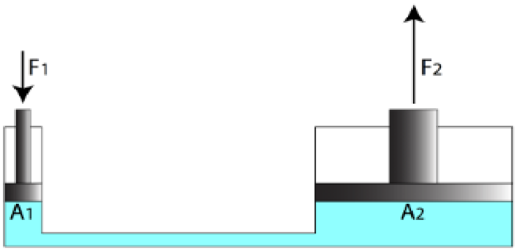
Pressure due to the weight of a liquid is given by

$$P = h\rho g,$$

where *P* is the pressure, *h* is the height of the liquid, *ρ* is the density of the liquid, and *g* is the acceleration due to the gravity.

Pascal's Law

Pascal's principle, also called **Pascal's law**, in fluid (gas or liquid) mechanics, statement that, in a fluid at rest in a closed container, a pressure change in one part is transmitted without loss to every portion of the fluid and to the walls of the container. The principle was first enunciated by the French scientist Blaise Pascal.



Since the changes in pressures at the left end and the right end are the same:

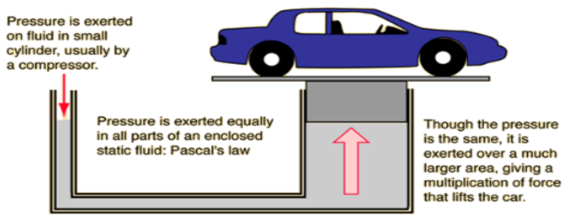
$$\Delta P_1 = \Delta P_2$$
$$\frac{F_1}{A_1} = \frac{F_2}{A_2}$$

APPLICATIONS OF PASCAL'S LAW

The application of Pascal's Law can be seen throughout industries. Some of the applications are as follows:

Hydraulic Lift
Hydraulic Jack

This has applications:



The force in the small cylinder must be exerted over a much larger distance. A small force exerted over a large distance is traded for a large force over a small distance.

SURFACE TENSION

At the interface between a liquid and a gas or two immiscible liquids, forces develop forming an analogous “skin” or “membrane” stretched over the fluid mass which can support weight.

This “skin” is due to an imbalance of cohesive forces. The interior of the fluid is in balance as molecules of the like fluid are attracting each other while on the interface there is a net inward pulling force.

Surface tension is the intensity of the molecular attraction per unit length along any line in the surface.

Surface tension is a property of the liquid type, the temperature, and the other fluid at the interface.

This membrane can be “broken” with a surfactant which reduces the surface tension.

Surface tension allows insects (e.g. water striders), usually denser than water, to float and slide on a water surface. At liquid–air interfaces, surface tension results from the greater attraction of liquid molecules to each other than to the molecules in the air.

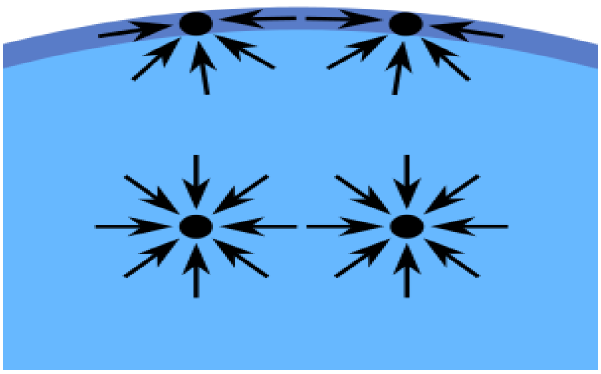
Cause of Surface tension

- ☒ Due to the cohesive forces a molecule is pulled equally in every direction by neighboring liquid molecules, resulting in a net force of zero.

- ☒ The molecules at the surface do not have the same molecules on all sides of them and therefore are pulled inward.

- ☒ This creates some internal pressure and forces liquid surfaces to contract to the minimum area.

There is also a tension parallel to the surface at the liquid-air interface which will resist an external force, due to the cohesive nature of water molecules.



Physical units

Surface tension, represented by the symbol γ (alternatively σ or T), is measured in force per unit length. Its SI unit is newton per meter but the cgs unit of dyne per centimeter is also used. For example

$$\gamma = 1\,\frac{\mathrm{dyn}}{\mathrm{cm}} = 1\,\frac{\mathrm{erg}}{\mathrm{cm}^2} = 1\,\frac{10^{-7}\,\mathrm{m}\cdot\mathrm{N}}{10^{-4}\,\mathrm{m}^2} = 0.001\,\frac{\mathrm{N}}{\mathrm{m}} = 0.001\,\frac{\mathrm{J}}{\mathrm{m}^2}.$$

Effects of surface tension

Several effects of surface tension can be seen with ordinary water:

A. Beading of rainwater on a waxy surface, such as a leaf. Water adheres weakly to wax and strongly to itself, so water clusters into drops. Surface tension gives them their near-spherical shape, because a sphere has the smallest possible surface area to volume ratio.

B. Formation of drops occurs when a mass of liquid is stretched. The animation (below) shows water adhering to the faucet gaining mass until it is stretched to a point where the surface tension can no longer keep the drop linked to the faucet. It then separates and surface tension forms the drop into a sphere. If a stream of water were running from the faucet, the stream would break up into drops during its fall. Gravity stretches the stream, then surface tension pinches it into spheres.

C. Flotation of objects denser than water occurs when the object is nonwearable and its weight is small enough to be borne by the forces arising from surface tension. For example, water striders use surface tension to walk on the surface of a pond in the following way. The no wettability ofthe water strider's leg means there is no attraction between molecules of the leg and molecules of the water, so when the leg pushes down on the water, the surface tension of the water only tries to recover its flatness from its deformation due to the leg. This behavior of the water pushes the water strider upward so it can stand on the surface of the water as long as its mass is small enough that the water can support it. The surface of the water behaves like an elastic film: the insect's feet cause indentations in the water's surface, increasing its surface area and tendency of minimization of surface curvature (so area) of the water pushes the insect's feet upward.

D. Separation of oil and water (in this case, water and liquid wax) is caused by a tension in the surface between dissimilar liquids. This type of surface tension is called "interface tension", but its chemistry is the same.

E. Tears of wine is the formation of drops and rivulets on the side of a glass containing an alcoholic beverage. Its cause is a complex interaction between the differing surface tensions of water and ethanol; it is induced by a combination of surface tension modification of water by ethanol together with ethanol evaporating faster than water.

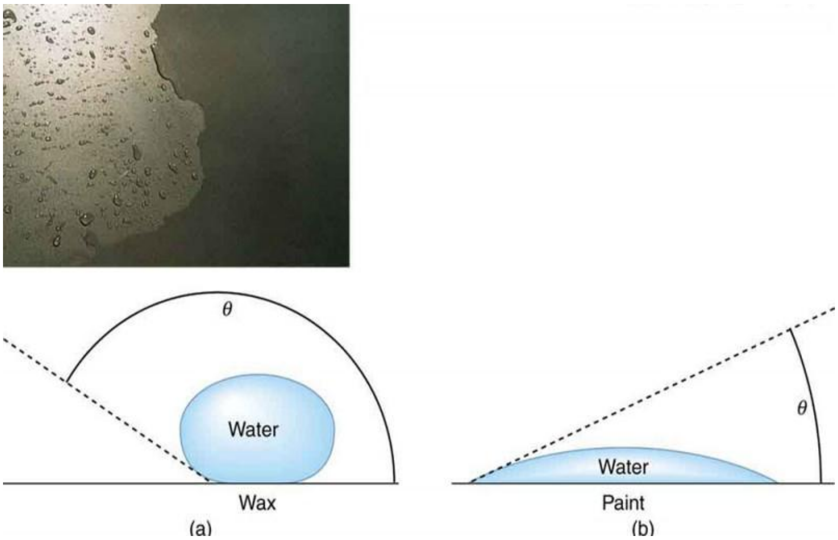
COHESIVE FORCES
Attractive forces between molecules of the same type are called cohesive forces.
ADHESIVE FORCES
Attractive forces between molecules of different types are called adhesive forces.

Adhesion and Capillary Action

Why is it that water beads up on a waxed car but does not on bare paint? The answer is that the adhesive forces between water and wax are much smaller than those between water and paint. Competition between the forces of adhesion and cohesion are important in the macroscopic behavior of liquids. An important factor in studying the roles of these two forces is the angle θ between the tangent to the liquid surface and the surface. (See Figure 7.) The *contact angle* θ is directly related to the relative strength of the cohesive and adhesive forces. The larger the strength of the cohesive force relative to the adhesive force, the larger θ is, and the more the liquid tends to form a droplet. The smaller θ is, the smaller the relative strength, so that the adhesive force is able to flatten the drop.

CONTACT ANGLE

The angle θ between the tangent to the liquid surface and the surface is called the contact angle.

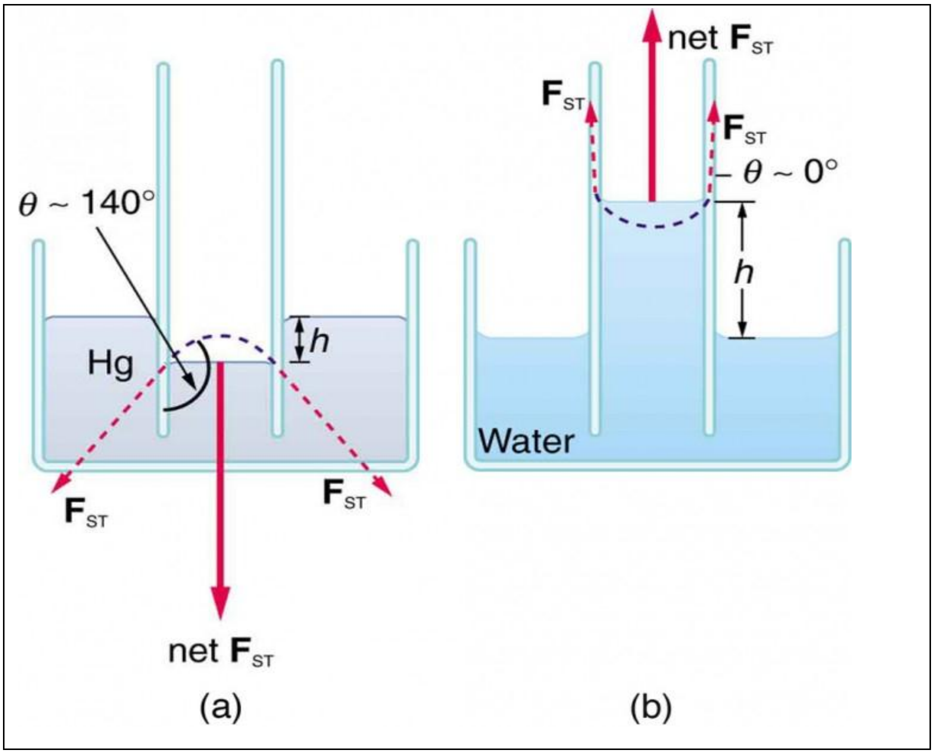


One important phenomenon related to the relative strength of cohesive and adhesive forces is *capillary action*—the tendency of a fluid to be raised or suppressed in a narrow tube, or *capillary tube*. This action causes blood to be drawn into a small-diameter tube when the tube touches a drop.

CAPILLARY ACTION

The tendency of a fluid to be raised or suppressed in a narrow tube, or capillary tube.

If a capillary tube is placed vertically into a liquid, as shown in Figure 8, capillary action will raise or suppress the liquid inside the tube depending on the combination of substances. The actual effect depends on the relative strength of the cohesive and adhesive forces and, thus, the contact angle θ given in the table. If θ is less than 90º, then the fluid will be raised; if θ is greater than 90º, it will be suppressed. Mercury, for example, has a very large surface tension and a large contact angle with glass. When placed in a tube, the surface of a column of mercury curves downward, somewhat like a drop. The curved surface of a fluid in a tube is called a meniscus. The tendency of surface tension is always toreduce the surface area. Surface tension thus flattens the curved liquid surface in a capillary tube. This results in a downward force in mercury and an upward force in water, as seen in Figure 8.



A simple relationship determines how far the water is pulled up the tube (see Figure 5). The force upwards due to the surface tension is given by the following relationship: $F_{up} = \gamma\,(2\pi a)\cos\theta$

in this relationship, γ is the liquid-air surface tension at 20° C, 2πa is the circumference of the tube, and θ is the contact angle of water on glass, a measure of the attraction of the liquid to the walls. The opposing force down is given by the force of gravity on the water that is pulled above the reservoir level.

$$F_{down} = \rho g(h\pi a^2)$$

Here, ρ = 1000 kg/m^3 is the density of water, g = 9.8 m/s^2 is the acceleration due to gravity, and (hπa^2) is the volume of the water in the column above the reservoir.

Measuring Surface Tension

One method to measure the surface tension of a liquid is to measure the height the liquid rises in a capillary tube. By setting the two forces above equal, we find the surface tension to **be:**

$$\gamma = \frac{\rho g a}{2} \frac{h}{\cos \theta}$$

For pure water and clean glass, the contact angle is nearly zero. In a typical high school lab, this may not be the case, but θ is small and we assume that cos θ is close to 1.

$$\gamma = \frac{\rho g a}{2} \frac{h}{\cos \theta}$$

where

- h is the height the liquid is lifted,
- γ is the liquid–air surface tension,
- ρ is the density of the liquid,
- a is the radius of the capillary,

- g is the acceleration due to gravity,
- θ is the angle of contact

Example:

Can capillary action be solely responsible for sap rising in trees? To answer this question, calculate the radius of a capillary tube that would raise sap 100 m to the top of a giant redwood, assuming that sap's density is 1050 kg/m³, its contact angle is zero, and its surface tension is the same as that of water at 20.0º C.

Strategy

The height to which a liquid will rise as a result of capillary action is given by $h = \frac{2\gamma cos\theta}{\rho g a}$ and every quantity is known except for a.

Solution

Solving for a and substituting known values produces

$$a = \frac{2\gamma cos\theta}{\rho g h} = \frac{2(0.0728\, N/m)\, cos(0)}{(1050\, Kg/m^3)(9.8\, m/s^2)(100\, m)}$$
$$= 1.41x10^{-7} m$$

Fluid Dynamics

Fluid dynamics refers to a sub-discipline of fluid mechanics that revolves around fluid flow in motion. Furthermore, fluid dynamics comprises of some branches like aerodynamics and hydrodynamics. Fluid dynamics involves the calculation of various fluid properties, such as flow velocity, pressure, density, and temperature, as functions of space and time.

What is Fluid?

Fluid is the name given to a substance which begins to flow when external force is applied to it.

Fluids possess characteristic physical properties that govern how they behave when forces are applied to them

Streamline Flow

A streamline is a curve the tangent to which at any point gives the direction of the fluid velocity at that point. It is analogous to a line of force in an electric or a magnetic field. In steady flow the pattern of the streamline is stationary with time and therefore, a streamline gives the actual path of a fluid particle. A steady flow is therefore also called a streamlined flow or laminar flow. No two streamlines can ever cross one another, for if they did, a fluid particle arriving at that point could go one way or the other and the flow would not be steady

Continuity equation represents that the product of cross-sectional area of the pipe and the fluid speed at any point along the pipe is always constant. This product is equal to the volume flow per second or simply the flow rate. The continuity equation is given as:

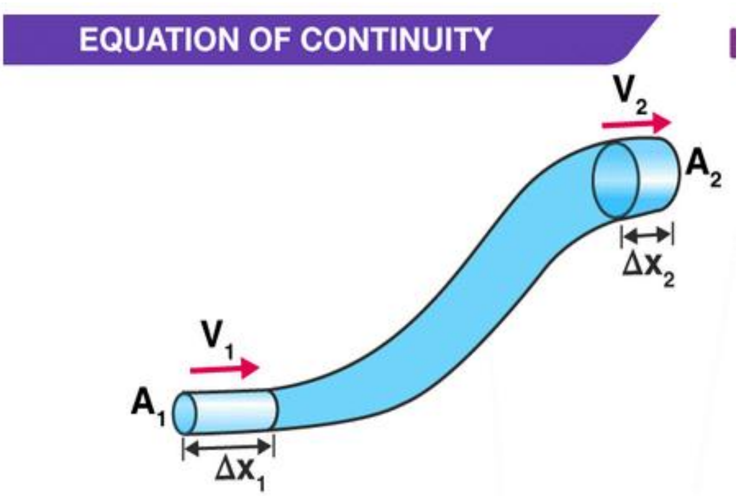
$$R = A\,v = \text{constant}$$

،Where

- R is the volume flow rate
- A is the flow area
- v is the flow velocity

Derivation

Consider the following diagram:



Now, consider the fluid flows for a short interval of time in the tube. So, assume that short interval of time as Δt. In this time, the fluid will cover a distance of Δx_1 with a velocity v_1 at the lower end of the pipe.

At this time, the distance covered by the fluid will be:

$$\Delta x_1 = v1\Delta t$$

Now, at the lower end of the pipe, the volume of the fluid that will flow into the pipe will be:

$$V = A_1 \, \Delta x1 = A1 \, v1 \, \Delta t$$

It is known that *mass (m) = Density (ρ) × Volume (V).* So, the mass of the fluid in $\Delta x1$ region will be:

$$\Delta m_1 = Density \times Volume$$

($\Delta m_1 = \rho_1 A_1 v_1 \Delta t$ ———(Equation 1 <=

Now, the mass flux has to be calculated at the lower end. Mass flux is simply defined as the mass of the fluid per unit time passing through any cross-sectional area. For the lower end with cross-sectional area *A1,* mass flux will be:

$$\Delta t = \rho_1 A_1 v_1 \text{ ——–(Equation 2(}$$

Similarly, the mass flux at the upper end will be:

$$\Delta m_{2/\Delta t} = \rho_2 A_2 v_2 \text{ ———(Equation 3(}$$

Here, v_2 is the velocity of the fluid through the upper end of the pipe i.e. through Δx_2 , in Δt time and A_2, is the cross-sectional area of the upper end.

In this, the density of the fluid between the lower end of the pipe and the upper end of the pipe remains the same with time as the flow is steady. So, the mass flux at the lower end of the pipe is equal to the mass flux at the upper end of the pipe i.e. *Equation 2 = Equation 3.*

Thus,

$$\rho_1 A_1 v_1 = \rho_2 A_2 v_2 \text{ ———(Equation 4(}$$

This can be written in a more general form as

$$\rho\, A\, v = constant$$

The equation proves the law of conservation of mass in fluid dynamics. Also, if the fluid is incompressible, the density will remain constant for steady flow. So, $\rho_1 = \rho_2$.

Thus, *Equation 4* can be now written as

$$A_1\, v_1 = A_2\, v_2$$

This equation can be written in general form as

$$A\, v = constant$$

Now, if ***R*** is the volume flow rate, the above equation can be expressed as

$$R = A\,v = \text{constant}$$

This was the derivation of continuity equation

Liquid possesses three types of energy.

They are as follows

Kinetic Energy: Energy possessed by a fluid due to its motion

Potential Energy: Energy possessed by mass m at a height h

Pressure Energy: Energy possessed by a liquid by virtue of its pressure that depends upon volume

EXAMPLE

A 250 mm diameter pipe carries water flowing at 87 litres per second. The main pipe divides into two pipes, each 100 mm diameter. Calculate the velocity in the smaller pipes.

Assuming that the flow in each of the smaller pipes is equal and is half the main flow:

$$Q = vA$$

$$\frac{0.087}{2} = v \times \frac{\pi \times 0.1^2}{4}$$

$$v = 5.53 \text{ m/s}$$

Bernoulli's Principle and Equation

Bernoulli's Principle states that the total energy of the water always remains constant, therefore, when the water flow in a system increases, the pressure must decrease. When water starts to flow in a hydraulic system the pressure drops. When the flow stops, the pressure rises again.

Consider the flow at two regions 1 (i.e., BC) and 2 (i.e., DE). Consider the fluid initially lying between B and D. In an infinitesimal time interval Δt, this fluid would have moved. Suppose v1 is the speed at B and v2 at D, then fluid initially at B has moved a distance $v_1\Delta t$ to C ($v_1\Delta t$ is small enough to assume constant cross-section along

BC). In the same interval Δt the fluid initially at D moves to E, a distance equal to $v_2\Delta t$. Pressures P_1 and P_2 act as shown on the plane faces of areas A_1 and A_2 binding the two regions. The work done on the fluid at left end (BC) is $W_1 = P_1A_1(v_1\Delta t) = P_1\Delta V$. Since the same volume ΔV

passes through both the regions (from the equation of continuity) the work done by the fluid at the other end (DE) is $W_2 = P_2A_2(v_2\Delta t) = P_2\Delta V$ or,the work done on the fluid is $-P_2\Delta V$. So the total work done on the fluid is

$$W_1 - W_2 = (P_1 - P_2)\,\Delta V$$

Part of this work goes into changing the kinetic energy of the fluid, and part goes into changing the gravitational potential energy. If the density of the fluid is ρ and $\Delta m = \rho A_1 v_1 \Delta t = \rho\Delta V$ is the mass passing through the pipe in time Δt, then change in gravitational potential energy is

$$\Delta U = \rho g \Delta V \,(h2 - h1)$$

The change in its kinetic energy is

$$\Delta K = \frac{1}{2} \rho \, \Delta V \,(v_2^2 - v_1^2)$$

We can employ the work – energy theorem

(Chap 6) to this volume of the fluid andthis yields

$$(P_1 - P_2)\,\Delta V = \frac{1}{2} \rho \, \Delta V (v_2^2 - v_1^2) + \rho g \Delta V \,(h_2 - h_1)$$

$$(P_1 - P_2) = \frac{1}{2} \rho \,(v_2^2 - v_1^2) + \rho g \,(h_2 - h_1)$$

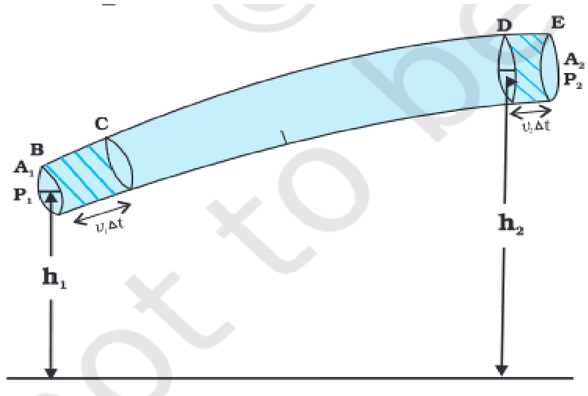
We now divide each term by ΔV to obtain

We can rearrange the above terms to obtain

$$P_1 + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g h_2$$

This equation is known as Bernoulli's equation and it is very useful in studying the flow of liquid.

$$P + \frac{1}{2}\rho v^2 + \rho g h = \text{constant}$$



VISCOSITY

Informally, viscosity is the quantity that describes a fluid's resistance toflow. Fluids resist the relative motion of immersed objects through themas well as to the motion of layers with differing velocities within them

The dimensions of dynamic viscosity are force × time ÷ area. The unit ofviscosity, accordingly, is newton-second per square metre, which isusually expressed as pascal-second in SI units. The dimensional formula

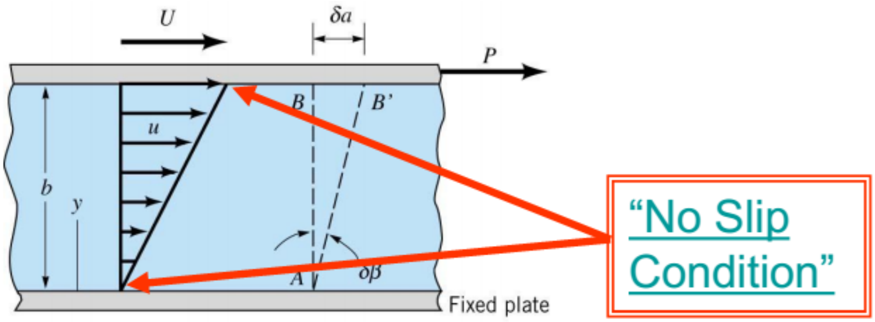
of viscosity is [ML-1T-1]

The viscosity of liquids decreases rapidly withan increase in temperature, and the viscosity of gases increases with anincrease in temperature.

The viscosity is measure of the “fluidity” of the fluid which is not captured simply by density or specific weight. A fluid cannot resist a shear and under shear begins to flow. The shearing stress and shearing strain can be related with a relationship of the following form for common fluids such as water, air, oil, and gasoline:

$$\tau = \mu \frac{du}{dy}$$

μ is the absolute viscosity or dynamics viscosity of the fluid, u is the velocity of the fluid and y is the vertical coordinate as shown in the schematic below:



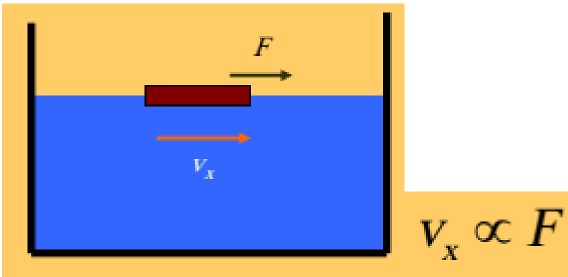
We feel resistance if we walk into a lake. This means the existence of a force of friction in water. It is notable that this force differs from a liquid to another; there are liquids of high friction force and others of low friction force. Forces of friction of these liquids are known as viscosity of liquids or fluids. If the force is high the liquid or fluid is said to be highly viscous and vice versa.

Fluid Resistance

– An object moving through or on a fluid meets resistance.

– Force causes the fluid to move.

– The velocity is proportional to the force.



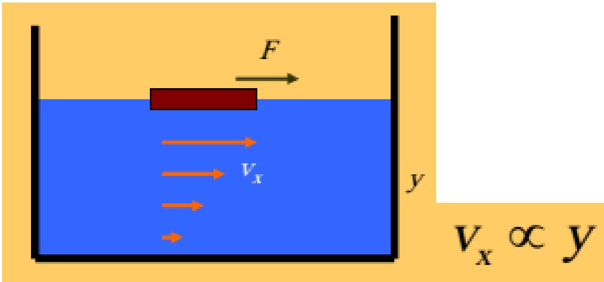
Velocity Gradient

– The resistance tends to keep the fluid in place.

  • Law of inertia

– The fluid moves most near the object and least farther away.

– This is a velocity *gradient*.



Coefficient of viscosity and Newton's formula:

Newton coined a term to denote friction force among layers of the liquid, besides a term referring to coefficient of viscosity. He confirmed this through scientific experiments. He stated that the friction force (F) relied on the surface area of the liquid (A) besides velocity of the flowing of the liquid (V) and it is indirectly proportionate to distance x its measure at the static layer; the one next to the wall of the tube through which the liquid runs. This is mathematically expressed as follows:

$$f \propto -A.V.\ \frac{1}{X}$$

$$f = \eta.V.\ \frac{1}{X}$$

The previous negative sign reveals that direction of the friction force is opposite to that of the velocity of the liquid's flowing. The constant of this ratio (η) is known as coefficient of viscosity. It depends on the nature of the liquid. In case of the previous equation, it is possible to place V/X as dV/dX in which case the quantity dV/dX is known as velocity gradient.Newton's formula is expressed in this following way:

$$f = -\eta.A.\ \frac{dV}{dX}$$

Or $$\eta = -A\ \frac{F}{dV \mid dX}$$

Accordingly, the coefficient of viscosity may be defined as the friction force needed for keeping velocity gradient equal to a unit in a surface area of a unit, too.

If this force is equal to a unit, the coefficient of viscosity is also equal to a unit. In this case, it is called poise, named after scientist Poiseuille. Viscosity in liquids is similar to friction forces among solid bodies as both.

Motion in a viscous medium:

Scientist Stocks investigated motions of metal balls inside viscous media and coined a term expressing the friction force produced by viscosity of the medium. Supposing that the diameter of the ball is (r) and it moves with a velocity (V) in a medium whose viscosity coefficient is (η), this force is expressed by the following relation:

$$F = 6\pi V r \eta$$

This law is known as Stocks law. This may be concluded by the theory of dimensions. Supposing that there is a ball of a radius (r) is dropped into a liquid whose coefficient of viscosity is (η), density o and density of the metal ball is 8 &o, at the beginning of dropping, velocity of the ball will be irregular, but it gets regular later. It is called terminal velocity, then. At this moment, acceleration of the forces influencing them is zero. In other words, the three forces are:

1- Weight of the ball downward

2- Force of pushing the liquid onto the ball upward.

3- Stocks force due to upward viscosity

Weight of the ball is

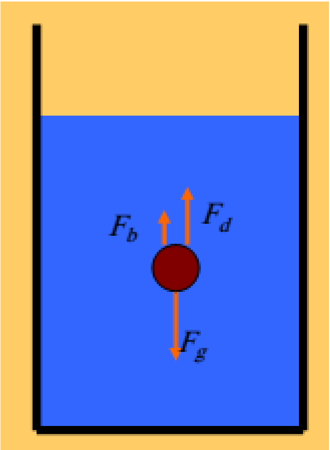
$$4/3\pi r^3 \delta . g$$

Were (g) is Earth gravity, force of pushing the liquid is

$$4/3\pi r^3 \delta . g$$

stocks force is

$6\pi V r \eta$



and at the terminal velocity, the following equation may be written:

Weight of the ball force of pushing on the ball + Stocks force.

$$4/3\pi r^3 \delta . g = 4/3\pi r^3 \delta . g + 6\pi V r \eta$$

Or $$6\pi V r \eta = 4/3\pi r^3 . g\,(\delta - \sigma)$$

Or $$V = \frac{(2r^2 g)}{9\eta}(\delta - \sigma)$$

This expression is written mathematically as follows:

This illustrates that terminal velocity is directly proportionate with its square radius, taking into account difference between the densities of the ball and liquid. The terminal velocity is also indirectly proportionate with coefficient of viscosity.