PROPERTIES OF FLUID

Fluid

A fluid is a substance that ***deforms continuously*** ***under the application of a shear (tangential) stress no matter how small the shear stress*** may be. Conversely, it follows that:

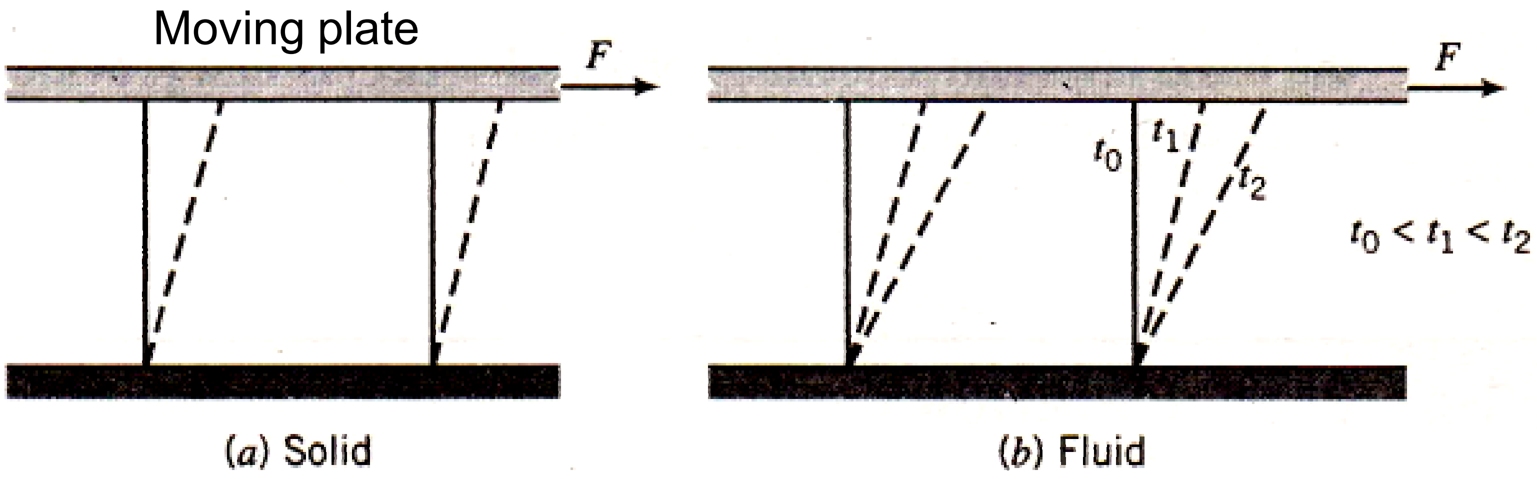


Fig: Behavior of a solid and a fluid, under the action of a constant shear force.

- Because the fluid motion continues under the application of a shear stress, so a ***fluid can be defined as any substance that cannot sustain (or resist) a shear stress when at rest***. Any shear stress applied to a fluid will result in motion of that fluid. The fluid moves and deforms continuously as long as the shear stress is applied. We can say ***a fluid at rest must be in a state of zero shear stress, a state often called***

hydrostatic stress condition in structural analysis.

- **If a fluid is at rest**, there can be no shearing forces acting and, therefore, ***all forces in the fluid must be perpendicular to the planes*** upon which they act.

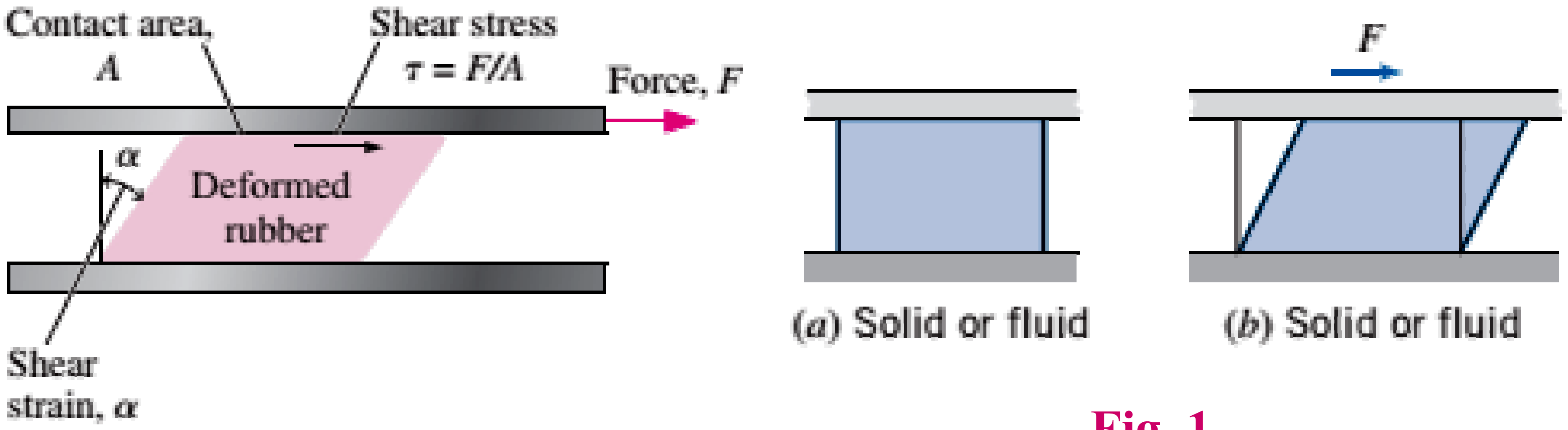
The difference between solid and fluid behavior

- A solid can resist an applied shear stress by deforming (provided that the elastic limit is not exceeded), whereas a fluid deforms continuously under the influence of shear stress, no matter how small.

- **In solids** ***stress is proportional to strain***, but **in fluids** ***stress is proportional to strain rate***. When a constant shear force is applied, a solid eventually stops deforming, at some fixed strain angle, whereas a fluid never stops deforming and approaches a certain rate of strain.

- ***The strain in a solid is independent of the time*** over which the force is applied and, if the elastic limit is not exceeded, the deformation disappears when the force is removed. ***A fluid continues to flow for as long as the force is applied and will not recover its original form when the force is removed.***

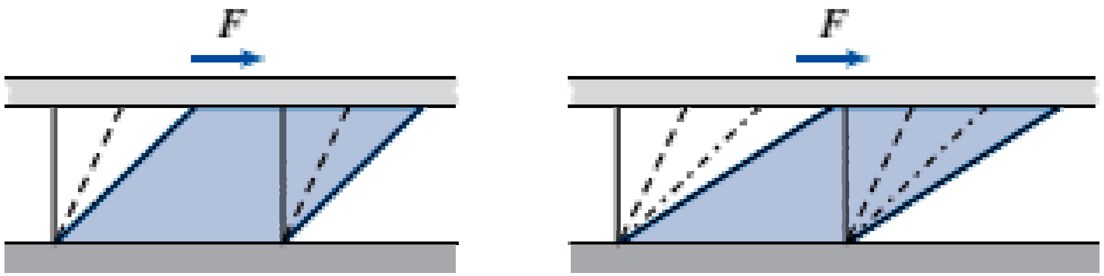
Consider a specimen of either substance (solid and fluid) are placed between two plates (Fig.1a) and then apply a shearing force F, each will initially deform. The block changes shapes in a manner conveniently characterized by the angle α when subjected to a shear stress τ and will be at rest (assuming the force is not large enough to go beyond its elastic limit fig.1b). When the force is removed, the solid returns to its original position. If this were an element of fluid as shown in fig. 1(c,d), there would be no fixed α even for an infinitesimal shear stress. The fluid will continue to deform as long as the force is applied. The shape of the fluid element, at successive instants of time $t_2 > t_1 > t_0$ is shown in fig 1(c,d) by the dashed lines.



(a) Solid or fluid

(b) Solid or fluid

Fig. 1



(c) Fluid only (d) Fluid only

Fig. 1

Note that a fluid in direct contact with a solid surface does not slip i.e. it "sticks" to the surface due to viscous effects — it has the same velocity as that surface and there is no slip. This is known as the **no-slip condition**, an experimental fact (this is one property).

Shear Stress in A Moving Fluid

Although there can be no shear stress in a fluid at rest, shear stresses are developed ***when the fluid is in motion, if the particles of the fluid move relative to each other so that they have different velocities, causing the original shape of the fluid to become distorted***. ***If, on the other hand, the velocity of the fluid is same at every point, no shear stresses will be produced, since the fluid particles are at rest relative to each other***.

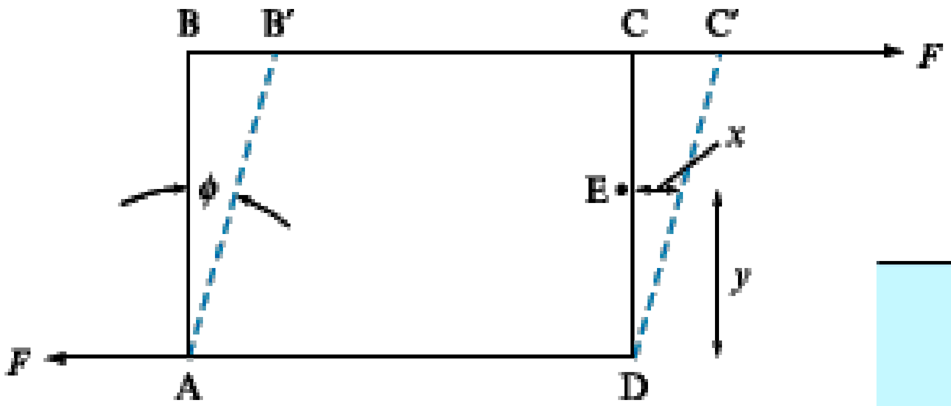
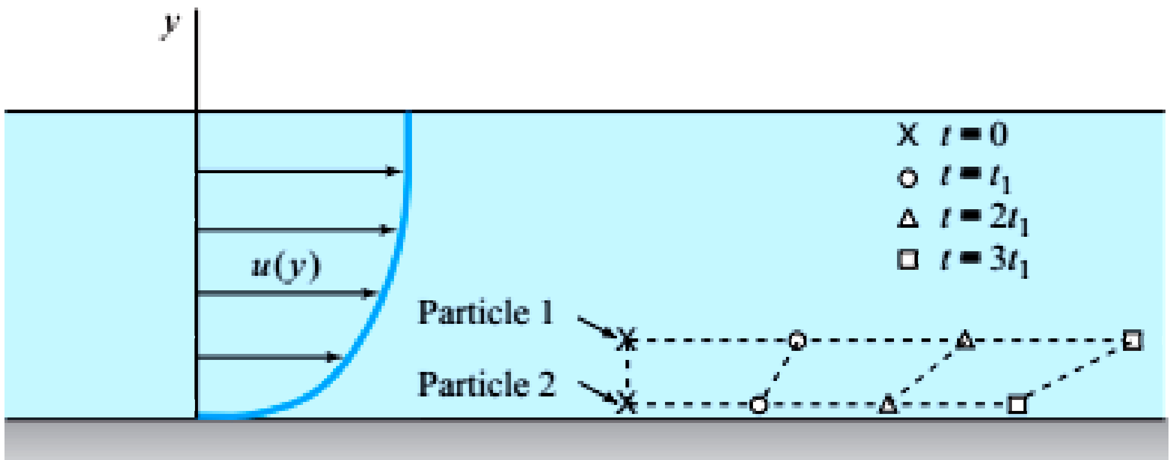
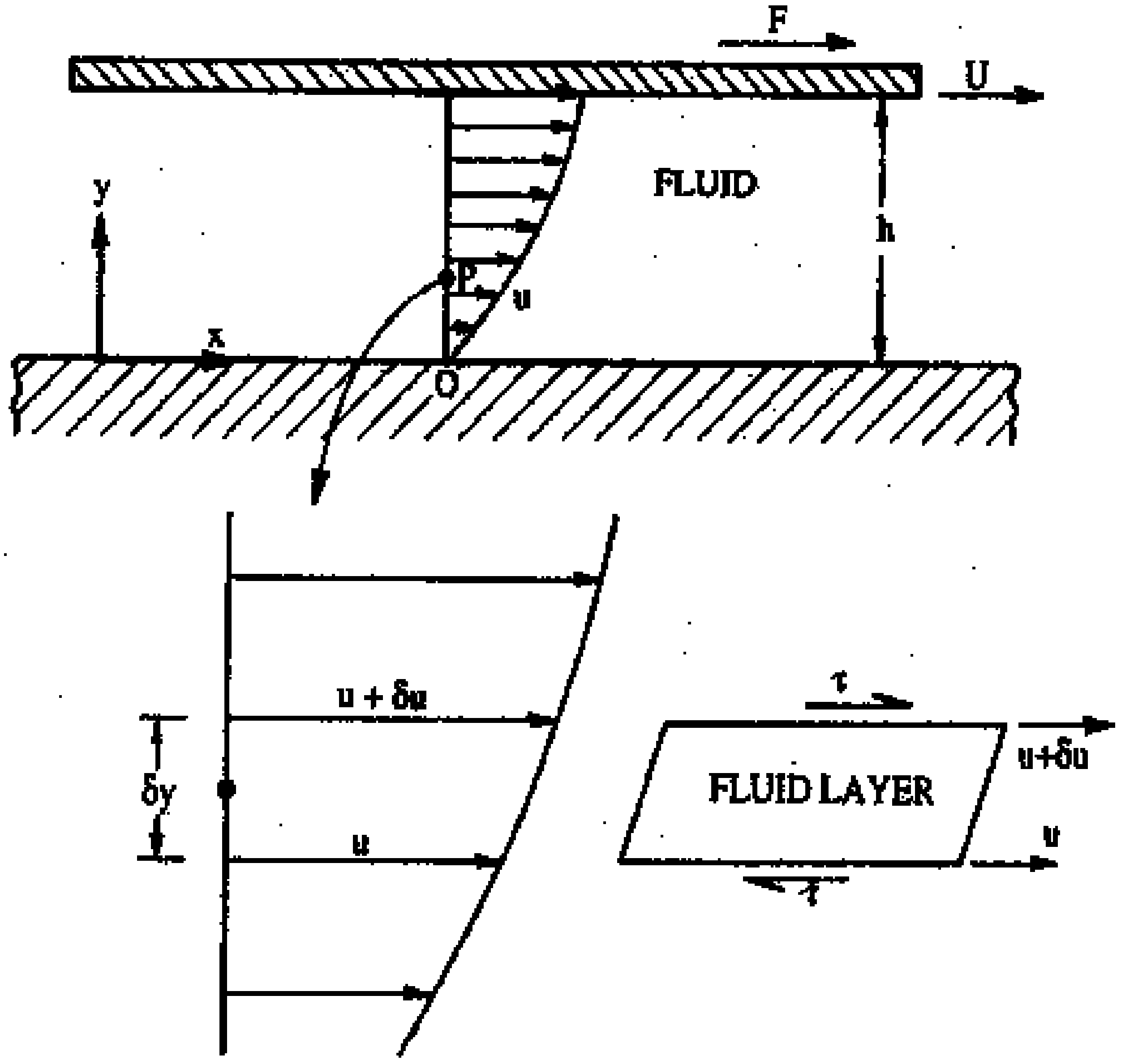


Fig. 2a (Deformation caused by shearing forces)



If ABCD (Fig. 2a) represents an element in a fluid with thickness s perpendicular to the diagram, then the force $\boldsymbol{F}$ will act over an area A equal to BC × s. The force per unit area F/A is the ***shear stress τ*** and **the deformation, measured by *the angle φ (the shear strain*), will be proportional to the shear stress**. In a solid, φ will be a fixed quantity for a given value of τ, since a solid can resist shear stress permanently. In a fluid, the shear strain φ will continue to increase with time and the fluid will flow. It is found experimentally that, in **a true fluid**, **the rate of shear strain (or shear strain per unit time) is directly proportional to the shear stress.**



Velocity Profile $\tau = \mu \dfrac{du}{dy}$

(Enlarged View at *P*)

Suppose that in time t a particle at E (Fig. 2a) moves through a distance x. If E is a distance y from AD then, for small angles,

Shear strain, $\varphi = x/y$,

Rate of shear strain $= x/yt = (x/t)/y = u/y$,

where $u = x/t$ is the velocity of the particle at E.

Assuming the experimental result that shear stress is proportional to shear strain, then

$$\tau = constant \times u/y$$

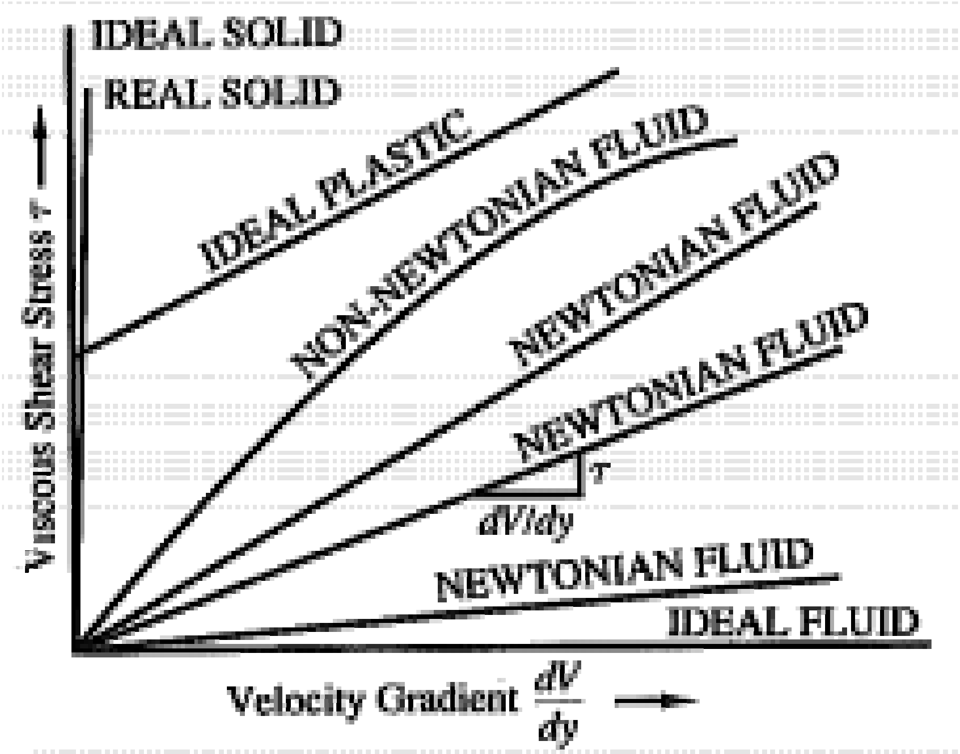
The term u/y is the change of velocity with y and may be written in the differential form du/dy. ***The constant of proportionality is known as the dynamic viscosity μ of the fluid***.

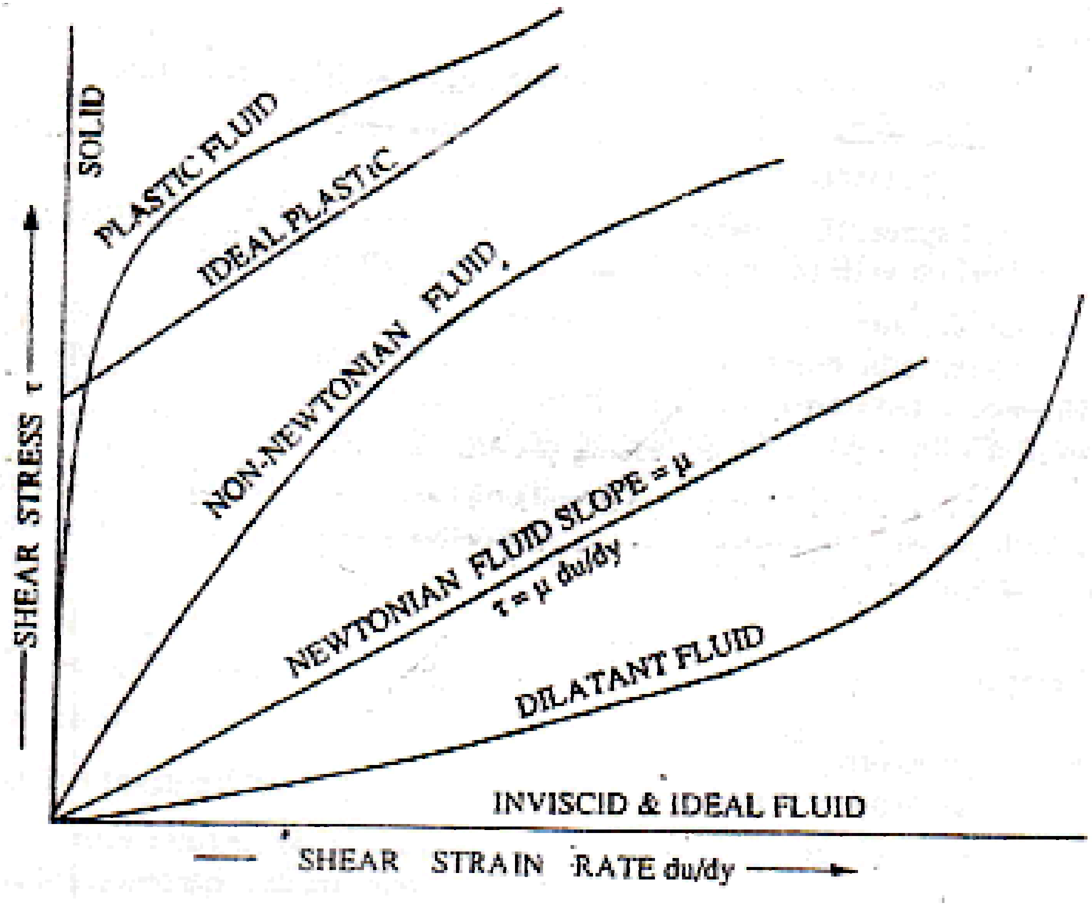
$$\tau = \mu \frac{du}{dy},$$

which is **Newton's law of viscosity**. The value of ***μ*** **depends upon the fluid** under consideration.

Fluids which obey this law are termed as **Newtonian fluids** and those which disobey it are broadly branded as **Non-Newtonian fluid**. Most engineering fluids such as water, air and molten metals fortunately belong to Newtonian class providing relatively easier study.

Fig: Shear characteristics of fluids.





Type of fluid	**Density**	**Viscosity**
1. Ideal Fluid	Constant	Zero
2. Incompressible Fluid	Constant	Non-zero
3. Inviscid Fluid	Constant or variable	Zero
4. Real Fluid	Variable	Non-zero
5. Newtonian Fluid	Constant or variable	$\tau = \mu \frac{du}{dy}$
6. Non-Newtonian Fluid	Constant or variable	$\tau \neq \mu \frac{du}{dy}$
7. Compressible	Variable	Zero
8. Perfact Gas	$P = \rho RT$; Variable	Zero

Newtonian Fluid: μ does not change with rate of deformation.

Water, air, alcohol, glycerol, and thin motor oil.

Non-Newtonian Fluid: μ changes with rate of deformation

Many salt solutions and molten polymers, custard, honey, corn flour.

Ideal Plastic: can resist a finite shear stress and thus behave as a solid, but deform continuously when the shear stress exceeds the yield stress and behave as a fluid. Exam: Tooth paste

Dilatant Fluid: also known as **shear thickening fluid.** Dynamic viscosity increases with the rate of deformation. A dilatant is a non-Newtonian fluid
Exam: solutions with suspended starch or sand.

Ideal Fluid: $\mu = 0$

- **The ideal gas law** is often written in an empirical form: $PV = nRT$

where P, V and T are the pressure, volume and temperature; n is the amount of substance; and R is the ideal gas constant (**universal gas constant**). It is the same for all gases.

R has the value 8.314 J/(K·mol) ≈ 2 cal/(K·mol)

Molar form

An alternative form of the ideal gas law may be useful. The chemical amount (*n*) (in moles) is equal to total mass of the gas (*m*) (in kilograms) divided by the molar mass (*M*) (in kilograms per mole):

$$n = \frac{m}{M}$$

$$PV = \frac{m}{M} RT$$

$$PM = \frac{m}{V} RT = \rho RT$$

The specific gas constant (or **gas constant**) $R_{\text{specific(r)}} = R/M$

$$P = \rho \frac{R}{M} T = \rho R_{specific} T$$

For Air, M = 28.97 gm/mole. R_{sp} = 287 J/(kg. K)

Basic Equations

Fluid mechanics problem necessarily includes statement of the basic laws governing the fluid motion. The basic laws, which are applicable to any fluid, are:

1. The conservation of mass
2. The conservation of momentum (Newton's second law of motion)
3. The conservation of energy (The first law of thermodynamics)
4. Moment of momentum (The principle of angular momentum)
5. Entropy relations (The second law of thermodynamics)

Not all basic laws are always required to solve any one problem. On the other hand, in many problems it is necessary to bring into the analysis additional relations that describe the behavior of physical properties of fluids under given conditions.

Properties of Fluid

Any characteristic of a system is called a **property**.
Exam: pressure P, temperature T, volume V, mass m, viscosity, thermal conductivity, modulus of elasticity, thermal expansion coefficient, electric resistivity etc.

Properties are considered to be either ***intensive*** or ***extensive***.

Intensive properties are those that *are* ***independent of the mass of a system***, such as temperature, pressure, and density.

Extensive properties are those whose values ***depend on the size—or extent—of the system***. Total mass, total volume V, and total momentum are some examples of extensive properties.

- An easy way to determine whether a property is intensive or extensive is to divide the system into two equal parts with an imaginary partition, as shown in Fig. Each part will have the ***same value of intensive properties as the original system, but half the value of the extensive properties***.

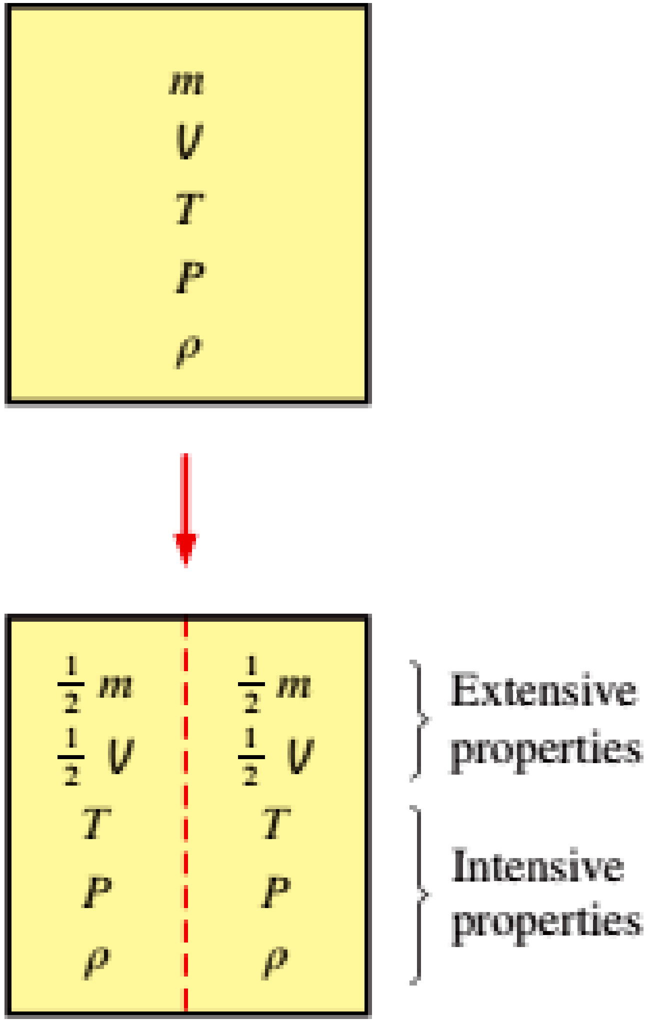


Fig: Criteria to differentiate intensive and extensive properties

- Generally, ***uppercase letters*** are used to ***denote extensive properties*** (with mass *m* being a major exception), and ***lowercase letters*** are used for ***intensive properties*** (with pressure *P* and temperature *T* being the obvious exceptions).

- ***Extensive properties per unit mass*** are called ***specific properties***. Some examples of specific properties are specific volume ($v = V/m$) and specific total energy ($e = E/m$).

- **The state of a system** is described by its properties. The number of properties required to fix the state of a system is given by the ***state postulate***: **The state of a simple compressible system is completely specified by two independent, intensive properties**. Two properties are independent if one property can be varied while the other one is held constant.

Density (*mass density*), ρ:

The ***density*** of a fluid is defined ***as its mass per unit volume***. For a fluid continuum, density must be a continuous function of space. If a fluid element enclosing a point *P* has a volume δV and mass δm, then the density is given by

$$\boxed{\rho = \underset{\delta V \to 0}{Lt} \frac{\delta m}{\delta V} = \frac{dm}{dV}} \qquad \boxed{\rho = \rho(x, y, z, t)}$$

The **density** of a substance, in general, **depends on temperature and pressure.** The ***density of most gases is proportional to pressure and inversely proportional to temperature***. **Liquids and solids**, on the other hand, ***are*** essentially ***incompressible substances***, and the variation of their ***density with pressure is usually negligible***.

Obviously, ***density is a local fluid property which may vary from point to point as well as at a point with the passage of time***.

Units: kilograms per cubic metre (kgm^{-3}), lbm/ft^3, or $slugs/ft^3$.
Dimensions: ML^{-3}. [One slug is a mass equal to 32.1740 lb (14.59390 kg)]

It is customary in the study of thermo-fluid dynamics to use the terms **'specific volume'.** The specific volume is the ***volume per unit mass of the fluid***. It follows, therefore, that ***the specific volume υ is the inverse of the mass density ρ*** ;. That is, $v = V/m = 1/\rho$.

Specific weight, γ

The ***weight of a substance per unit volume*** is called the specific weight. It is the ***force exerted by gravity on a unit volume***.

$$\boxed{\text{Specific weight} = \mathop{Lt}\limits_{\delta V \to 0} \frac{g.\delta m}{\delta V} = \frac{g\,dm}{dV} = \rho g} \qquad \boxed{\gamma = \frac{W}{V} = \frac{mg}{V} = \rho g}$$

Unit: F/L^3 (lbf/ft^3 or N/m^3). Dimensions: $ML^{-2}T^{-2}$.

- Since ***weight is dependent on gravitational attraction***, the specific weight **will vary from point to point**, according to the local value of gravitational acceleration g.
- The relationship between γ and ρ can be deduced from Newton's second law, since

$$\text{Weight per unit volume} = \text{Mass per unit volume} \times g$$

$$\gamma = \rho g.$$

Specific gravity (Relative density) SG

The specific gravity of *SG* ***of a liquid is the ratio of its density to that of water at 4°C*** and the specific gravity of ***a gas is the ratio of its density to that of air at STP***; water and air being accepted as the reference liquid and gaseous fluids respectively.

$$\boxed{SG = \frac{\rho}{\rho_{H_2O@4°C}}}$$

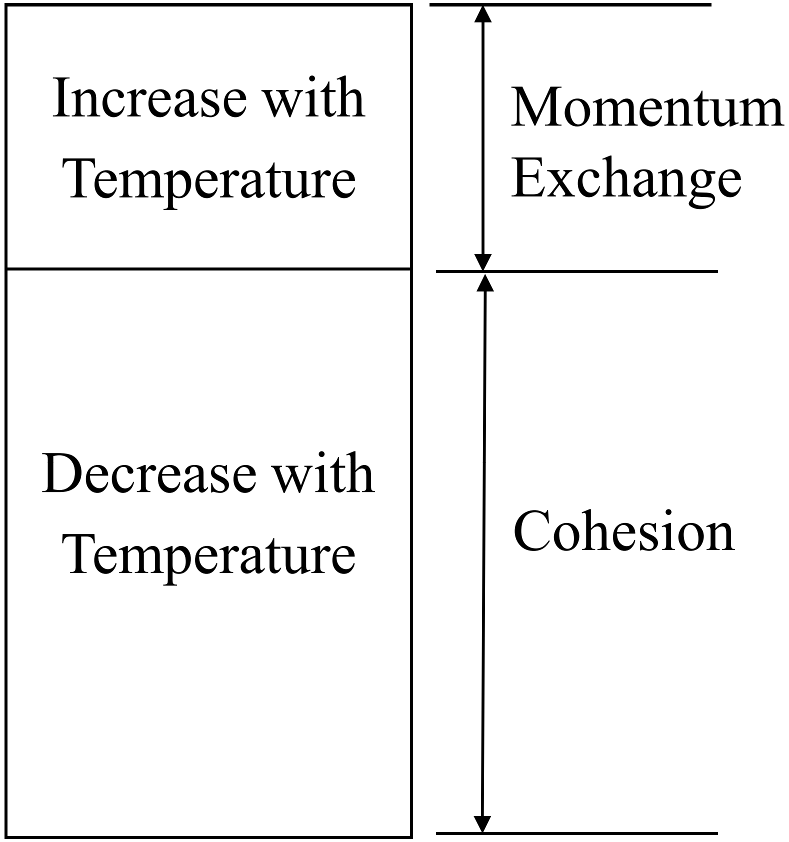
Dimensions: as a pure number, its dimensions are $M^0L^0T^0 = 1$

Viscosity

It is a ***measure of the internal fluid friction which cause resistance to flow.***

The **origin of viscosity** is **due to cohesion and molecular momentum transfer.** These two factors add to provide the resistance to shearing reckoned by the property of viscosity.

The viscosity of liquids drops with temperature whereas the reverse happens for gases. Because, ***in liquids*, *the cohesive forces predominate*** due to closely packed molecules and with a rise in temperature those



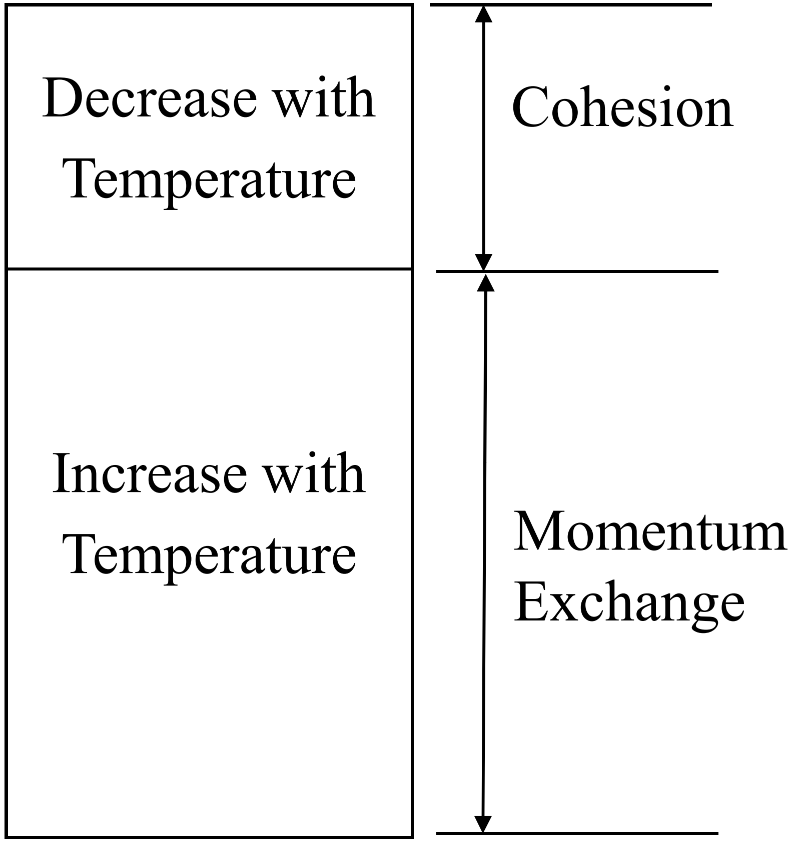
Increase with Temperature

Momentum Exchange

Decrease with Temperature

Cohesion

Liquid viscosity



Decrease with Temperature

Cohesion

Increase with Temperature

Momentum Exchange

Gas viscosity

forces decrease resulting in decrease of viscosity.

In gases, cohesive forces are small and the ***molecular momentum transfer predominates which increases with a rise of temperature*** causing a rise of viscosity.

Figure presents the effect of change in temperature on the viscosity of some engineering fluids. Properties of some common fluids are listed in Table .

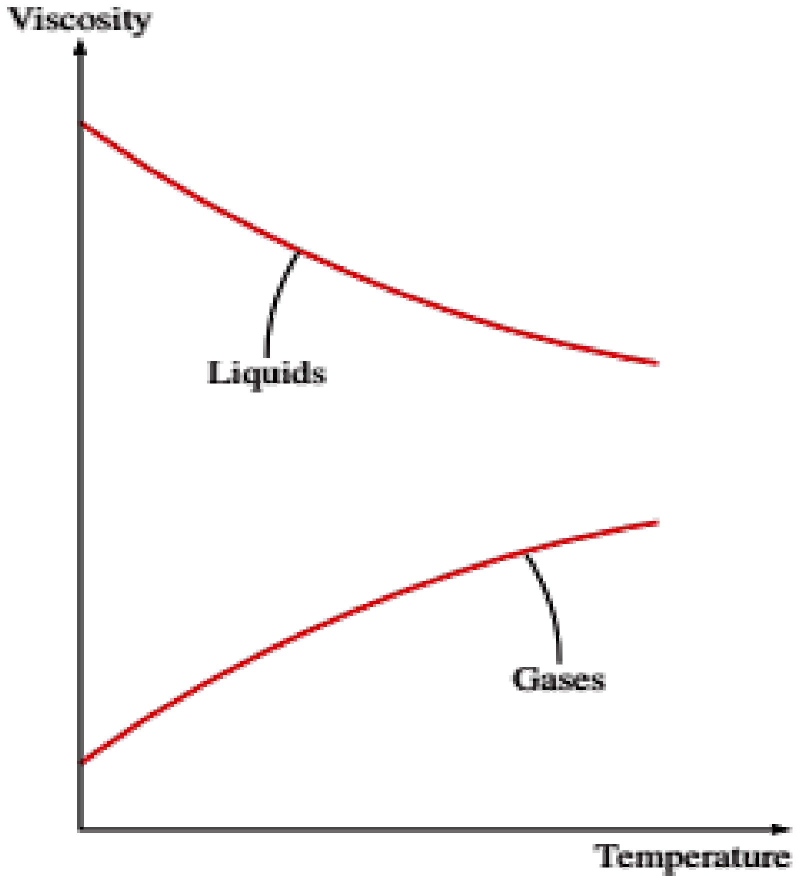
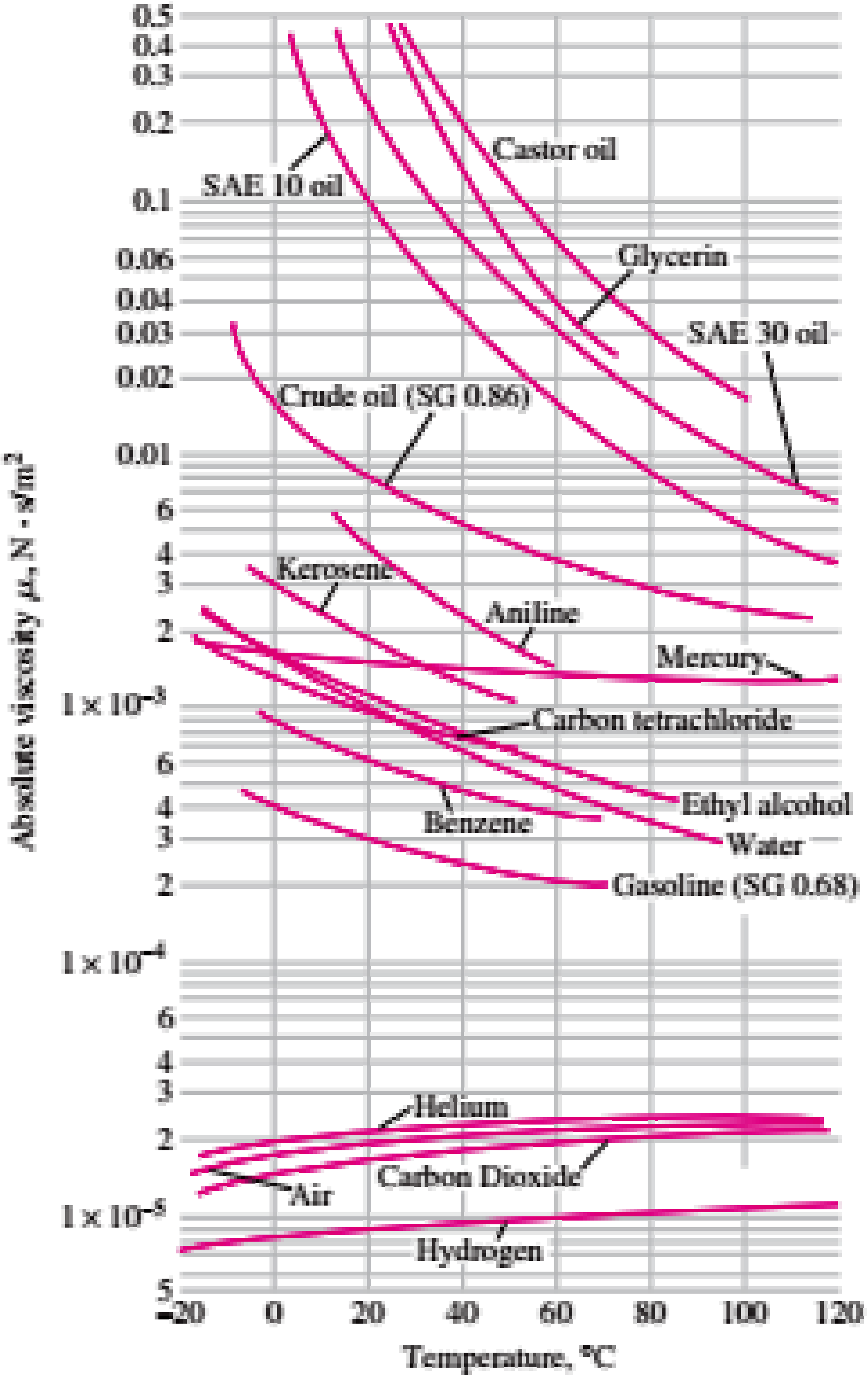


Fig: Viscosity vs. Temperature for Common Fluids



In one-dimensional shear flow of Newtonian fluids, shear stress can be expressed by the linear relationship

$$\boxed{\tau = \mu \frac{du}{dy}} \quad (\mathrm{N/m^2})$$

where the constant of proportionality μ is called the **coefficient of viscosity** or the **dynamic** (or **absolute**) **viscosity** of the fluid.

Unit: kg/m · s, or equivalently, N · s/m^2 (or Pa.s where Pa is the pressure unit pascal). [**1 Poise = 0.1 Pa.s** and 1 centipoise = 1Poise/100]

Dimensions: ML−1T−1.

The **kinematic viscosity** ν is defined as the ***ratio of dynamic viscosity to mass density***.

$$\nu = \mu / \rho$$

Unit: m^2/s; stoke (1 stoke = 1cm^2/s = 0.0001 m^2/s)
Dimensions: L2T −1.

Compressible Fluids

Fluids are said to be compressible ***if their density varies with pressure***. Its variation formula:

$$\mathbf{P}/\rho^{k} = \text{constant} \quad \text{[for constant entropy]}$$

$$\frac{p}{\rho} = \text{constant} \quad \text{[for isothermal process]}$$

Incompressible Fluids

Incompressible fluids are considered those where ***density doesn't change with pressure***.

In reality, incompressible fluids do not exist in nature. It is relative term depends upon how much density change → tends to zero.

Liquids are ordinarily considered as incompressible fluids because its density change with pressure is negligible [but not zero].

Air may be considered as to be incompressible fluid when pressure & temperature change is too small.

Compressibility

The coefficient of compressibility (β) is defined as ***volumetric strain per unit compressive stress***. Or, it is the ***change in volume per unit volume for a unit change in pressure***.

It is reciprocal of **Bulk modulus (*K or* E$_v$) or volume modulus**. The bulk modulus of elasticity is defined as ***compressive stress per unit volume strain.***

$$\boxed{E_v = -\frac{dp}{d\rlap{/}V/\rlap{/}V}}$$

where dp is the differential change in pressure needed to create a differential change in volume, $d\rlap{/}V$, of a volume $\rlap{/}V$. The negative sign is included since an increase in pressure will cause a decrease in volume. Since a decrease in volume of a given mass, $m = \rho \rlap{/}V$, will result in an increase in density,

$$\boxed{E_v = \frac{dp}{d\rho/\rho}}$$

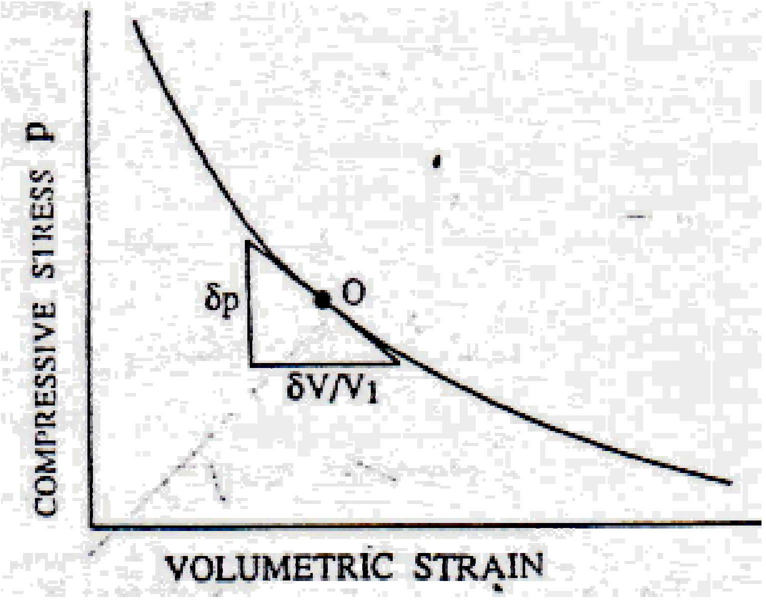


Fig. Compressibility of a Fluid

So, $\beta = 1 / E_v$

$$\boxed{\beta = -\frac{1}{\forall}\left(\frac{\partial \forall}{\partial p}\right)_T}$$

$$\boxed{E_v / \rho = \delta p / \delta \rho}$$

Let us now examine **the relationships between the bulk modulus of elasticity and the local pressure** for a perfect gas for two different processes of compression :

For an Isothermal Process:

$$\frac{p}{\rho} = \text{constant } C_1$$

From the equation of state for a perfect gas,

$$p = \rho RT$$

and
$$\frac{dp}{d\rho} = RT = \frac{p}{\rho} = C_1$$

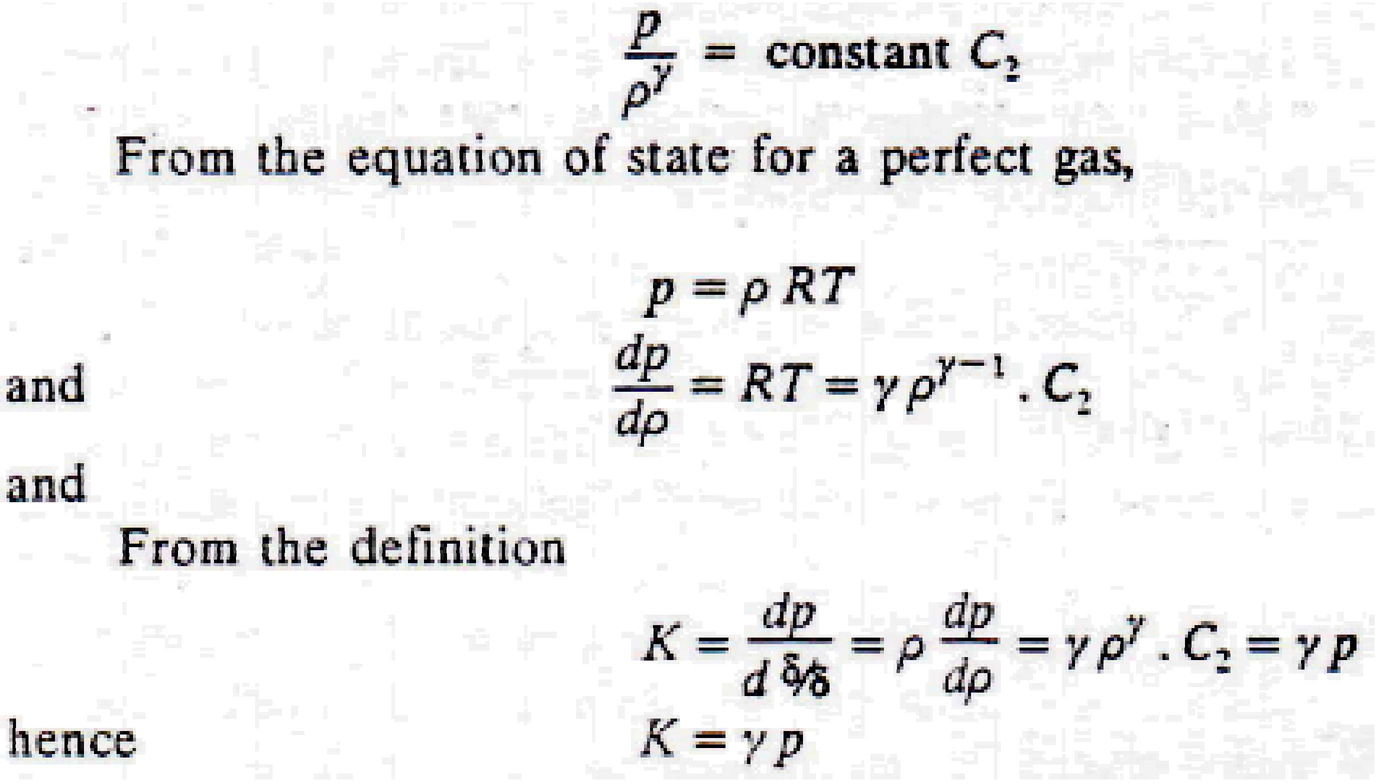
From the definition,

$$K = \frac{dp}{d\rho/\rho} = \rho\frac{dp}{d\rho} = \rho C_1 = p$$

hence,
$$K = p \text{ and } \frac{dp}{\rho} = \frac{dp}{K}$$

...

For an Isentropic Process :



$$\frac{p}{\rho^{\gamma}} = \text{constant } C_2$$

From the equation of state for a perfect gas,

$$p = \rho RT$$

and

$$\frac{dp}{d\rho} = RT = \gamma \rho^{\gamma-1} . C_2$$

and

From the definition

$$K = \frac{dp}{d\,\delta v/v} = \rho \frac{dp}{d\rho} = \gamma \rho^{\gamma} . C_2 = \gamma p$$

hence

$$K = \gamma p$$

It follows that, for a perfect gas, the ***bulk modulus of elasticity equals its pressure for an isothermal compression*** and ***the same equals γ times the pressure for an isentropic process***. In fact, the modulus of elasticity equals n times the pressure for a **polytropic compression of index n; the result for isothermal and isentropic process follow for the special cases of n = 1 and n = γ respectively.**

Speed of Sound

It is wave of pressure in substance. It is defined in terms of bulk modulus as

$$\boxed{c = \sqrt{\frac{E_v}{\rho}}}$$

c → sound speed

For moderate range of pressure, E_v doesn't vary much with temperature. So,

$$\boxed{c = \sqrt{\frac{dp}{d\rho}}}$$

For ***Liquid***: $\sqrt{(\Delta P/\Delta\rho)}$ **or,** $\sqrt{(E_v/\rho)}$

For ***Gas***: $c = \sqrt{nP/\rho}$ ***as*** $P/\rho^n = const.$ ***So,*** $dP/d\rho = nP/\rho$

For **Ideal Gas (isentropic process)**: $P = \rho RT$, $PV = nRT$, $\rho = nM/V$

so $c = \sqrt{(\gamma P/\rho)}$ **and** $c = \sqrt{(\gamma RT)}$, **where** $\gamma = c_p/c_v$

Surface Tension σ

It is the ***property of the apparent tension effect which occurs at the interface of a liquid and a gas or at the interface of two immiscible liquids***. It is the ***elastic tendency of a fluid surface which makes it acquire the least surface area possible***. The origin of surface tension is explained by considering the **mechanism of cohesive forces** within a liquid as in following Fig.

Water beading on a leaf

Water dripping from a tap

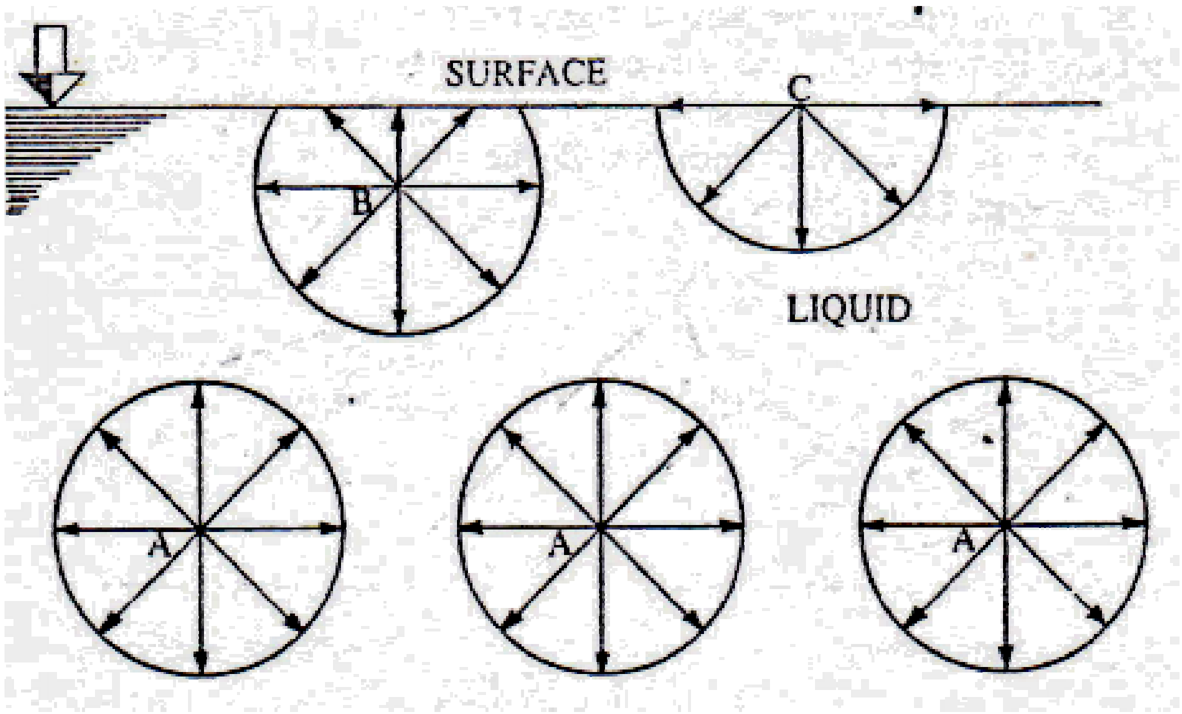
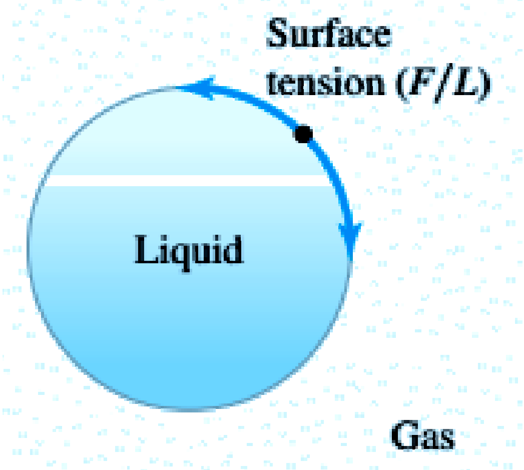
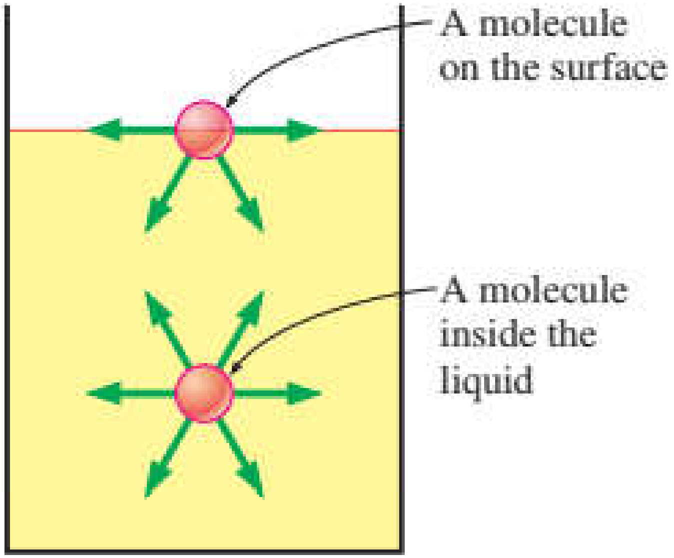


Fig. Origin of Surface Tension





A typical **molecule A** within the liquid is maintained in equilibrium by the action of cohesive forces exerted by the molecules surrounding it within a zone of action. ***The resultant force acting upon the molecule A is zero because the cohesive forces acting by the surrounding molecules balance each other because of symmetry***.

At liquid-gas interfaces, consider of a **molecule *B* located near the surface**, ***surface tension results from the greater attraction of liquid molecules to each other (due to cohesion) than to the molecules in the air (due to adhesion)***. The attractive forces acting on the surface molecule are not symmetric, and the attractive forces applied by the gas molecules above are usually very small. The net effect is an inward force at its surface that causes the liquid to behave as if its surface were covered with a stretched elastic membrane. Therefore, there is a net attractive force acting on the molecule at the surface of the liquid, which tends to pull the molecules on the surface toward the interior of the liquid. This force is balanced by the repulsive forces from the molecules below the surface that are being compressed. The resulting compression effect causes the liquid to minimize its surface area. This is the reason for the tendency of the liquid droplets to attain a spherical shape, which has the minimum surface area for a given volume.

A typical **molecule C** located at the surface of the liquid does experience a net downward force.

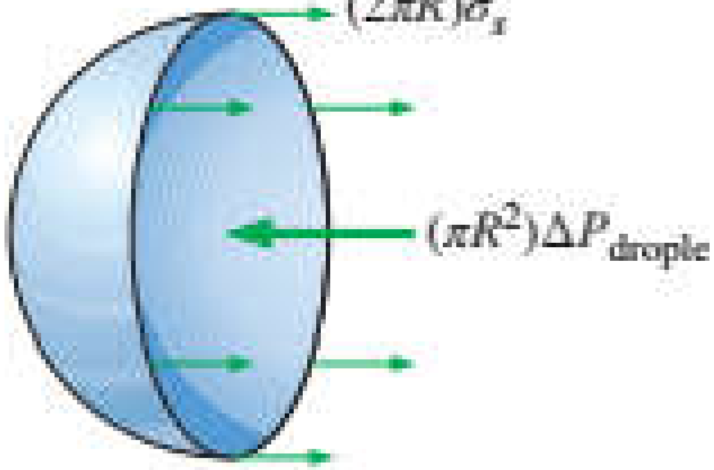
While discussing the mechanism of cohesive forces, one should not forget that the **zone of action of intermolecular cohesive forces is of the order of a millionth of a centimeter**. This fact ensures that the molecules experiencing net downward forces are confined to a layer which defines the surface of the liquid. ***The surface of a liquid is***, therefore, ***under a different state than the rest of the liquid*** ; ***the surface is in a state of tension akin to a stretched thin membrane.*** ***the surface tension decreases as the temperature of the liquid increases because the intermolecular cohesive forces decrease***. ***At the critical temperature of a liquid, the surface tension becomes zero and the boundary between the liquid and its vapor vanishes*** !

The force of surface tension is a line force ; it is expressed as ***force per unit length*** drawn on the free surface of a liquid. The phenomenon of *surface tension is alternatively explained by the existence of free-surface energy at the interface of a liquid and another fluid*. The surface tension is likewise expressed as free surface energy per unit length of the surface.

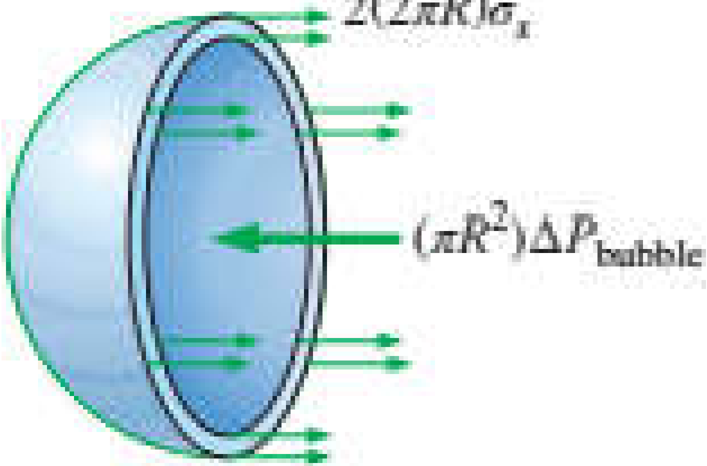
The effect of surface tension is to reduce the surface of a free body of liquid to a minimum, since to expand the surface area molecules have to be brought to the surface from the bulk of the liquid against the unbalanced attraction pulling the surface molecules inwards.

Water in contact with air has a surface tension of 0.073 N/m at 20°C. Mercury in contact with has a surface tension of 0.5 N/m. ***The surface tension of water is considerably reduced by adding a small quantity of an organic solute such as soap or detergent***. ***The surface tension of water increases if a salt such as sodium chloride is dissolved in it.*** Organic liquids such as alcohol have surface tension varying between 0.02 and 0.03 N/m.

Example: A drop of blood forms a hump on a horizontal glass; a drop of mercury forms a near-perfect sphere and can be rolled just like a steel ball over a smooth surface; water droplets from rain or dew hang from branches or leaves of trees; a liquid fuel injected into an engine forms a mist of spherical droplets; water dripping from a leaky faucet falls as spherical droplets; a soap bubble released into the air forms a spherical shape; and water beads up into small drops on flower petals.



(*a*) Half of a droplet or air bubble

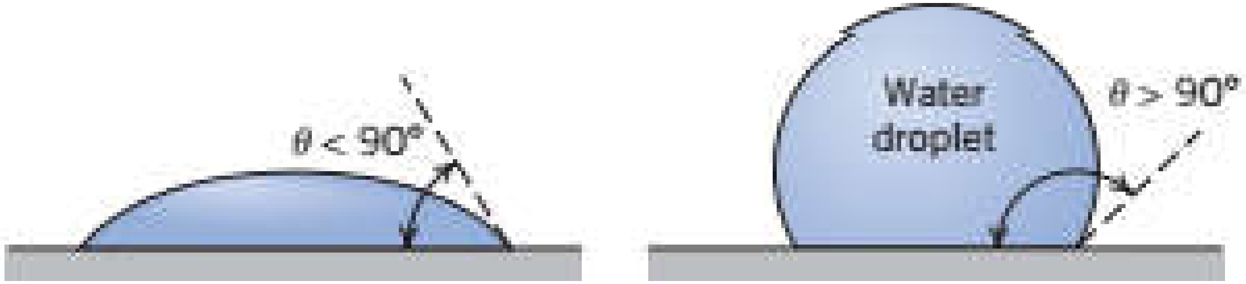


(*b*) Half of a soap bubble

Capillarity

The force due to surface tension is generally negligible in comparison with the pressure and gravitational forces but the same assumes predominance for narrow liquid columns such as those in capillary tubes, ***in bubble mechanics and liquid-jet studies and for flow through porous substances***.

Capillarity implies the rise or depression of the level of a liquid in a capillary tube when it is held vertically or inclined in the liquid. The ***phenomenon is explained*** *with reference to the angle of contact between the liquid and the capillary material and the balance of force on the column of the liquid in them*.



(a) Acute angle (for wetting)

(b) Obtuse angle (for non-wetting)

Fig. Angle of Contact

The angle of contact is defined as the angle between the tangent to a drop at the solid boundary with the surface of the solid boundary on which it is placed as shown in Fig.

If a liquid wets a surface and spreads out, the angle of contact between them is small but if a liquid does not do so, the angle of contact is large. Factors that affect the contact angle include the cleanliness of the surface and the purity of the liquid.

The extent to which a liquid may wet a solid surface depends upon the properties of adhesion and cohesion. At the interface this leads to the liquid surface being moved up or down forming a curved surface. **If adhesion more than cohesion**, the contact surface is lifted up forming a concave surface, ***the wetting tendency is more and the angle of contact is smaller. Oils, water etc. exhibit such behavior***. **When the adhesive forces are lower**, ***the contact surface is lowered at the interface*** and a convex surface results as in the case **of mercury**. Such liquids are called **nonwetting**.

Whether a liquid would rise or drop in a capillary tube depends upon the angle of contact between the liquid and the capillary material. ***Acute angle of contact corresponds with capillary rise and obtuse angle of contact with capillary depression.***

Capillary action is negligible for water and mercury for tube diameters of 1 cm or more.

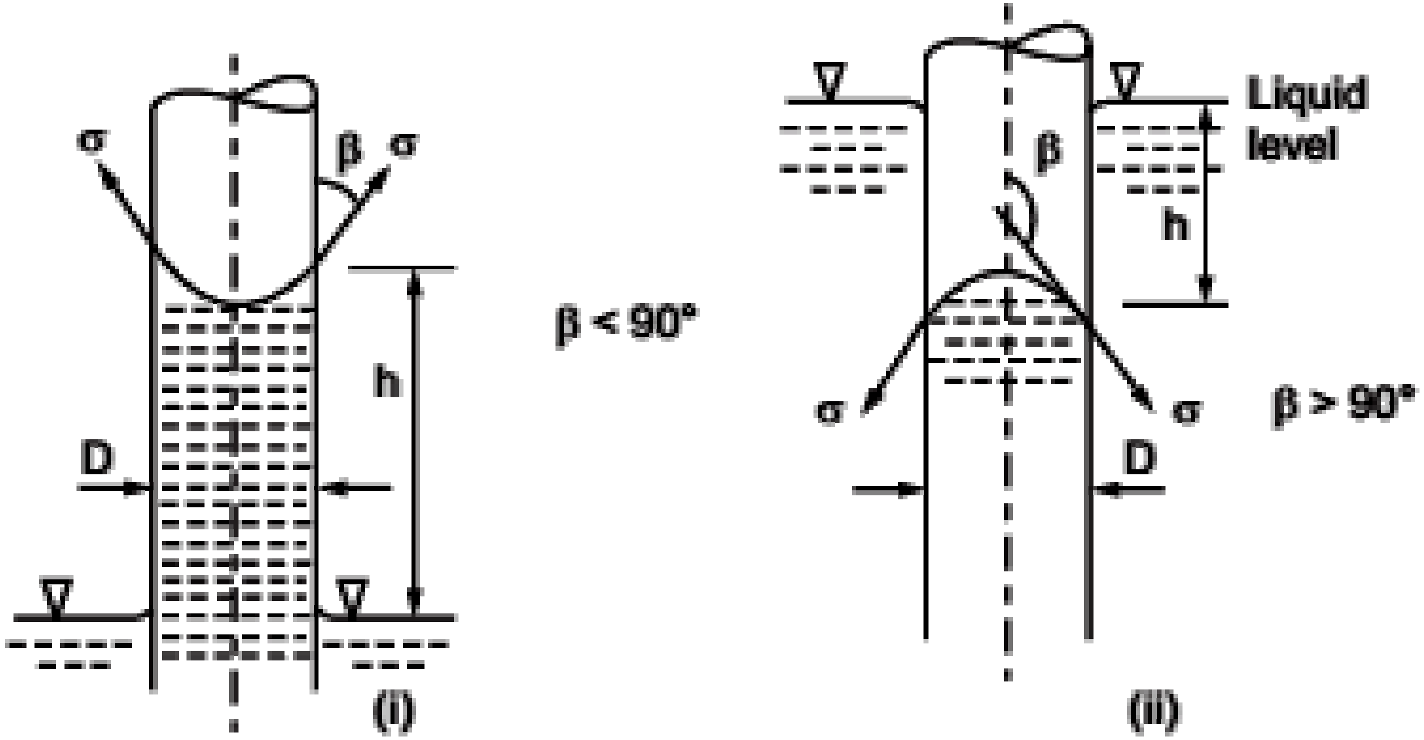
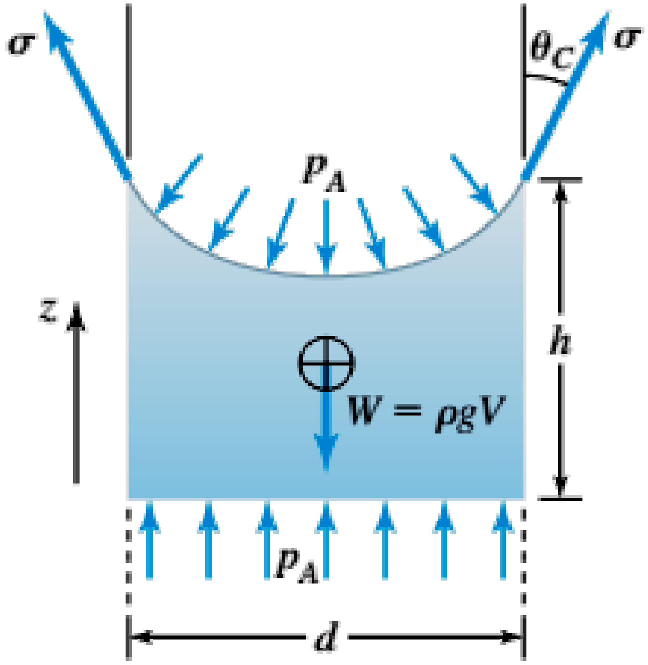
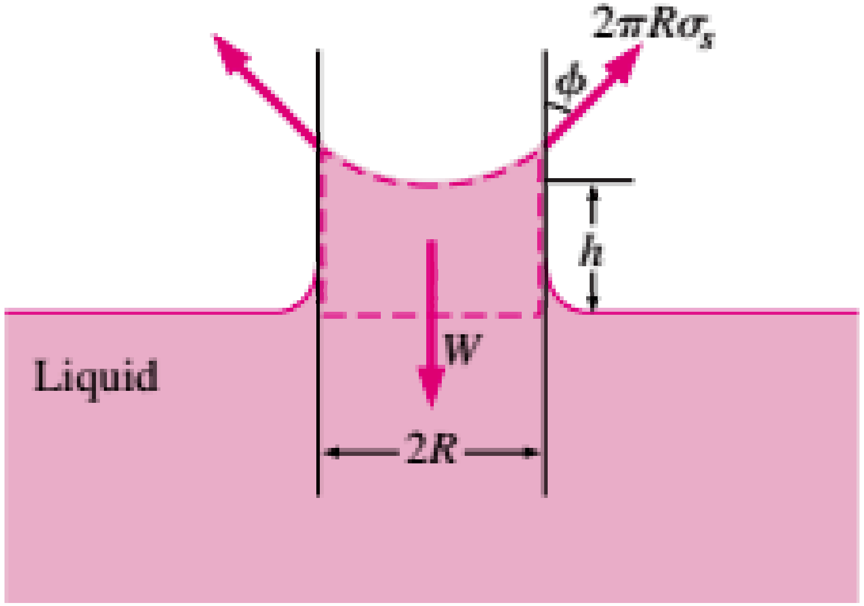


Fig.3 Surface tension, (i) capillary rise (ii) depression

In engineering, the most important effect of surface tension is the creation of a curved meniscus that appears in manometers or barometers, leading to a (usually unwanted) capillary rise (or depression), as shown in Fig. 3. This rise may be pronounced if the liquid is in a small-diameter tube or narrow gap.

Consider what happens if a thin glass tube is inserted into a liquid. **If the liquid wets the glass, it will enter the tube by capillary action.** **If the liquid does not wet the glass, it will be prevented from entering the tube**. Both effects are due to surface tension.





With reference to Fig. (i) for capillary rise,

Upward surface tension force = Weight of the column in the tube

$$\pi d \,.\, \sigma \,.\cos\theta = \pi\frac{d^2}{4} \,.\, h \,.\, \rho g \qquad \ldots(1.15)$$

whence $h = 4\,\sigma\cos\theta/\rho g d$

where σ = surface tension force per unit length and

θ = angle of contact between the liquid and the tube material.

For water and glass

$$\theta \approx 0$$

hence the capillary rise of water in a glass tube

$$h = 4\,\sigma/\rho g d$$

It may be noted that if a liquid surface supports another fluid of density ρ_b above the meniscus, then a balance of forces would result in

$$h = \frac{4\,\sigma\cos\theta}{(\rho - \rho_b)\,g d} \qquad \ldots(1.15\,a)$$

Referring now to Fig. (ii) for capillary depression, the ***depression is given by the balance of downward force, of surface tension and the upward hydrostatic force on the meniscus due to head h*** of the fluid outside the tube ;

$$\pi . d . \sigma \cos\theta = \rho . g . h . \pi \frac{d^2}{4}$$

$$h = 4\sigma \cos\theta / \rho g d.$$

Perfact Gas Law

Let p be the pressure of a gas, v the specific volume, T the absolute temperature and R the gas constant. Then the following equation results from Boyle's-Charles' law:

$$p = \rho RT \qquad \text{or} \qquad pv = RT$$

This equation is called the **equation of state of the gas.** ***A gas subject to this eqn. is called a perfect gas or an ideal gas***. Strictly speaking, all real gases are not perfect gases. However, any gas at a considerably higher temperature than its liquefied temperature may be regarded as approximating to a perfect gas.

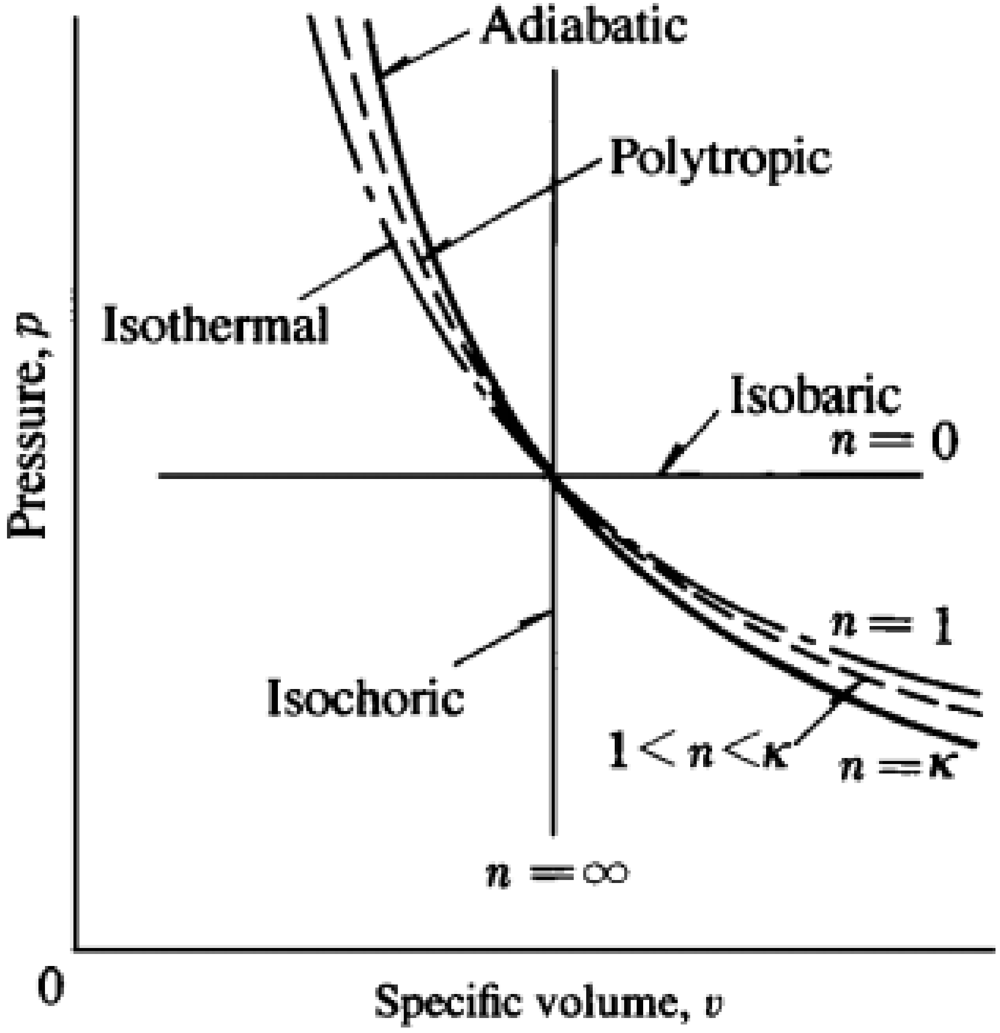


Fig. State change of perfect gas

The change in state of a perfect gas is expressed by the following equation:

$$pv^n = \text{constant}$$

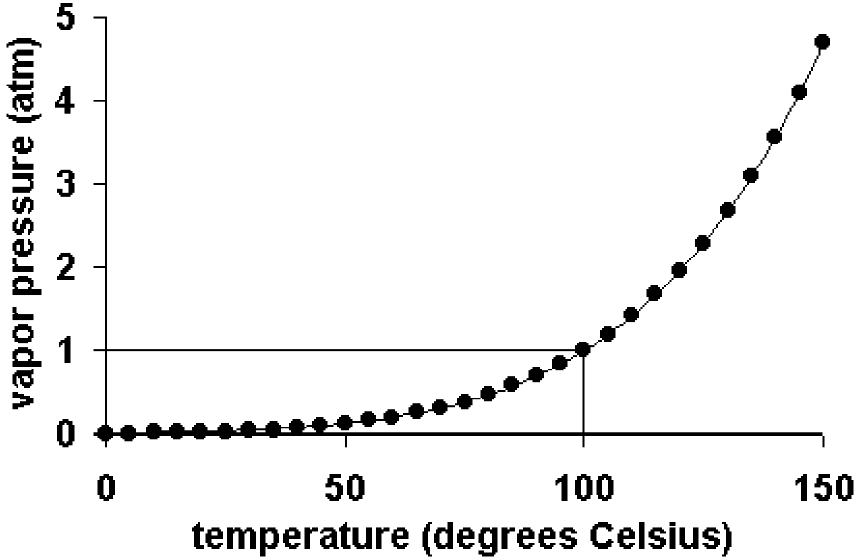
where **n is called the polytropic exponent**.

As **this value changes from 0 to ∞**, as shown in Fig., the state of gas makes five kinds of changes known as ***isobaric***, ***isothermal, polytropic, adiabatic and isochoric*** changes. In particular, in the case of adiabatic change, n = k is obtained. Here **k** is ***the ratio of specific heat at constant pressure c_p, to specific heat at constant volume c_v***, called the ratio of specific heats (isentropic index).

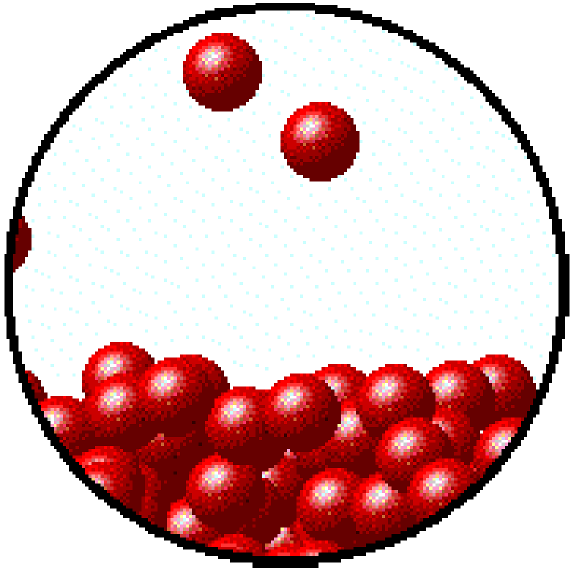
Vapour Pressure

Vapor pressure or equilibrium vapor pressure is defined as the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phases (solid or liquid) at a given temperature at the free surface in a closed system. The equilibrium vapor pressure is an indication of a liquid's evaporation rate. It relates to the tendency of particles to escape from the liquid (or a solid).

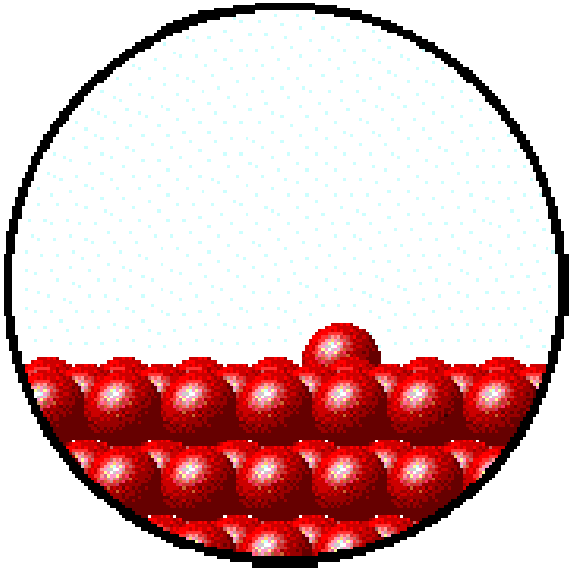
***The phenomenon of vaporization is due to the surface molecules escaping the liquid by overcoming the molecular attractive forces by virtue of their translational momentum*. *Vapor pressure of a liquid increases with its temperature due to increased molecular activity*.**



As the temperature of a liquid increases, the kinetic energy of its molecules also increases. As the kinetic energy of the molecules increases, the number of molecules transitioning into a vapor also increases, thereby increasing the vapor pressure.

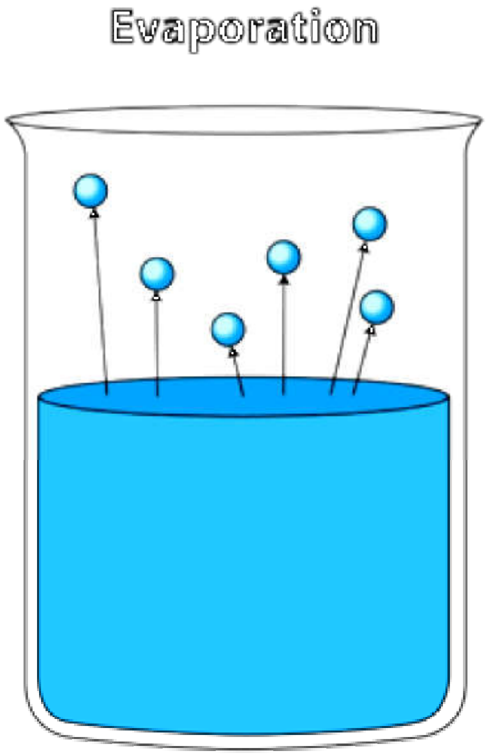


Microscopic equilibrium between gas and liquid. Note that the rate of evaporation of the liquid is equal to the rate of condensation of the gas.



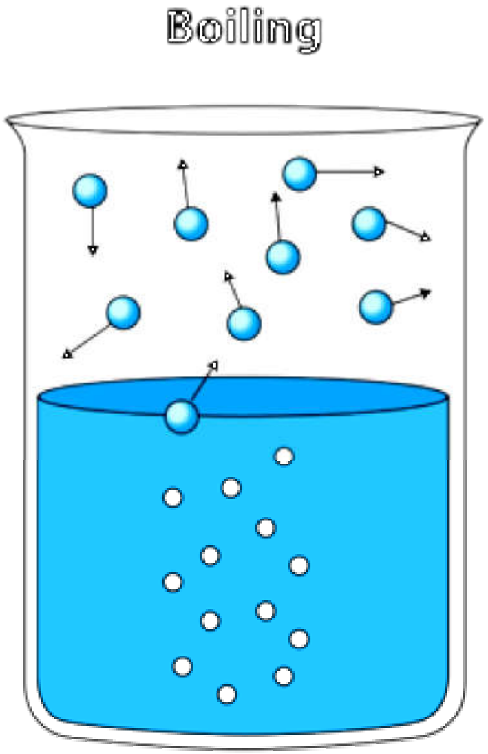
Microscopic equilibrium between gas and solid. Note that the rate of evaporation of the solid is equal to the rate of condensation of the gas.

Do not confuse vapor pressure with ***partial pressure***. ***Partial pressure is defined as the pressure of a gas or vapor in a mixture with other gases***. For example, atmospheric air is a mixture of dry air and water vapor, and atmospheric pressure is the sum of the partial pressure of dry air and the partial pressure of water vapor. The partial pressure of water vapor constitutes a small fraction (usually under 3 percent) of the atmospheric pressure since air is mostly nitrogen and oxygen.


Evaporation

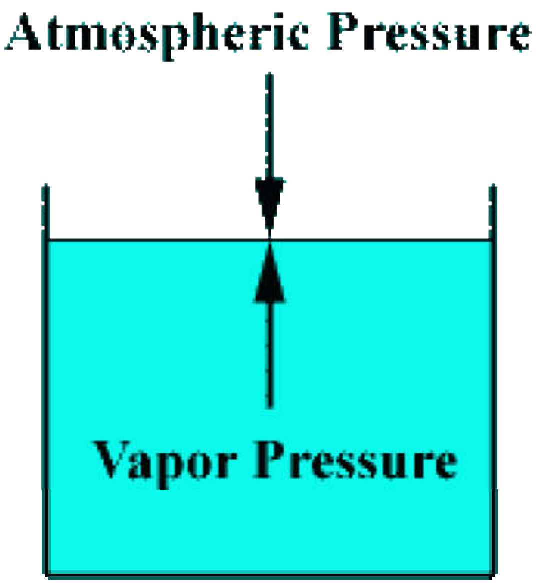
Vapor Pressure < Atmospheric Pressure

Bubbles cannot form


Boiling

Vapor Pressure = Atmospheric Pressure

Bubbles can form and rise



The phenomena of vaporization and boiling are differentiated as follows :

Vaporization: If

Vapour pressure < external pressure (atmospheric) imposed on the liquid surface at that temperature.

Boiling, if

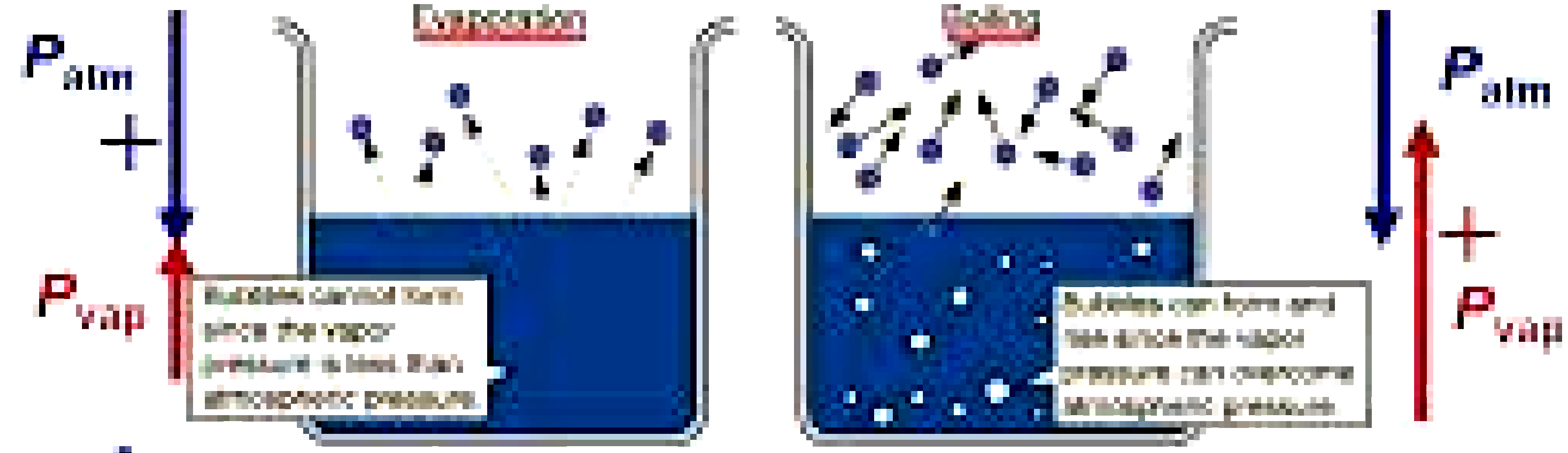
Vapour pressure = external pressure (atmospheric) imposed on the liquid surface at that temperature.

The partial pressure of a vapor must be less than or equal to the vapor pressure if there is no liquid present. However, when both vapor and liquid are present and the system is in phase equilibrium, ***the partial pressure of the vapor must equal the vapor pressure***, and the system is said to be ***saturated***.

The saturation vapor pressure is of great practical use in fluid problems. The reason for our interest in vapor pressure is the possibility of the liquid pressure in liquid-flow systems dropping below the vapor pressure at some locations, and the resulting unplanned vaporization. For example, **water at 10°C will flash into vapor and form bubbles at locations (such as the tip regions of impellers or suction sides of pumps) where the pressure drops below 1.23 kPa**. The **vapor bubbles** (called **cavitation bubbles** since they form "cavities" in the liquid) collapse as they are swept away from the low pressure regions, generating highly destructive, extremely high-pressure waves. This phenomenon, which is a common cause for drop in performance and even the erosion of impeller blades, is called **cavitation**, and it is an important consideration in the design of hydraulic turbines and pumps.

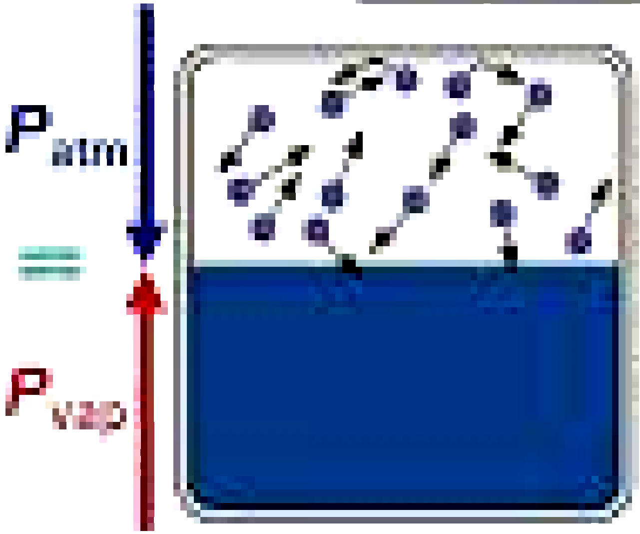
Cavitation must be avoided (or at least minimized) in flow systems since it reduces performance, generates annoying vibrations and noise, and causes damage to equipment. The pressure spikes resulting from the large number of bubbles collapsing near a solid surface over a long period of time may cause erosion, surface pitting, fatigue failure, and the eventual destruction of the components or machinery. The presence of cavitation in a flow system can be sensed by its characteristic tumbling sound.

Evaporation vs Boiling in terms of Vapor Pressure



Bubbles cannot form since the vapor pressure is less than atmospheric pressure.

Bubbles can form and rise since the vapor pressure can overcome atmospheric pressure.



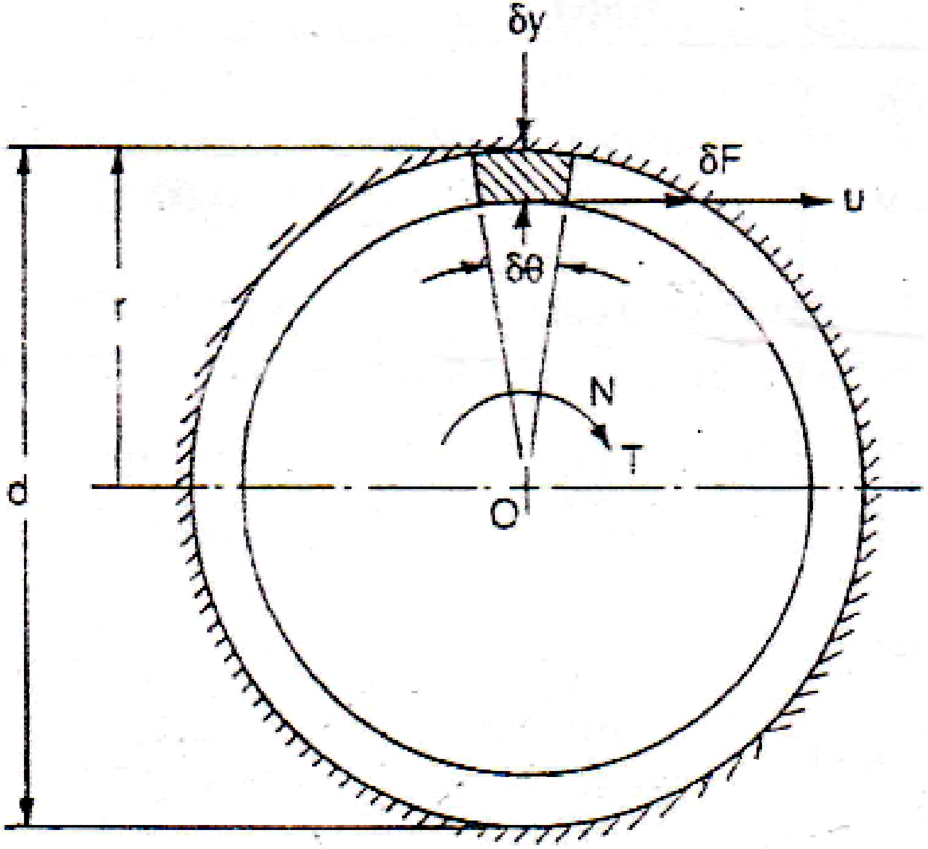
Evaporation which has reached equilibrium with the liquid surface is said to have reached saturation.

Vapor Pressure (v.p. or P_{vap})

- Caused by the tendency of solids & liquids to evaporate to gaseous form. It is temperature (K.E.) dependent.

Problem:

Determine the torque and power required to turn a 10-cm long, 5-cm diameter shaft at 500 revolutions per minute in a 5.1-cm concentric bearing flooded with a lubricating oil of viscosity 100 centipois.



Solution.

Peripheral speed u of the shaft $= \dfrac{\pi d N}{60} = \dfrac{\pi \times 0.05 \times 500}{60} = 1.31$ m/s

Since the bearing is at rest,

$$\delta u = 1.31 - 0 = 1.31 \text{ m/s} \; ; \qquad \delta y = \frac{5.1-5}{2} = 0.05 \text{ cm} = 0.0005 \text{ m}$$

$$\frac{du}{dy} = \frac{1.31}{0.0005} = 2620 \text{ rad/s}$$

$$\mu = 100 \text{ centipoise} = 1 \text{ poise} = 0.1 \text{ N s/m}^2$$

Shear stress $\tau = \mu \frac{du}{dy} = 0.1 \times 2620 = 262 \text{ N/m}^2.$

The force δF due to shearing of the fluid over an elementary length $r\,\delta\theta$ in the end-view is given by

$$dF = \tau \,.\, r\,\delta\,\theta \,.\, l = 262 \times \frac{0.05}{2} \times 0.10\,\delta\theta = 0.655\,\delta\theta.$$

The torque δT required to overcome the shearing action is given by

$$\delta T = r\,\delta F = \frac{0.05}{2} \times 0.655\,\delta\theta = 0.01638\,\delta\theta$$

The torque required to turn the shaft is

$$T = \int dT = \int_0^{2\pi} 0.01638\,d\theta = 0.1029 \text{ Nm}$$

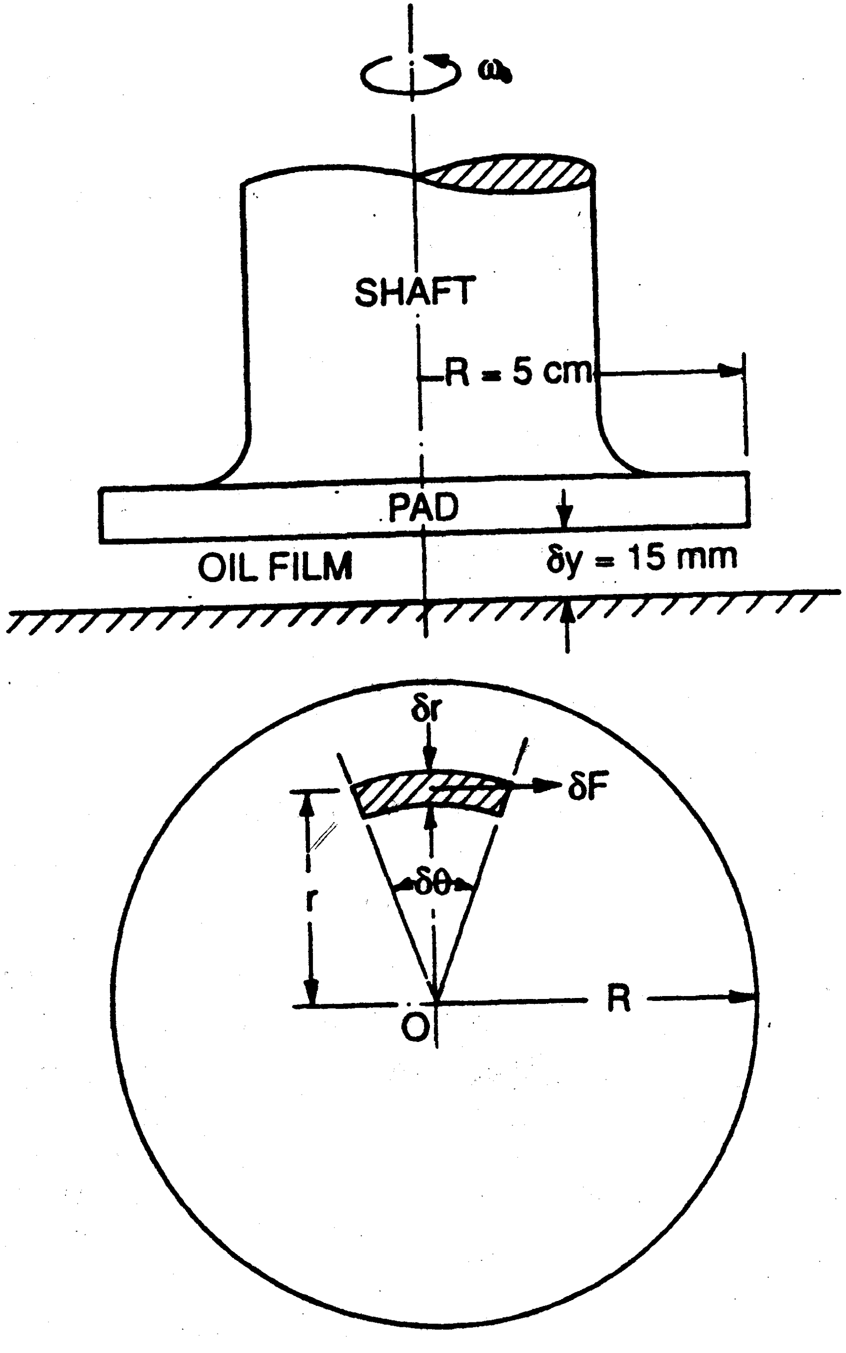
The power required to turn the shaft is given by

$$\text{Power} = T.\omega = 0.102 \times 1.31/0.025 = 5.387 \text{ W}$$

1 pascal second (N.s/m^2) = 1000 centipoise = 10 poise.

Problem:

A thrust bearing consists of a 10-cm diameter pad rotating on another pad separated by an oil film μ = 80cP, by 1.5 mm. Compute the power dissipated in the bearing if it rotates at 100 revolutions per minute.



Thrust Bearing

Solution.

Consider a small element of width δr at a radius r subtending a small angle $\delta\theta$ at the centre of the pad as shown in the plan view. The area of the element is $\delta r \times r\,\delta\theta$.

It experiences a shear force δF due to the shearing action of the fluid contained between the pads.

The rotational speed of the pad is given by

$$\omega = 2\pi \times \frac{100}{60} = 10.47 \text{ rad/s}$$

The linear velocity u at a radial distance r must be

$$u = r\omega = 10.47r \text{ m/s}$$

Since the lower pad is at rest, the velocity gradient

$$\frac{du}{dy} = \frac{10.47r - 0}{0.0015} = 6980r \text{ rad/s}$$

From the data,

$$\mu = 80 \text{ cP} = 0.8 \text{ P} = 0.08 \text{ N s/m}^2$$

The shearing stress at the location of the element must be

$$\tau = \mu\frac{du}{dy} = 0.08 \times 6980r = 558.4r \text{ N/m}^2$$

1 pascal second ($N.s/m^2$) = 1000 centipoise = 10 poise.

and the shearing force δF is given by

$$\delta F = \tau.\delta r\,.\,r\delta\theta = 558.4r^2\,\delta r\,\delta\theta \quad \text{N}$$

The torque δT required to provide the shearing force over the element is

$$\delta T = r.\delta F = 558.4r^3\,\delta r\,\delta\theta \quad \text{Nm}$$

and the total torque on the shaft must be

$$T = \int_0^R \int_0^{2\pi} 558.4r^3\,dr\,d\theta = 2\pi \times 558.4 \int_0^R r^3\,dr$$

$$= 2\pi \times 558.4 \times \frac{R^4}{4} = 2\pi \times 558.4 \times \frac{0.05^4}{4}$$

$$= 0.00548 \text{ Nm}$$

The power dissipated, *i.e.*., the rate of energy lost in the bearing is given by

$$\text{Power} = T.\omega = 0.00548 \times 10.47 = 0.0574 \text{ W.}$$