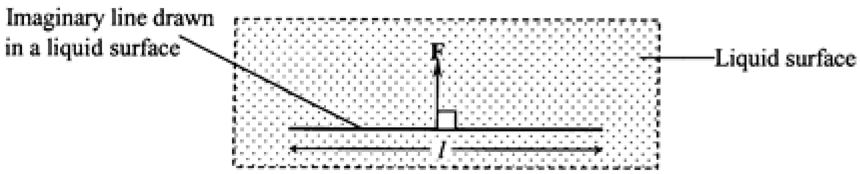
SURFACE TENSION

Consider a liquid surface below



Definition: Surface tension (γ) is the tangential force acting normally on one side of an imaginary line of length one meter drawn in the surface of a liquid

$$\text{Surface tension } (\gamma) = \frac{\text{Force}}{\text{Length}}$$

Dimensions of surface tension.

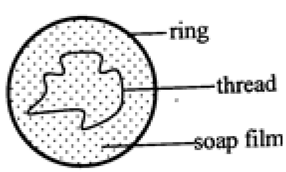
$$[\text{Surface tension}] = \frac{[\text{Force}]}{[\text{Area}]} = \frac{MLT^{-2}}{L}$$

$$[\gamma] = MT^{-2}$$

The S.I unit of γ is Nm^{-1} or kgs^{-2}

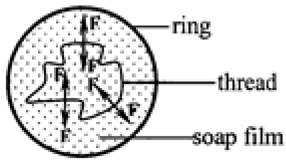
Common observations that are explained by surface tension

1. A drop of water may remain clinging on to the tap for some time before falling as if the water particles were held in a bag.
2. Mercury forms spherical droplets when spilt on glass.
3. Rain drops are spherical due to surface tension.
4. Formation of soap bubbles and films. Consider a thread placed on a soap film which is supported by a ring as shown below.

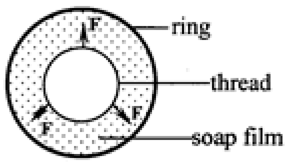


You are required to copy the notes in your mechanics book after writing the notes for elasticity.

There are equal and opposite forces (surface tensional forces) on each side of the thread and therefore the thread stays where it has been placed.



However if the soap film is broken in the middle of the loop in the region bounded by the thread, there are no more forces inside the thread, and so the only forces acting on it are outward.

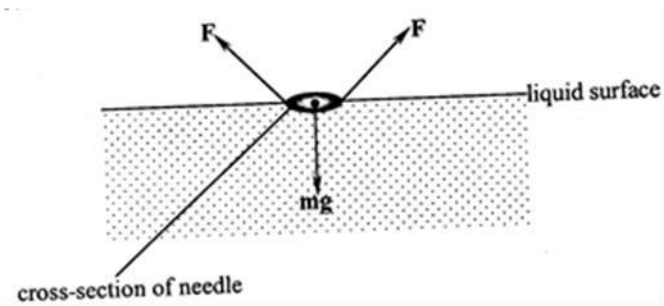


As a result, the thread is pulled into a circle.

Therefore, surface tension is a property which makes a free liquid surface act like a stretched skin/elastic membrane. Surface tension is due to intermolecular attraction in the liquid surface and it's these forces that produce a stretched skin effect on the surface.

5. Some insects such as pond skaters are able to walk over the surface of the water without getting wet.

6. A steel needle can be made to float on water despite its greater density.



The floating needle creates a depression in the liquid surface so that the surface tensional forces, F which act in the surface now have upward directed components which are capable of supporting the weight of the needle.

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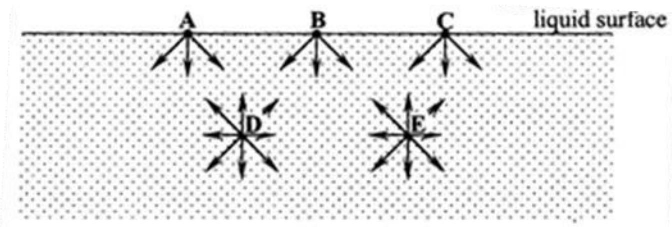
N.B: The value of surface tension does not increase with increase in surface area since more molecules enter the surface layer keeping the molecular separation constant hence surface tension. However, increase in molecular separation will increase the attractive force between the molecules hence surface tension.

Molecular theory explanation of surface tension

Consider a liquid shown below



Molecules in the bulk of the liquid such as D and E are surrounded by equal number of molecules on all sides. As a result they are attracted equally in all directions by the surrounding molecules. The average distance of these molecules is such that attractive and repulsive forces on such molecules balance. So the net force on these molecules is equal to zero.

Molecules in the liquid surface such as A, B and C have fewer vapour molecules above than the liquid molecules below. The resultant attractive force on such molecules acts downwards.

On the other hand, molecules in the liquid surface are more widely spaced than the molecules in the bulk. Since the intermolecular attraction increases with separation between the molecules, the molecules in the surface attract each other with a greater force. This puts the surface molecules in a state of tension hence behave like an elastic skin a phenomenon called surface tension.

In terms of energy

Molecules in the liquid surface have potential energy because if they were to be moved to infinity, a definite amount of work is needed to overcome the net inward force on the molecules due to those below them.

Molecules in the bulk of the liquid form bonds with more neighbours than those in the surface. Work must be done to break these bonds to bring such a molecule into the surface.

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Molecules in the surface of the liquid have more potential energy than those in the bulk. For a system in stable equilibrium, its potential energy is minimum. For a liquid to minimize its potential energy, the number of higher energy surface molecules must be minimized. The minimized number of surface molecules results in a minimum area a phenomenon called surface tension.

Surfactants

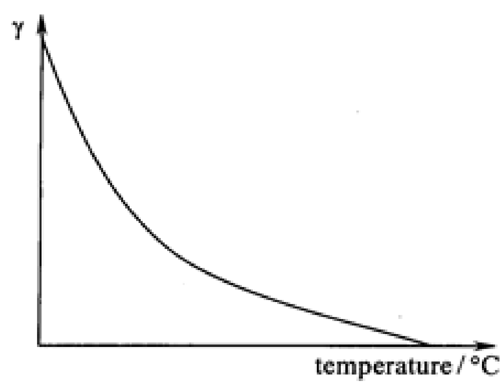
These are substances that reduce the surface tension e.g impurities, detergents and temperature.

Factors affecting surface tension

Temperature. When the temperature of a liquid increases, the mean kinetic energy of the molecules of the liquid increases. The forces of attraction between the molecules will decrease since the molecules spend less time in the neighborhood of a given molecule hence surface tension decreases with increase in temperature.

N.B: At the boiling point, the surface tension of the liquid becomes zero and maximum at the freezing point.

A graph of surface tension against temperature.



Impurities. The molecules of the impurity get in the spaces between the liquid molecules and this reduces the cohesive forces between the liquid molecules. This reduces the surface tension of the liquid.

Calmness of the liquid surface. When the liquid surface is calm, the surface tension is high due to high intermolecular attraction whereas when the liquid surface becomes turbulent, the intermolecular forces are reduced and thus surface tension.

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Experiment to show that surface tension of a liquid decreases with increase in temperature

Procedure

Lycopodium powder or some light dust is sprinkled on the surface of water in a flat metal dish. One side of the dish is heated for some time and observations are made.

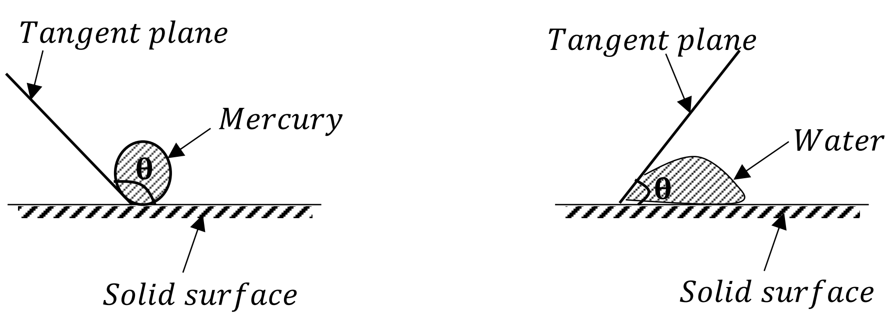
It is observed that the particles of the powder are swept away from the heated part, implying that the surface tensional forces can longer hold the particles in their previous positions.

This shows that surface tension of liquids decreases with increase in temperature.

Explain why when a drop of methylated spirit (soap solution) is dropped into the centre of a dish of water whose surface has been sprinkled with lycopodium powder, the powder rushed out to the sides leaving a clear patch.

This is due to the surface tension of water being greater than that of methylated spirit (soap solution) causing an imbalance between the surface tension forces at the boundary of the two liquids. The powder is thus carried away from the centre by water.

ANGLE OF CONTACT

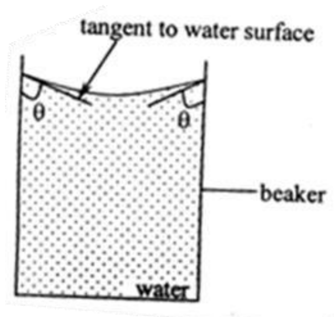


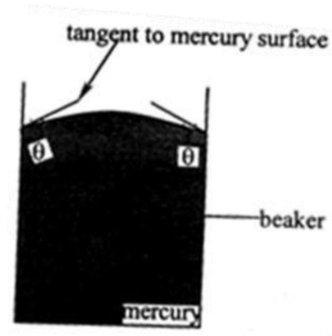
Angle of contact:

This is the angle between the solid surface and the tangent plane at the point of intersection of the liquid surface and the solid surface measured through the liquid.

(OR)

When water is poured in a clean beaker or a capillary tube, the meniscus curves upwards (concave), whereas for mercury the meniscus curves downwards (convex).





Angle of contact is the angle between the solid surface and the tangent to the meniscus at the point where it touches the liquid, and measured through the liquid.

For water, θ is acute, i.e. less than 90^0. This is due to the fact that the adhesion forces between the liquid **and** the solid surface are greater than the cohesion forces between the liquid molecules.

For mercury, θ is obtuse, i.e. $90^0 < \theta < 180^0$. This due to the fact that the cohesion forces between the liquid molecules are greater than the adhesion forces between the liquid molecules and the solid surface.

Factors affecting magnitude of angle of contact

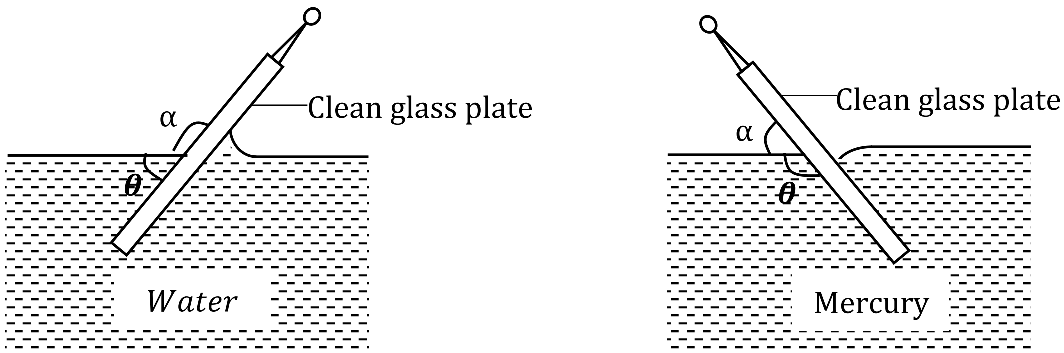
1. Nature of the liquid,
2. Nature of the surface of the container (solid surface),
3. Impurities of the liquid.

NOTE:

1. Liquids with acute angles of contact such as water rise in a capillary tube, and for the same reason, they spread over and wet a clean glass surface when split on it.
2. On the other hand liquids with obtuse angles of contact such as mercury are depressed in a capillary tube. For the same reason, mercury gathers itself into spherical drops when spilt on a clean glass surface. It therefore does not wet the glass.

3. Water has **zero angle of contact** when with clean glass surface. This is because the adhesive forces are so much greater than the cohesive forces and the water surface is parallel to the glass where it meets it.

Experiment to determine angle of contact



A clean glass plate with a provision of adjusting its angle of inclination on the liquid surface is dipped into the liquid under investigation.

The glass plate is tilted until the liquid surface on one side of the plate is horizontal up to the line of contact.

The angle, α between the glass plate and the liquid surface is measured by means of a protractor, suitably placed against the edge of the plate.

The angle of contact, θ is obtained from $\theta = 180 - \alpha$

CAPILLARITY

When a capillary tube is immersed in a beaker with water, the water rises in the tube to a height above the surface due to surface tension. The narrower the tube, the greater the height. This is due to the fact that the adhesive forces between water molecules and glass molecules are greater than the cohesive forces between the water molecules. The water therefore rises up the tube so that more water molecules are in contact with the glass, and a concave meniscus is formed.

When on the other hand the capillary tube is placed inside mercury, the liquid is depressed below the outside mercury level. The depression decreases as the diameter of the capillary tube increases.

This is because the cohesive forces between mercury molecules are greater than the adhesive forces between the mercury and the glass molecules. Mercury therefore sinks down the tube such that more mercury molecules remain together, and a convex meniscus is formed.

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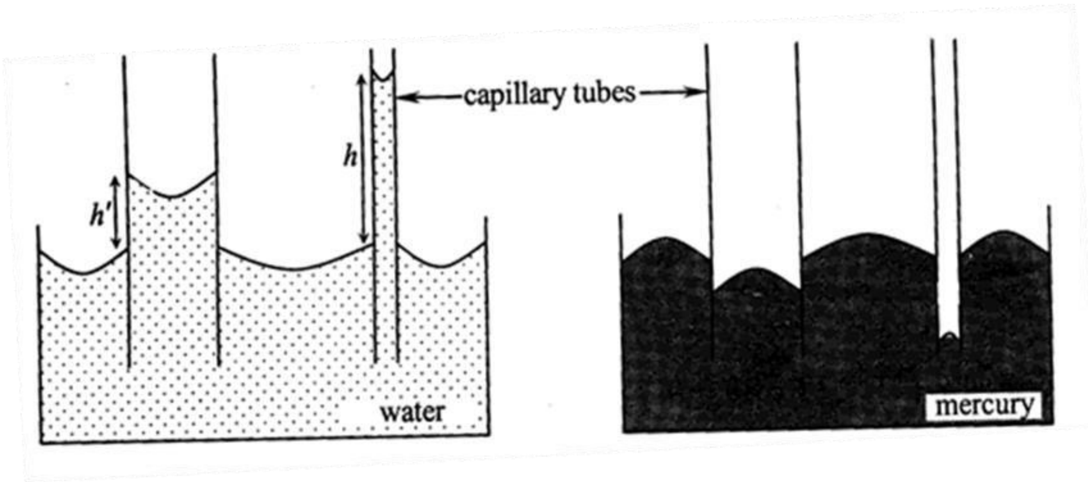


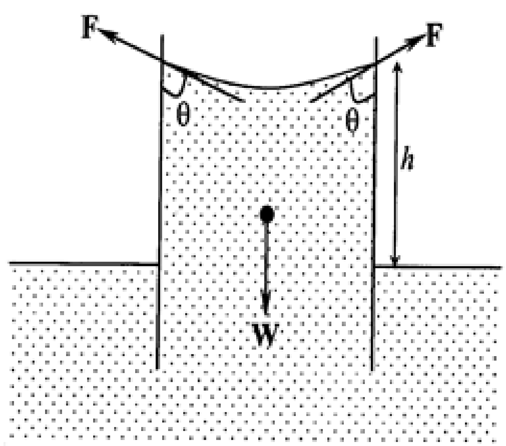
Definition: Capillarity is the rise or fall of a liquid in a narrow tube.

Tube of insufficient length

If a capillary tube of insufficient length is put in a liquid, the liquid rises to the top of the tube, the meniscus changes its shape until an equilibrium at a smaller height is reached, and the meniscus acquires a new radius of curvature.

Derivation of an expression for h

Suppose a capillary tube of radius, r is dipped into a liquid of density, ρ and surface tension, γ Consider a liquid which rises up in a clean glass capillary tube, the liquid stops rising when the weight of the raised column acting vertically downwards equals the vertical component of the upward forces exerted by the tube on the liquid.



At equilibrium, $F\cos\theta = mg$ but $m = \rho \times V$ and $\gamma = \dfrac{F}{2\pi r} \Rightarrow F = 2\pi\gamma r$

$$2\pi r\gamma\cos\theta = \rho \times V \times g \quad \text{but} \quad V = \pi r^2 h$$

$$2\pi r\gamma\cos\theta = \rho \times \pi r^2 h \times g$$

$$2\gamma\cos\theta = \rho r h g$$

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

Note: if θ is acute, then cos θ is positive and therefore h is positive, implying that the liquid rises up in the tube. If θ is obtuse, $cos\theta$ is negative and therefore h is negative, implying that the liquid falls in the capillary tube, below the level of the surrounding.

If $\theta = 0^0$ like for water, $h = \frac{2\gamma}{\rho r g}$

Examples

1. A capillary tube of diameter 0.4mm is placed vertically inside the liquid. Calculate the height to which liquid rises in the tube if;

   i) A liquid of density 800kgm^{-3} and surface tension 0.05Nm^{-1} angle of contact 30^0,

   ii) Mercury of angle of contact 139^0 and surface tension 0.52Nm^{-1}.

$$d = 0.4mm \quad \Rightarrow r = 2.0\times10^{-4}m$$

(i) $\gamma = 0.05\text{Nm}^{-1}$, $\theta = 30^0$

$$h = \frac{2\gamma\cos\theta}{\rho g r} = \frac{2\times0.05\times\cos30^0}{800\times9.81\times2.0\times10^{-4}} = 0.055175m$$

(ii) $\gamma = 0.52\text{Nm}^{-1}$, $\theta = 139^0$, $\rho = 13600\text{kgm}^{-3}$

$$h = \frac{2\gamma\cos\theta}{\rho g r} = \frac{2\times0.05\times\cos139^0}{13600\times9.81\times2.0\times10^{-4}} = -0.0294m$$

The negative sign just means a depression.

2. The internal diameter of the glass tube of mercury barometer is $3.5mm$. The barometer reads 752.4mm . Find the correct reading of the barometer after allowing for the error due to

surface tension. (angle of contact between mercury and glass is 140^0, surface tension of mercury is $0.52Nm^{-1}$, density of mercury is $13600kgm^{-3}$)

The fall, $h = \frac{2\gamma\cos\theta}{\rho gr}$

$$h = \frac{2 \times 0.52 \times \cos 140^0}{13600 \times 9.81 \times (1.75 \times 10^{-3})} = -3.41 \times 10^{-3} m = -3.41mm$$

$$\text{Correct reading of the barometer} = 752.4 + 3.41 = 755.81\text{mmHg}$$

N.B: The negative sign indicates that the barometer reading is lower by 3.41mm.

3. Water is placed in a clean glass tube of radius 0.0005m . If the density of water is 1000kgm^{-3} and the surface tension 0.073Nm^{-1} , calculate the height to which water rises.

$$h = \frac{2\gamma}{\rho gr} = \frac{2 \times 0.073}{1000 \times 9.81 \times 0.0005} = 0.0298m$$

4. Water is placed in a clean glass tube of radius 0.0002m. if the density of water is 1000kgm^{-3} and water rises to a height of 6.6cm, calculate the surface tension of water.

$$h = \frac{2\gamma}{\rho gr} \quad \Rightarrow \gamma = \frac{h\rho gr}{2} = \frac{(6.6 \times 10^{-2}) \times 1000 \times 9.81 \times 0.0002}{2} = 0.064746\,Nm^{-1}$$

5. Water rises to a height of 10cm in a capillary tube dipped in water. When the same capillary tube is dipped in mercury, it is depressed by 2.60mm. Compare the surface tension of water and mercury. (Density of water$= 1000kgm^{-3}$, Density of mercury $= 13600kgm^{-3}$, angle of contact of water$= 5^0$, angle of contact of mercury$= 135^0$)

For water, $\gamma_w = \frac{h_w \rho_w gr}{2\cos\theta_w}$............................(i)

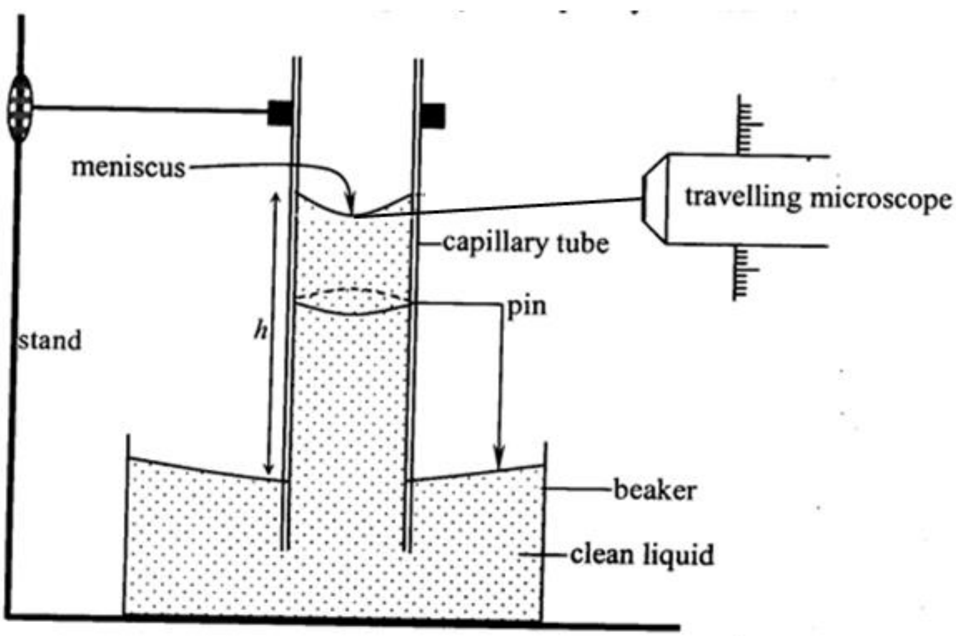
For mercury, $\gamma_m = \frac{-h_m \rho_m gr}{2\cos\theta_m}$............................(ii)

$$\frac{\gamma_w}{\gamma_m} = \frac{\frac{h_w \rho_w gr}{2\cos\theta_w}}{\frac{-h_m \rho_m gr}{2\cos\theta_m}} \quad \Rightarrow \frac{\gamma_w}{\gamma_m} = \frac{h_w \rho_w \cos\theta_m}{-h_m \rho_m \cos\theta_w}$$

$$\frac{\gamma_w}{\gamma_m} = \frac{0.1 \times 1000 \times \cos 135^0}{-2.60 \times 10^{-3} \times 13600 \times \cos 5^0} = 2.01$$

6. The internal diameter of the glass tube of mercury barometer is $2.0mm$. The barometer reads $74.45cmHg$. Find the correct reading of the barometer after allowing for the error due to surface tension. (angle of contact between mercury and glass is 135^0, surface tension of mercury is $3.5 \times 10^{-1} Nm^{-1}$, density of mercury is $13600 kgm^{-3}$)$(74.821 cmHg)$

EXPERIMENT TO MEASURE THE SURFACE TENSION OF A LIQUID BY CAPILLARY TUBE METHOD.



A clean capillary tube which is supported by a retort stand is placed in a beaker containing a clean liquid of known density, ρ and angle of contact, θ

A pin bent at right angles at two places is attached to a capillary tube with a rubber band. The pin is adjusted until its sharp point just touches the horizontal level of the liquid in the beaker.

A travelling microscope is focused on the meniscus and the reading, S_1 on the scale is recorded.

The beaker is removed and the travelling microscope is focused on the tip of the pin. The scale reading, S_2 is recorded.

The height, h of the liquid column is calculated from, $h = |S_1 - S_2|$

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The diameter of the capillary tube, and hence its radius, r are measured using the travelling microscope.

The surface tension, γ of the liquid is calculated from; $\gamma = \frac{\rho g r h}{2\cos\theta}$.

NOTE:

It is assumed that the weight of the small quantity of the liquid in the meniscus is negligible, and that temperature remains constant throughout the experiment.

BUBBLES AND DROPS

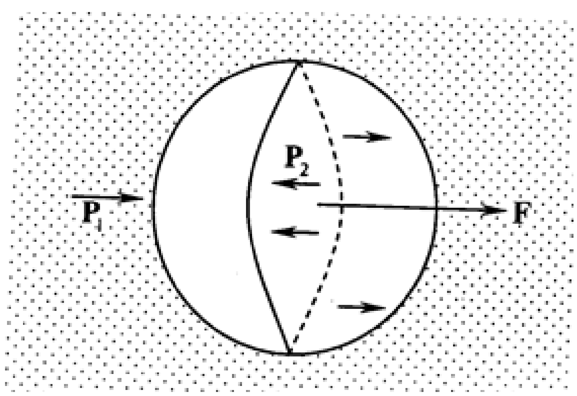
A bubble is a thin sphere of liquid enclosing/containing air or gas or vapour. E.g. air bubbles, soap bubbles etc.…

A drop is a thin sphere containing a liquid.

N.B:

For bubbles and drops, the inside pressure is always greater than the outside pressure otherwise the combined effect of the external pressure and surface tension would cause the bubble or drop to collapse. (Pressure is greater on the concave side of the drop or bubble)

Pressure difference across an air bubble (Excess pressure within an air bubble)



Consider an air bubble of radius r formed inside a liquid of surface tension, γ

In the figure shown F is the surface tensional force, P_1 is the external pressure acting on the bubble, P_2 is the internal pressure acting inside the bubble.

Let the cross sectional area, A of the bubble be $A = \pi r^2$

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$$\gamma = \frac{F}{l} \Rightarrow F = \gamma l \text{ but } l = 2\pi r$$

$$F = 2\pi r\gamma \text{ since it acts around the circumference of the bubble}$$

When the bubble is in equilibrium,

$$\text{Force due to } P_1 + \text{Surface tensional forces} = \text{Force due to } P_2$$

$$P_1 \times A + 2\pi r\gamma = P_2 \times A$$

$$P_1 \times \pi r^2 + 2\pi r\gamma = P_2 \times \pi r^2$$

$$2\gamma = (P_2 - P_1) \times r$$

$$(P_2 - P_1) = \frac{2\gamma}{r}$$

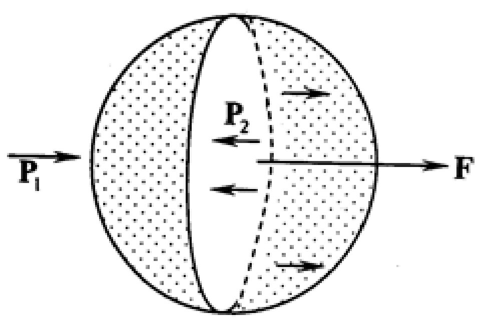
Therefore pressure difference across an air bubble is $\Delta P = \frac{2\gamma}{r}$

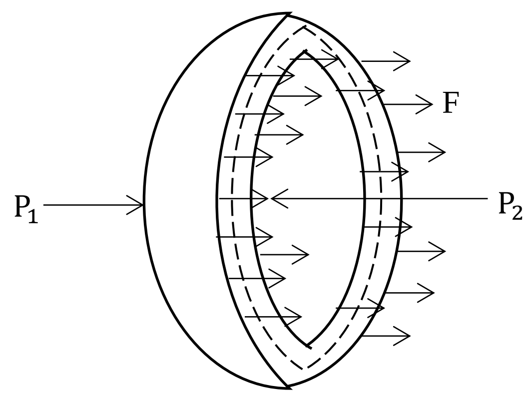
Pressure Difference across a soap bubble in air

A soap bubble has two liquid surfaces in contact with air, one inside the bubble and the other outside the bubble.

Consider a soap bubble of radius, r

Let γ be the surface tension of soap solution





Consider equilibrium of one half, B of the bubble

The surface tensional forces, $F = 2 \times 2\pi r\gamma = 4\pi\gamma r$

If the bubble is in equilibrium,

$$\text{Force due to } P_1 + \text{Surface tensional forces} = \text{Force due to } P_2$$

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$$P_1 \times A + 4\pi\gamma r = P_2 \times A$$

$$P_1 \times \pi r^2 + 4\pi\gamma r = P_2 \times \pi r^2$$

$$(P_2 - P_1) \times r = 4\gamma$$

$$(P_2 - P_1) = \frac{4\gamma}{r}$$

$$\text{Excess pressure, } \Delta P = \frac{4\gamma}{r}$$

N.B:

The excess pressure of bubbles is inversely proportional to the radius of the bubble. This explains why;

(i) **The pressure needed to form a very small bubble is high.**

(ii) One needs to blow hard to start a balloon growing. Once the balloon has grown, less air pressure is needed to make it expand more.

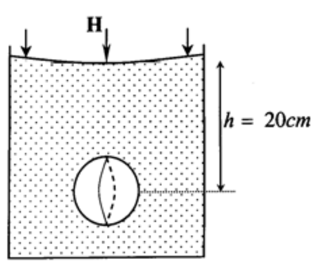
Examples

7. (a) Define the term surface tension and derive its dimensions

(b) Explain using the molecular theory the occurrence of surface tension.

(c) Show that the excess pressure in a soap bubble of radius, r is given by $\Delta P = \frac{4\gamma}{r}$

8. Calculate the pressure inside a spherical air bubble of diameter 0.1cm blown at a depth of 20cm below the surface of a liquid of density $1.26 \times 10^3 kgm^{-3}$ and surface tension $0.064 Nm^{-1}$.(Given: Height of mercury barometer is $76 cmHg$ and density of mercury is $1.36 \times 10^4 kgm^{-3}$)



$$H = (\text{barometric height}) \times \text{density of mercury} \times g$$

$$H = 0.76 \times 1.36 \times 10^4 \times 9.81 = 101396.16 \text{Pa}$$

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Let P_2 = internal pressure P_1 = External pressure

Pressure due to liquid column = h × density of the liquid × g

Pressure due to the liquid column $= 0.2\times1.26\times10^3\times9.81 = 2472.12\text{Pa}$

Total external pressure, $P_1 = 2472.12 + 101396.16 = 103868.28\text{Pa}$

Excess pressure, $P_2 - P_1 = \frac{2\gamma}{r}$

$$P_2 = P_1 + \frac{2\gamma}{r} = 103868.28 + \frac{2\times0.064}{0.05\times10^{-2}}$$

$$P_2 = 103868.28 + 256 = 104124.28\text{Nm}^{-2}$$

9. Calculate the total pressure within an air bubble of radius 0.1mm in water if the bubble is formed 10cm below the water surface given that the surface tension of water is $7.27\times10^{-2}\,Nm^{-1}$, density of water is 1000kgm^{-3} and atmospheric pressure is 1.01×10^5 Pa. $(103435\,Nm^{-2})$

10. A soap bubble has a radius of 0.005m. Calculate the excess pressure in the bubble if the surface tension of soap solution is $2.5\times10^{-2}\,Nm^{-1}$ $(20\,Nm^{-2})$

11. A soap bubble has a radius of 0.001m. Calculate the excess pressure in the bubble if the surface tension of soap solution is $2.5\times10^{-2}\,Nm^{-2}$. $(10\,Nm^{-2})$

12. A soap bubble has a diameter of 4mm. calculate the pressure inside it, if the atmospheric pressure is $10^5\,Nm^{-2}$ and that the surface tension of soap solution is $2.8\times10^{-2}\,Nm^{-1}$.

$$P_2 - P_1 = \frac{4\gamma}{r} \quad \Rightarrow P_2 = P_1 + \frac{4\gamma}{r}$$

$$P_2 = 10^5 + \frac{4\times(2.8\times10^{-2})}{2\times10^{-3}} = 100056\text{ Pa}$$

Pressure difference across a spherical liquid surface

Consider the two situations as illustrated bellow.

The pressure on the concave side of each liquid surface exceeds the pressure on the convex side by $\frac{2\gamma}{r}$ where, r is the radius of curvature of the surface provided the angle of contact is zero.

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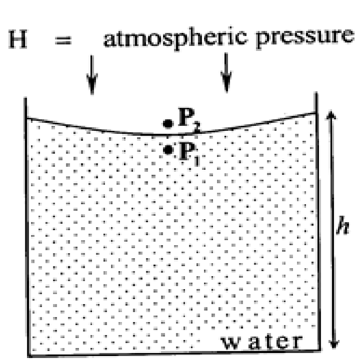
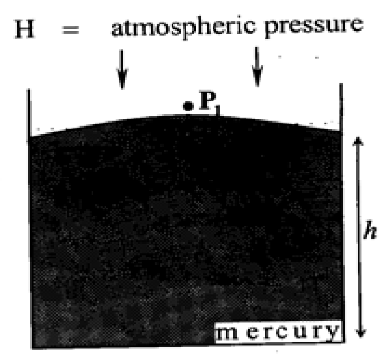




If the angle of contact is θ , the formula is modified as follows.

For water:

$$P_2 - P_1 = \frac{2\gamma\cos\theta}{r} \text{ but } P_2 = H \text{ and } P_1 = H - h\rho g$$

$$H - (H - h\rho g) = \frac{2\gamma\cos\theta}{r}, \quad \Rightarrow h\rho g = \frac{2\gamma\cos\theta}{r}$$

$$\text{If } \theta = 0, \quad h = \frac{2\gamma}{\rho g r}$$

$$\text{If } \theta \neq 0, \quad h = \frac{2\gamma\cos\theta}{\rho g r}$$

For mercury:

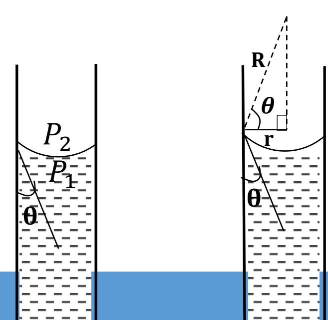
$$P_2 - P_1 = \frac{2\gamma\cos\theta}{r} \text{ but } P_1 = H \text{ and } P_2 = H + h\rho g$$

$$(H + h\rho g) - H = \frac{2\gamma\cos\theta}{r} \quad \Rightarrow h = \frac{2\gamma\cos\theta}{\rho g r}$$

$$\therefore (H + h\rho g) - H = \frac{2\gamma cos\theta}{r} \Rightarrow h = \frac{2\gamma cos\theta}{\rho g\, r}$$

Pressure difference across a liquid meniscus in terms of angle of contact, θ and radius, r of the capillary tube.

Consider a liquid of surface tension, γ which makes an angle of contact θ



You are required to copy the notes in your mechanics book after writing the notes for elasticity.

Let, $\mathrm{R = rsduius\ of\ curvature\ of\ the\ meniscus}$

$\mathrm{r = radius\ of\ the\ cappilary\ tube}$

$$\frac{R}{r} = \cos\theta \quad \Rightarrow \quad R = r\cos\theta \text{.........................(i)}$$

$$P_2 - P_1 = \frac{2\gamma}{R} \text{..(ii)}$$

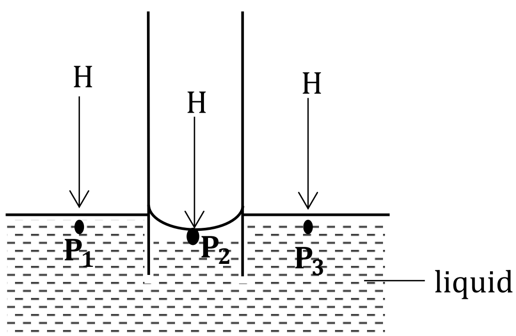
Combining equations (i) and (ii) gives

$$P_2 - P_1 = \frac{2\gamma\cos\theta}{r}$$

Capillary rise or fall by pressure difference method

(a) Capillary rise

Consider a capillary tube of radius, r dipped in a liquid with acute angle of contact, θ with the glass.



P_1, P_2 and P_3 are on the same horizontal level in the liquid.

Outside the tube,

$P_1 = P_3 = H$

Inside the tube,

$H \rangle P_2 \Rightarrow$ The liquid is not at equilibrium, the liquid then rises in the tube to achieve equilibrium

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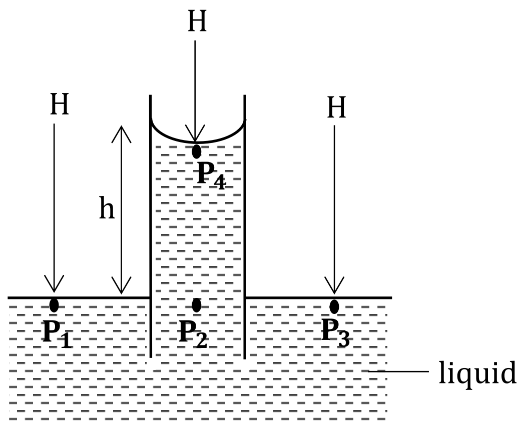


At equilibrium,

$P_1 = P_2 = P_3 = H$..................................(i)

$P_2 = P_4 + h\rho g \quad \Rightarrow \quad H = P_4 + h\rho g$

$P_4 = H - h\rho g$...(ii)

Also, $H - P_4 = \dfrac{2\gamma\cos\theta}{r}$...........................(iii)

Put equation (ii) in equation (iii)

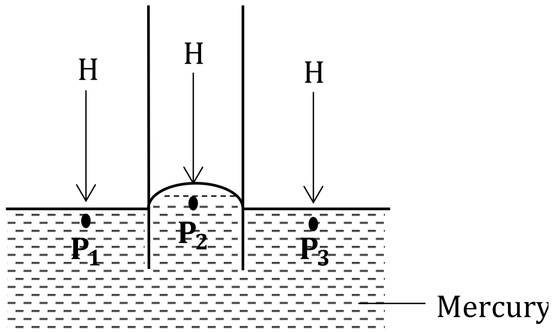
$$H - (H - h\rho g) = \frac{2\gamma\cos\theta}{r} \quad \Rightarrow \quad h\rho g = \frac{2\gamma\cos\theta}{r}$$

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

$\Rightarrow h \alpha \dfrac{1}{r}$. The larger the capillary tube the smaller the rise and vice versa.

(b) Capillary depression

Consider a capillary tube of radius, r dipped in a liquid which makes an obtuse angle of contact, θ with glass.



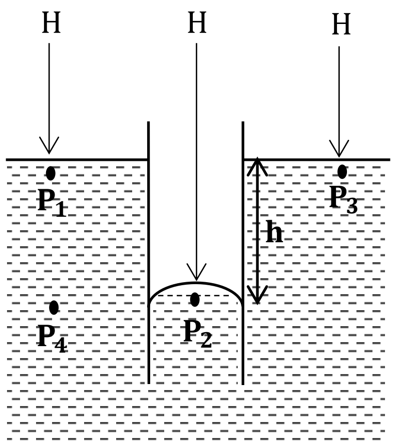
P_1, P_2 and P_3 are on the same horizontal level in the liquid.

Outside the tube,

$P_1 = P_3 = H$

Inside the tube,

$P_2 \rangle H \Rightarrow$ The liquid is unstable. The liquid inside the tube falls to attain equilibrium.



At equilibrium,

$P_1 = P_3 = H$......................................(i)

$P_2 = P_4$..(ii)

$P_4 = h\rho g + P_1$ But $P_4 = P_2$

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$P_2 = h\rho g + H$..(iii)

Also, $P_2 - H = \frac{2\gamma\cos\theta}{r}$........................(iv)

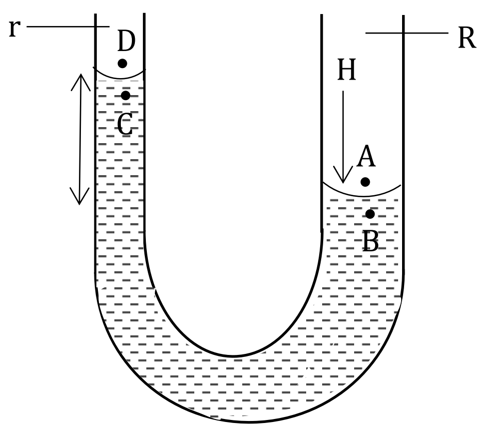
Put equation (iii) in equation (iv) gives

$$(h\rho g + H) - H = \frac{2\gamma\cos\theta}{r}$$

$$h\rho g = \frac{2\gamma\cos\theta}{r} \quad \Rightarrow \quad h = \frac{2\gamma\cos\theta}{\rho g r}$$

Examples

1. A U-tube with limbs of diameter 5.00mm and 2.00mm contains water of surface tension 0.07Nm^{-1} , angle of contact zero and density 1000kgm^{-3} , find the difference in water levels. $(\text{Use } g = 10\text{ms}^{-2})$



For the wider limb.

$$P_A - P_B = \frac{2\gamma}{R} \quad \Rightarrow \quad H - P_B = \frac{2\gamma}{R}$$

$$H - P_B = \frac{2\times 0.07}{2.5\times 10^{-3}} \quad \Rightarrow H - P_B = 56\text{Pa}$$......................(i)

For a smaller limb

$$P_D - P_C = \frac{2\gamma}{r} \quad \Rightarrow H - P_C = \frac{2\times 0.07}{1\times 10^{-3}}$$

$H - P_C = 140\text{Pa}$..(ii)

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But $P_B = P_C + h\rho g \quad \Rightarrow P_B - P_C = h\rho g$....................(iii)

Equation (ii) – Equation (i)

$(H - P_C) - (H - P_B) = (140 - 56) \quad \Rightarrow P_B - P_C = 84Pa$............(iv)

Solving equation (iii) and equation (iv) gives

$$h\rho g = 84 \quad \Rightarrow h = \frac{84}{\rho g} = \frac{84}{1000 \times 10} = 8.4 \times 10^{-3} m = 8.4 mm$$

(OR)

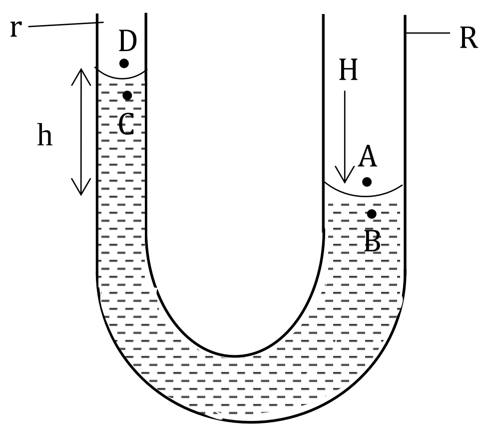
$$P_B = P_C + h\rho g \quad \Rightarrow \quad P_B - P_C = h\rho g$$

$$\left(H - \frac{2\gamma\cos\theta}{R}\right) - \left(H - \frac{2\gamma\cos\theta}{r}\right) = h\rho g$$

$$h = \frac{2\gamma\cos\theta}{\rho g}\left(\frac{1}{r} - \frac{1}{R}\right)$$

$$h = \frac{2 \times 0.07 \times \cos 0}{1000 \times 10}\left(\frac{1}{1 \times 10^{-3}} - \frac{1}{2.5 \times 10^{-3}}\right) = 8.4 \times 10^{-3} m = 8.4 mm$$

2. A U-tube with limbs of diameter 7.0mm and 4.0mm contains water of surface tension $7.0 \times 10^{-2} Nm^{-1}$ angle of contact zero and density $1000 kgm^{-3}$. Find the difference in water levels.



For the wider limb.

$$P_A - P_B = \frac{2\gamma}{R} \quad \Rightarrow \quad H - P_B = \frac{2\gamma}{R}$$

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

$$H - P_B = \frac{2 \times 0.07}{3.5 \times 10^{-3}} \Rightarrow H - P_B = 40\text{Pa}.....................(i)$$

For a smaller limb

$$P_D - P_C = \frac{2\gamma}{r} \Rightarrow H - P_C = \frac{2 \times 0.07}{2 \times 10^{-3}}$$

$$H - P_C = 70\text{Pa}...(ii)$$

But $P_B = P_C + h\rho g \quad \Rightarrow P_B - P_C = h\rho g..................(iii)$

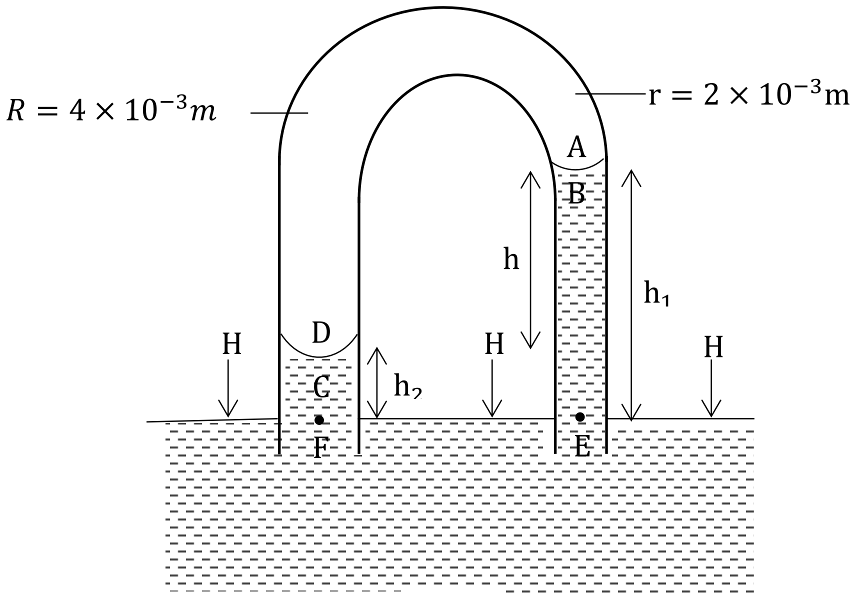
Equation (ii) – Equation (i)

$$(H - P_C) - (H - P_B) = (70 - 40) \quad \Rightarrow P_B - P_C = 30\text{Pa}......(iv)$$

Solving equation (iii) and equation (iv) gives

$$h\rho g = 30 \quad \Rightarrow h = \frac{30}{\rho g} = \frac{30}{1000 \times 9.81} = 3.06 \times 10^{-3} m = 3.06 mm$$

3. A glass U-tube is such that the diameter of one limb is 4.0mm while that of the other is 8.0mm. The tube is inverted vertically with the open ends below the surface of water in a beaker. Given that surface tension of water is 0.072Nm^{-1}, angle of contact between water and glass is zero, and that density of water is 1000kgm^{-3}, what is the difference between the heights to which water rises in the two limbs



For the smaller limb.

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$$P_A - P_B = \frac{2\gamma}{r}$$

$$P_A = P_B + \frac{2\gamma}{r} \text{..(i)}$$

$$P_E = h_1\rho g + P_B \quad \Rightarrow \; H = h_1\rho g + P_B$$

$$P_B = H - h_1\rho g \text{..(ii)}$$

Put equation (ii) in equation (i) gives

$$P_A = H - h_1\rho g + \frac{2\gamma}{r} \text{......................................(iii)}$$

For the wider limb

$$P_D - P_C = \frac{2\gamma}{R} \quad \Rightarrow \; P_D = P_C + \frac{2\gamma}{R} \text{......................(iv)}$$

$$P_F = h_2\rho g + P_C \;\; \text{But} \;\; P_F = H \quad \Rightarrow \; H = h_2\rho g + P_C$$

$$P_C = H - h_2\rho g \text{ ....(v)}$$

Put Equation (v) – Equation (iv) gives

$$P_D = H - h_2\rho g + \frac{2\gamma}{R} \quad \text{But} \;\; P_D = P_A$$

$$H - h_2\rho g + \frac{2\gamma}{R} = H - h_1\rho g + \frac{2\gamma}{r}$$

$$(h_1 - h_2)\rho g = \frac{2\gamma}{r} - \frac{2\gamma}{R} \quad \Rightarrow \; h\rho g = 2\gamma\left(\frac{1}{r} - \frac{1}{R}\right)$$

$$h = \frac{2\gamma}{\rho g}\left(\frac{1}{r} - \frac{1}{R}\right) = \frac{2\times 0.072}{1000\times 9.81}\left(\frac{1}{2\times 10^{-3}} - \frac{1}{4\times 10^{-3}}\right) = 3.6697\times 10^{-3} = 3.67mm$$

(OR)

$$h = \frac{2\gamma\cos\theta}{\rho g}\left(\frac{1}{r} - \frac{1}{R}\right)$$

$$h = \frac{2\times 0.072\cos 0}{1000\times 9.81}\left(\frac{1}{2\times 10^{-3}} - \frac{1}{4\times 10^{-3}}\right) = 3.6697\times 10^{-3} = 3.6697mm$$

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4. A glass tube is such that the diameter of one limb is 3.0mm and that of the other limb is 6.00mm is inverted in water of surface tension 0.01Nm^{-1}. What is the difference in the heights to which water rises in the two limbs? $(h = 0.6796mm)$

5. Mercury is poured into a glass U -tube with vertical limbs of diameters 2.0mm and 12.0mm respectively. If the angle of contact between mercury and the glass is 140^0 and the surface tension of mercury is 0.52Nm^{-1}, calculate the difference in the levels of mercury if the density of mercury is 13600kgm^{-3}.

N.B: For mercury the expression for the fall, h is modified as follows $h = \frac{2\gamma\cos\theta}{\rho g}\left(\frac{1}{\text{R}} - \frac{1}{\text{r}}\right)$

$$h = \frac{2\gamma\cos\theta}{\rho g}\left(\frac{1}{\text{R}} - \frac{1}{\text{r}}\right) = \frac{2\times 0.52\times\cos 140}{13600\times 9.81}\left(\frac{1}{6.0\times 10^{-3}} - \frac{1}{1\times 10^{-3}}\right) = 4.98\times 10^{-3}m = 4.98mm$$

6. A clean glass capillary tube of diameter 0.04cm is held with its lower end dipped in water in the beaker with 12cm of the tube above the liquid surface. Given that the surface tension of water is $7\times 10^{-2}\,Nm^{-1}$ and its density is 1000kgm^{-3},

(i) To what height will water rise in the tube

(ii) What will happen if the tube is now depressed until only 4cm of its length is above the liquid surface.

SURFACE ENERGY (δ)

Surface energy is the work done to increase the area of the liquid surface by 1m^2 under isothermal conditions.

(OR)

Surface tension is the amount of work done (energy required) to produce a fresh surface of liquid film of area 1m^2 under isothermal conditions.

$$\text{Surface energy} = \frac{\text{Work done}}{\text{Change in Area}}$$

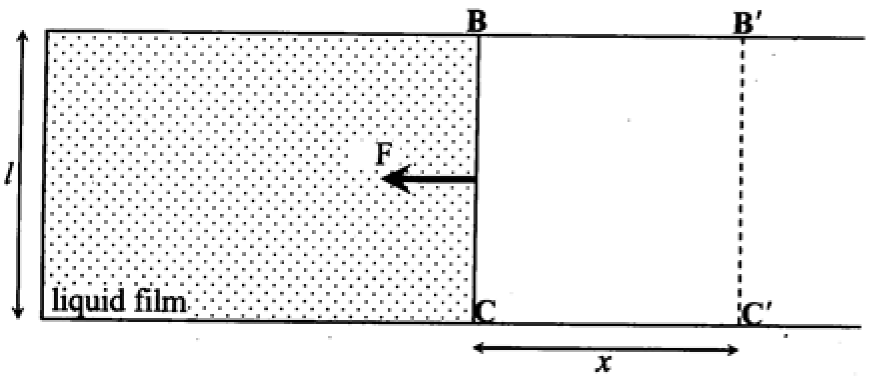
The S.I unit is joules per square metre (Jm^{-2})

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

Relationship between surface tension and surface energy

Consider a liquid film of surface tension, γ stretched across a rectangular wire frame.

Suppose the film is stretched isothermally from BC to B^1C^1 through a distance *x* against the surface tensional force, F so that the surface area of the film increases



Surface tensional force, $F = \gamma l$. However since there are two liquid surfaces in contact with air,

$F = 2 \times (\gamma l) = 2\gamma l$

Work done to stretch the film from BC to $B^1C^1 = (\text{Force}) \times (\text{distance}) = (2\gamma l) \times (x)$

$\text{Work done} = \gamma (2lx)$

But $(2lx) = \text{Change in area} (\Delta A)$

Therefore, $\text{Work done} = \gamma \Delta A$

But Surface energy, $\delta = \dfrac{\text{Work done}}{\text{Change in Area}} = \dfrac{\gamma \Delta A}{\Delta A}$

Surface energy, $\delta = \gamma$

$\therefore$ Surface energy $=$ Surface tension

We can therefore have an alternative definition of surface tension in terms of surface energy as:

Surface tension is the work done to increase the area of a liquid surface by 1m^2 under isothermal conditions.

An alternative S.I unit of surface tension is joules per square metre (Jm^{-2}).

N.B: This work done is stored as surface energy in the liquid film.

$$\text{Work done} = (\text{Surface tension}) \times (\text{Change in Area}) = \gamma \Delta A$$

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

Examples

1. (a) Define surface tension in terms of surface energy.

(b) Calculate the work done against surface tension forces in blowing a soap bubble of diameter 15mm $\left(\text{Surface tension of soap solution} = 0.03\text{Nm}^{-1}\right)$

$$d_1 = 0m,\ d_2 = 15mm = 1.5\times10^{-2}m \Rightarrow r_2 = 7.5\times10^{-3}m$$

$$\text{Iinitial area, } A_1 = 0m^2$$

$$\text{Final area, } A_2 = 2\times4\pi r_2^2 = 2\times4\pi\times\left(7.5\times10^{-3}\right)^2 = 1.414\times10^{-3}m^2$$

$$\text{Change in area, } \Delta A = A_2 - A_1 = 1.414\times10^{-3} - 0 = 1.414\times10^{-3}m^2$$

$$\text{Work done} = (\text{Surface tension})\times(\text{Changein area})$$

$$\text{Work done} = (0.03)\times\left(1.414\times10^{-3}\right) = 4.24\times10^{-5}\text{ J}$$

2. (a)(i) Define surface tension

(ii) Explain the origin of surface tension using molecular theory.

(b) Aspherical drop of mercury of radius 2mm falls to the ground and breaks into 10 drops of equal size.

(i) Calculate the amount of work that has to be done to achieve this.

(ii) What is the minimum speed with which the original drop would have to hit the ground? $\left(\text{Density of mercury} = 13600\text{kgm}^{-3}, \text{Surface tension of mercury} = 0.472\text{Nm}^{-1}\right)$

(b)(i) $R = 2.0\times10^{-3}m$, Let, r be radius of the small drops

$$\text{Volume of the big drop} = \text{Total volume of the small drops}$$

$$\frac{4}{3}\pi R^3 = 10\times\frac{4}{3}\pi r^3 \quad \Rightarrow r = \sqrt[3]{\frac{R^3}{10}}$$

$$r = \sqrt{\frac{\left(2.0\times10^{-3}\right)^3}{10}} = 9.283\times10^{-4}m$$

$$\text{Surface area of the big drop, } A_1 = 4\pi R^2 = 4\pi\times\left(2.0\times10^{-3}\right)^2 = 5.0265\times10^{-5}m^2$$

$$\text{Total surface area of small drops, } A_2 = 10\times4\pi r^2 = 10\times4\pi\times\left(9.283\times10^{-4}\right)^2 = 1.083\times10^{-4}m^2$$

$$\text{Work done} = (\text{surface tension})\times(\text{Change in area}) = \gamma\times(A_2 - A_1)$$

$$\text{Work done} = (0.472)\times\left(\left(1.083\times10^{-4}\right) - \left(5.0265\times10^{-5}\right)\right) = 2.739\times10^{-5}\text{ J}$$

(ii) Kinetic energy of the bg drop before impact = Work done to split the drop into 10 small drops

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$$\frac{1}{2}mv^2 = 2.739\times10^{-5} \Rightarrow v = \sqrt{\frac{(2.739\times10^{-5})\times 2}{m}}$$

But $m = \frac{4}{3}\pi R^3 \times \rho \quad \Rightarrow v = \sqrt{\frac{(2.739\times10^{-5})\times 2\times 3}{4\pi\times R^3\times\rho}}$

$$v = \sqrt{\frac{(2.739\times10^{-5})\times 2\times 3}{4\pi\times(2.0\times10^{-3})^3\times 13600}} = 0.3467\,ms^{-1}$$

3. Calculate the amount of work done in breaking up a drop of water of radius 0.5cm into tiny droplets of water, each of radius 1mm, assuming isothermal conditions. Also determine the number of droplets formed given that the surface tension of water is $7\times10^{-2}\,Nm^{-1}$

$R = 0.5cm = 5\times10^{-3}\,m$ and $r = 1mm = 1\times10^{-3}\,m$

Let n be the number of droplets formed

Volume of the big drop = Total Volume of tiny droplets

$$\frac{4}{3}\pi R^3 = n\times\frac{4}{3}\pi r^3$$

$$(5\times10^{-3})^3 = n\times(1\times10^{-3})^3 \quad \Rightarrow n = 125$$

Therefore, there are 125 droplets.

Surface area of big drop, $A_1 = 4\pi R^2 = 4\pi\times(5\times10^{-3})^2 = 3.14\times10^{-4}\,m^2$

Total surface area of 125 small droplets, $A_2 = 125\times(4\pi r^2) = 125\times4\pi\times(1\times10^{-3})^2 = 1.571\times10^{-3}\,m^2$

Change in area, $\Delta A = A_2 - A_1 = (1.571\times10^{-3}) - (3.14\times10^{-4}) = 1.257\times10^{-3}\,m^2$

Work done = (Surface tension) × (Change in area) = $(7\times10^{-2})\times(1.257\times10^{-3}) = 8.799\times10^{-5}\,J$

4. A liquid drop of diameter 0.5cm breaks up into 27 tiny droplets all of the same size. If the surface tension of the liquid is 0.07Nm^{-1}, calculate the resulting change in energy.

Diameter $= 0.5\text{cm} \Rightarrow \text{R} = 0.25\text{cm} = 2.5\times10^{-3}\text{m}$, $\text{n} = 27$

Let the radius of the tiny droplets be r.

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

$$\text{Volume of the big drop} = \text{Total volume of tiny droplets}$$

$$\frac{4}{3}\pi R^3 = n\times\frac{4}{3}\pi r^3 \quad \Rightarrow r^3 = \frac{R^3}{n}$$

$$r = \sqrt[3]{\frac{R^3}{n}} = \sqrt[3]{\frac{\left(2.5\times10^{-3}\right)^3}{27}} = 8.33\times10^{-4}\,m$$

$$\text{Surface area, } A_1 = 4\pi R^2 = 4\pi\times\left(2.5\times10^{-3}\right)^2 = 7.85\times10^{-5}\,m^2$$

$$\text{Total surface area of small drops} = n\times4\pi r^2 = 27\times4\pi\times\left(8.33\times10^{-4}\right)^2 = 2.35\times10^{-4}\,m^2$$

$$\text{Change in area, } \Delta A = \left(2.35\times10^{-4}\right) - \left(7.85\times10^{-5}\right) = 1.56\times10^{-4}\,m^2$$

$$\text{Work done} = \left(\text{Surface tension}\right)\times\left(\text{Change in surface areea}\right)$$

$$\text{Work done} = \left(7\times10^{-2}\right)\times\left(1.56\times10^{-4}\right) = 1.096\times10^{-5}\,\text{J}$$

$$\text{Change in energy} = \text{Work done} = 1.096\times10^{-5}\,\text{J}$$

5. Calculate the change in surface energy of a soap bubble when its radius decreases from 5cm to 1cm, given that the surface tension of soap solution is $2\times10^{-2}\,Nm^{-1}$.

$$\text{Iniatial area, } A_1 = 2\times4\pi R^2 = 2\times4\pi\times\left(5\times10^{-2}\right)^2 = 6.28\times10^{-2}\,m^2$$

$$\text{Final area, } A_2 = 2\times4\pi r^2 = 2\times4\pi\times\left(1\times10^{-2}\right)^2 = 2.51\times10^{-3}\,m^2$$

$$\text{Change in surface area, } \Delta A = \left(6.28\times10^{-2}\right) - \left(2.51\times10^{-3}\right) = 6.03\times10^{-2}\,m^2$$

$$\text{Work done} = \left(\text{surface tension}\right)\times\left(\text{change in area}\right)$$

$$\text{Work done} = \left(2\times10^{-2}\right)\times\left(6.03\times10^{-2}\right) = 1.206\times10^{-3}\,\text{J}$$

Relationship between surface area and shape of a drop

The area of a liquid surface has the least number of molecules in it under surface tensional forces.

Surface area of a given volume of a liquid is therefore a minimum, and according to mathematics, the shape of a given volume of a liquid with minimum surface area is a sphere.

This is why the meniscus and small droplets of a mercury and rain drops are spherical in shape approximately.

Explain why water dripping out of the tap does so in spherical shapes.

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

For a given volume, a sphere is a shape with minimum surface area, hence minimum surface energy therefore it is the most stable.

Small mercury droplets are spherical while large ones flatten out

A small drop takes on a spherical shape to minimize the surface energy which tends to be greater than the gravitational potential energy. Therefore the gravitational force cannot distort the spherical shape due to the very small mass of tiny droplets.

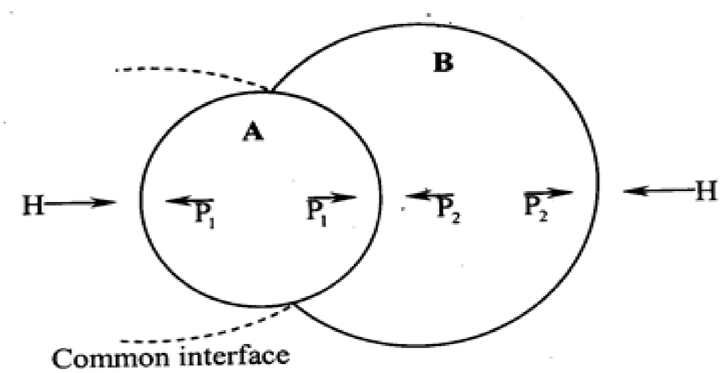
A large drop flattens out in order to minimize the gravitational potential energy, which tends to exceed the surface energy. Due to its large weight, gravitational force distorts the spherical shape of large drops. For the shape of the drop to conform to the principle that the sum of gravitational potential energy and surface energy must be a minimum, the centre of gravity of the drop moves down as much as possible hence flattening.

COMBINED BUBBLES

1. Case 1

Consider two soap bubbles, A and B of radii r_1 and r_2 respectively, where $r_2 \rangle r_1$. If the two soap bubbles come into contact and have a common interface, then the radius of curvature, r of the common interface can be calculated using pressure differences.

Let, γ be the surface tension of soap solution



For A

$$P_1 - H = \frac{4\gamma}{r_1} \quad \Rightarrow \quad P_1 = H + \frac{4\gamma}{r_1} \text{..................(i)}$$

For B

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

$$P_2 - H = \frac{4\gamma}{r_2} \quad \Rightarrow \quad P_2 = H + \frac{4\gamma}{r_2} \text{.....................(ii)}$$

Since the interface is convex towards B, $P_1 > P_2$

Therefore, $P_1 - P_2 = \frac{4\gamma}{r}$.............................(iii)

Substituting for P_1 and P_2 in equation (iii) gives:

$$\left(H + \frac{4\gamma}{r_1}\right) - \left(H + \frac{4\gamma}{r_2}\right) = \frac{4\gamma}{r} \Rightarrow \frac{1}{r_1} - \frac{1}{r_2} = \frac{1}{r}$$

$$\frac{1}{r} = \frac{r_2 - r_1}{r_1 r_2} \quad \Rightarrow \quad r = \frac{r_1 r_2}{r_2 - r_1}$$

$$\text{Pressure difference across the common interface} = \frac{4\gamma}{r} = \frac{4\gamma(r_2 - r_1)}{r_1 r_2}$$

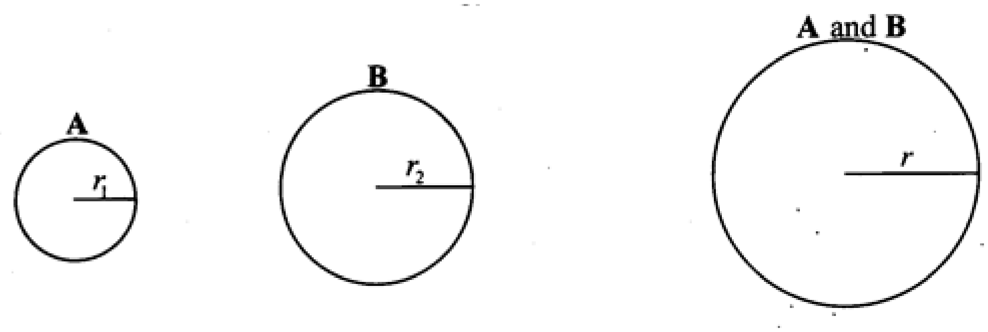
Question.

A soap bubble of radius, r_1 is attached to another bubble of radius, r_2. If r_1 is less than r_2 , show that the radius of curvature of the common interface is $\frac{r_1 r_2}{r_2 - r_1}$.

2. Case 2

Consider two soap bubbles, A and B of radii r_1 and r_2 which come together and coalesce to form a single bubble. To find the radius, r of the resulting soap bubble, we use conservation of surface energy.

Let, γ be the surface tension of soap solution.



For A: $\text{Work done in forming bubble A(Surface Energy)} = 2 \times (4\pi r_1^2) \times \gamma$.........(i)

For B: $\text{Work done in forming bubble B(Surface Energy)} = 2 \times (4\pi r_2^2) \times \gamma$..........(ii)

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

When the bubbles combine to form a bubble of radius, r

$$\text{Work done in forming a new bubble orf radius, r (Surface energy)} = 2\times\left(4\pi r^2\right)\times\gamma\text{......(iii)}$$

By conservation of energy,

$$\text{Original work done} = \text{Work done in forming a new bubble}$$

$$8\pi\gamma r_1^2 + 8\pi\gamma r_2^2 = 8\pi\gamma r^2$$

$$r_1^2 + r_2^2 = r^2 \quad \Rightarrow \quad \mathrm{r} = \sqrt{\left(\mathrm{r}_1^2 + \mathrm{r}_2^2\right)}$$

$$\text{Pressure difference (Excess pressure)} = \frac{4\gamma}{\mathrm{r}} = \frac{4\gamma}{\sqrt{\left(\mathrm{r}_1^2 + \mathrm{r}_2^2\right)}}$$

Examples

1. Two soap bubbles of radii 2cm and 4cm respectively coalesce under isothermal conditions. If the surface tension of the soap solution is $2.5\times10^{-2}\,Nm^{-1}$, calculate the excess pressure inside the resulting soap bubble.

Let, r be the radius of the bubble formed.

$$\text{work done (Surface energy)} = \text{(Surface tension)}\times\text{(Change in area)}$$

By conservation of energy;

$$\text{Original work done} = \text{Work done in forming a new bubble}$$

$$\left(2\times\left(4\pi r_1^2\right)\times\gamma\right) + \left(2\times\left(4\pi r_2^2\right)\times\gamma\right) = \left(2\times\left(4\pi r^2\right)\times\gamma\right)$$

$$r_1^2 + r_2^2 = r^2 \quad \Rightarrow \quad \mathrm{r} = \sqrt{\left(\mathrm{r}_1^2 + \mathrm{r}_2^2\right)}$$

$$\mathrm{r} = \sqrt{\left(2\times10^{-2}\right)^2 + \left(4\times10^{-2}\right)^2} = 0.0447\,m$$

$$\text{Excess pressure} = \frac{4\gamma}{r} = \frac{4\times2.5\times10^{-2}}{0.0447} = 2.237\,Nm^{-2}$$

2. Two soap, A and B of radii 67cm and 10cm respectively coalesce so as to have a portion of their surfaces in common. Calculate the radius of curvature of this common surface and hence the pressure difference if the surface tension of soap solution is $2.8\times10^{-2}\,Nm^{-1}$.

Let r be the radius of curvature of the common interface

$$\mathrm{r} = \frac{\mathrm{r}_1\mathrm{r}_2}{\mathrm{r}_2 - \mathrm{r}_1} = \frac{\left(6.7\times10^{-1}\right)\times\left(1.0\times10^{-1}\right)}{\left(6.7\times10^{-1}\right) - \left(1.0\times10^{-1}\right)} = 0.118\,m$$

You are required to copy the notes in your mechanics book after writing the notes for elasticity.

$$\text{Pressure difference} = \frac{4\gamma}{r} = \frac{4\times 2.8\times 10^{-2}}{0.118} = 0.94915\,Nm^{-2}$$

Exercise

1) A soap bubble of radius 0.03m and another bubble of radius 0.04m are brought together so that they combine. Calculate the radius of curvature of the common interface. $(0.12m)$

2) A soap bubble in vacuum has a radius of 3cm and another soap bubble in vacuum has a radius of 6cm. If the two bubbles coalesce under isothermal conditions, calculate the radius of the bubble formed. $(r = 6.7cm)$

3) (a) How can you measure the angle of contact of a liquid in the laboratory?

(b) Define the term surface tension and deduce its dimensions.

(b) A clean glass capillary tube of diameter 0.04cm is held with its lower end dipped in water in a beaker and with 12cm of the tube above the liquid surface. If the surface tension of water is $7\times 10^{-2}\,Nm^{-1}$ and density of water is 1000kgm^{-3},

(i) to what height will the water rise in the tube.

(ii) what will happen if the tube is now depressed until only 4cm of its length is above the liquid surface.

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