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Laboratory Studies on the Capillarity of Water & Some Selected Liquids

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Abstract: The Laboratory studies on Capillarity of water and some selected liquids involved investigating and analyzing the capillary actions of the liquids.

The result obtained shows that at constant temperature, the potential energy of a capillary risen liquid is constant. The result shows that besides surface tension of a liquid, the density of the liquid is a determining factor of the capillarity of the liquid or its capillary rise in a particular kind of capillary material. Ebukapillarity (i.e False Capillarity) was deduced, hypotheses and Formulas were generated to show the mathematical relation of these and other derived relevant parameters.

Index Items: Capillarity, Capillary Action, Ebukapillarity, Ebukapillary Constant, Ebukapillary Rise, Inter Molecular Energy, Specific Capillary Rise, Specific Ebukapillary Rise, Surface Tension.

INTRODUCTION

1.1 Background

Capillarity is the elevation or depression of the surface of a liquid where it is in contact with a solid such as the sides of a glass tube (The Columbia Encyclopedia, 6th Edition). Starting from the basic, if there is no intermolecular force of attraction between the particles or molecules of a liquid (water), There would be nothing like cohesion (surface tension) or adhesion of the liquid to any solid surface (surface wetting).

If there is no adhesion or cohesion, there would be no surface tension, there would be nothing like capillarity.

The study of physics has made us understand that matter is anything that has weight and can occupy space.

It is known that matter exists in three different states and they are as follows:

Solid state

Liquid state

Gaseous state

They exist in three different states owing to the nature of (intermolecular) forces of attraction holding the individual atoms and molecules of the matter.

The intermolecular (binding) forces existing between the particles of a solid is greater than that of a liquid, so it is very much more difficult to piece (the surface of) a solid with a pen than piecing the surface of a liquid. Although a liquid offers little resistance to the piecing of its surface, this resistance is as a result of the unbalanced intermolecular (cohesion) forces at the surface of the liquid. As the surface particles are been pulled inward, (cohesion), a kind of tensile force is being created at the surface. This force is called the surface tension of the liquid.

Surface tension is a condition existing at the free surface of a liquid, resembling the properties of an elastic skin under tension (R.M 2001). Specifically speaking, the tension is the force per unit length of any straight line on the liquid surface that the surface layers on the opposite sides (inner) of the line exert upon each other. Surface tension alone can support a needle placed horizontally on a liquid surface.

When you place a tiny (small diameter) tube in water, a column of water tends to rise to a height into the tube. This phenomenon is known as capillarity or capillary action (www.wikipedia).

Capillarity depends on the forces created by surface tension and by wetting of the sides of the glass tube (R.M 2001). If the surface of adhesion of the liquid to the solid (wetting) exceeded the force of cohesion within the liquid (surface tension), the surface of the liquid will be concave, and the liquid will rise above the hydrostatic level. This action is typified by water in clean glass tubes (www.wikipedias). If the forces of cohesion exceed the force of adhesion, the surface of the liquid will be convex, and liquid will be repelled from the sides of the tube, that is, it will fall below the hydrostatic level (www.wikipedias). This action is typified by water in greasy glass tubes (in which the adhesion is small) and by Mercury in clean glass tubes (in which the cohesion is great). The attraction of liquid molecules to each other is an example of cohesion. The attraction of a liquid to other materials such as the sides of glass tube, soil or plant root is a type of adhesion. Capillarity action occurs when the attraction of a liquid's molecules to themselves differ from their attraction for a liquid that the liquid contacts (R.M 2001).

The water in the glass tube for instance climbs the tube because water molecules are more attracted to the tube than they are to each other.

Capillarity is demonstrated in the physics lab using a glass tube called a capillary tube and a beaker. A liquid climbs the glass tube when it is dipped in the beaker because the liquid is more attracted to the sides of the glass tube than to itself (www.capillaryaction.wikipedias). Several forces acts on the liquid: The attraction of the liquid molecules to the glass tube, the attraction of the water molecules for each other and the force of gravity, pressing down on the water in the tube. The liquid rises in the tube until all the forces balances. In other word, when a glass capillary tube is placed in a liquid such as water, diesel or kerosene, a concave meniscus forms. Surface tension pulls the liquid column up until there is a sufficient mass of water for gravity to overcome the intermolecular forces. The contact length between the top of the solid column and the tube is proportional to the diameter of the tube, while the weight of the liquid column is proportional to the square of the tubes diameter, so a narrow tube will draw a higher liquid column than a wide tube (Albert Einstein 1901).

Capillary rise of a liquid in a narrow glass tube can be insignificant or small depending on the size of the capillary tube. For the fact the liquid rises to a height in the glass tube, it can be stated that a force (pressure) sucks the liquid up the capillary tube until it is balanced or exactly counteracted by gravity.

1.2 Statement of Problem

This project was necessitated by a lot of desires, in the quest to serve man and better his life through research, analysis, and invention of facts and new technologies that directly or indirectly suites mans activities on earth. The problems that necessitated this project are defined and are listed as follow;

- The need to generate a modified formula that governs or expresses the effects and relationship between the radius of a capillary tube and capillary rise.
- The need to elucidate capillarity through research and experiments and finally come up with hypothesis that could be relevant for Engineering designs for mans benefit.
- To acquire basic and relevant knowledge by further research on capillarity so as to ascertain the possibility of developing useful head from capillary rise.
- The need to generate models for the evaluation and analysis of capillarity in nature.

- The need to carry out research on capillarity which was sensed to be partially unexplored.
- To successfully explain or contribute to the explanation of the natural phenomenon "Capillarity".
- The need to investigate capillarity, evaluate observations from it and unravel possible unknown facts about capillarity.

1.3 Objectives

This project is aimed at demonstrating capillarity using water, kerosene and diesel as the capillary fluids. It also aims at investigating the resulting capillary actions, stating with experimental prove the effects or relationship between the radius of capillary tube with capillary rise and other relevant parameter. The objectives are split as follows:

- To demonstrate capillarity with several diameters of glass tubes (capillary tubes) and beakers, using water, kerosene and diesel respectively as the capillary liquids (mediums) in each case.
- To investigate the resulting capillary actions with respect to observations made, and come up with new or relevant deductions
- To develop some relationship from the results obtained.
- To compare the capillary actions of the liquids used.

1.4 Significance of Study

This project work provides knowledge about capillarity, and which can be relevant for innovations and invention of technologies for the good of man. Science is the building block of technology. Knowledge about the nature of our environment and the activities (natural and artificial) that occurs there in, makes us fit into the environment and device or improvise means of survival almost without limitation. The significance of this study can further be distinguished as follows:

It provides basis for engineering predictions or estimations of capillary effects in nature or such, encountered in the course of an engineering project (task).

The possible hypothesis would serve as standards for relevant engineering designs and fabrications.

The mathematical relations of the effects of capillary action and relevant parameters can be used by engineers in solving engineering problems encountered in the course of designing a capillary related or dependent system.

1.5 Scope of Study

This project does not claim to be entirely a non attempted endeavor.

It only strives to unravel any possible ignorance about capillary, and provide relevant experimental deductions that can serve as a solution or stepping stone to certain engineering quest.

It approaches and demonstrates capillarity from the perspective of just the noticed effects related to the capillarity experiments conducted.

1.6 Limitation of Study

Owing to the lack of desired facilities and time, i could not encompass or investigate capillarity in all ramification proof, why capillary would or would not occur in space.

This project demonstrates capillary action, using glass tube and beaker. Although there are other applications or instances where capillarity occurs, i didn't investigate them so i can compare our observation and come up with a much more generalized deductions.

CHAPTER TWO

LITERATURE REVIEW

2.1 Capillary Action

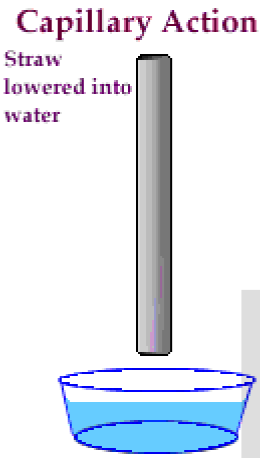
Capillary action, or **capillarity**, is a phenomenon where liquid spontaneously rises in a narrow space such as a thin tube, or in porous materials. This effect can cause liquids to flow against the force of gravity (RM 2001). It occurs because of inter-molecular attractive forces between the liquid and solid surrounding surfaces; If the diameter of the tube is sufficiently small, then the combination of surface tension and forces of adhesion between the liquid and container act to lift the liquid (http://science.jrank.org/pages/1182/Capillary-Action.html). **Capillary action**, **capillarity**, c**apillary motion**, or **wicking** refers to two phenomena:

1. The movement of liquids in thin tubes.
2. The flow of liquids through porous media, such as the flow of water through soil.

Capillarity or capillary action is a phenomenon in which the surface of a liquid is observed to be elevated or depressed where it comes into contact with a solid (R.M 2001). For example, the surface of water in a clean drinking glass is seen to be slightly higher at the edges, where it contacts the glass, than in the middle. Capillarity can be explained by considering the effects of two opposing forces: adhesion, the attractive (or repulsive) force between the molecules of the liquid and those of the container, and cohesion, the attractive force between the molecules of the liquid (adhesion and cohesion). Adhesion causes water to it a glass container and thus causes the water's surface to rise near the container's walls. If there were no forces acting in opposition, the water would creep higher and higher on the walls and eventually overflow the container. The forces of cohesion act to minimize the surface area of the liquid (surface tension); when the cohesive force acting to reduce the surface area becomes equal to the adhesive force acting to increase it (e.g., by pulling water up the walls of a glass), equilibrium is reached and the liquid stops rising where it contacts the solid. In some liquid-solid systems, e.g., mercury and glass or water and polyethylene plastic, the liquid does not it the solid, and its surface is depressed where it contacts the solid. Capillarity is one of the causes of the upward flow of water in the soil and in plants.

A common apparatus used to demonstrate the first phenomenon is the *capillary tube*. When the lower end of a vertical glass tube is placed in a liquid such as water, a concave meniscus is formed. Surface tension pulls the liquid column up until there is a sufficient mass of liquid for gravitational forces to overcome the intermolecular forces. The contact length (around the edge) between the top of the liquid column and the tube is proportional to the diameter of the tube, while the weight of the liquid column is proportional to the square of the tube's diameter (Albert Einstein 1901), so a narrow tube will draw a liquid column higher than a wide tube. When a glass tube of small internal diameter is inserted into water, the surface water molecules are attracted to the glass and the water level in the tube rises. The narrower the tube, the higher the water rises. The water is said to "it" the tube. Water will also be drawn into the fibers of a towel, even if the toil is in a horizontal position. Conversely, if a glass tube is inserted into mercury, the level of the liquid in the tube falls. The mercury does not it the tube. Capillarity is caused by the difference in attraction of the liquid molecules to each other and the attraction of the liquid molecules to those of the tube.

Fig 2.1



Surface tension is related to the cohesive properties of water. Capillary action however, is related to the adhesive properties of water. You can see capillary action 'in action' by placing a straw into a glass of water. The water 'climbs' up the straw. What is happening is that the water molecules are attracted to the straw molecules. When one water molecule moves closer to the straw molecules the other water molecules (which are cohesively attracted to that water molecule) also move up into the straw. Capillary action is limited by gravity and the size of the straw. The thinner the straw or tube the higher up capillary action will pull the water.

Plants take advantage of capillary action to pull water from the soil into them. From the roots water is drawn through the plant by another force, transpiration.

In hydrology, capillary action describes the attraction of water molecules to soil particles. Capillary action is responsible for moving groundwater from it areas of the soil to dry areas. Differences in soil potential (Ψ_m) drive capillary action in soil.

2.1.1 Applications of Capillarity

Capillary action is also essential for the drainage of constantly produced tear fluid from the eye. Two canaliculi of tiny diameter are present in the inner corner of the eyelid, also called the lachrymal ducts; their openings can be seen with the naked eye within the lacrymal sacs when the eyelids are averted.

Wicking is to absorb something and then drain like a wick. Paper toils absorb liquid through capillary action, allowing a fluid to be transferred from a surface to the toil. The small pores of a sponge act as small capillaries, causing it to absorb a comparatively large amount of fluid. Some modern sport and exercise fabrics use capillary action to "wick" sweat away from the skin. These are often referred to as wicking fabrics, after the capillary properties of a candle and lamp wicks.

Capillary action is observed in thin layer chromatography, in which a solvent moves vertically up a plate via capillary action. Dissolved solutes travel with the solvent at various speeds depending on their affinity for the solvent (the mobile phase) or the absorbent coating on the plate (the stationary phase).

With some pairs of materials, such as mercury and glass, the intermolecular forces within the liquid exceed those between the solid and the liquid, so a convex meniscus forms and capillary action works in reverse.

2.1.2 Miscellaneous

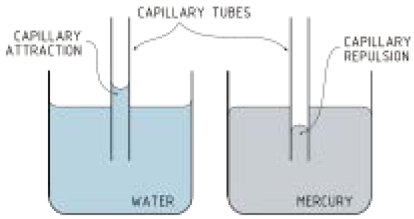


Fig 2.2

1. The height h of a liquid column is given by (http://science.jrank.org/pages/1182/Capillary-Action.html)

$$h = \frac{2\gamma \cos\theta}{\rho g r} \quad \text{...(1)}$$

where:

- γ is the liquid-air surface tension (energy/area)
- θ is the contact angle
- ρ is the density of liquid (mass/volume)
- g is acceleration due to gravity (length/time^2)
- r is radius of tube (length).

For a water-filled glass tube in air at sea level, using SI units:

γ is 0.0728 J/m^2 at 20 °C

θ is 20° (0.35 rad)

ρ is 1000 kg/m^3

g is 9.8 m/s^2

Therefore, the height of the water column is given by:

$$h \approx \frac{1.4 \times 10^{-5}}{r} \text{ m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Thus for a 2 m (6.6 ft) diameter tube, the water would rise an unnoticeable 0.014 mm (0.00055 in). However, for a 2 cm (0.79 in) diameter tube, the water would rise 1.4 mm (0.055 in), and for a 0.2 mm (0.0079 in) diameter tube, the water would rise 140 mm (5.5 in) (http://science.jrank.org/pages/1182/Capillary-Action.html).

Albert Einstein's first paper submitted in 1900 to Annalen der Physik was on capillarity. It was titled *Folgerungen aus den Capillaritätserscheinungen*, which was translated as *Conclusions from the capillarity phenomena*, found in volume 4, page 513 (published in 1901).

2.2 SURFACE TENSION

Surface tension is a property of the surface of a liquid. It is what causes the surface portion of liquid to be attracted to another surface, such as that of another portion of liquid (as in connecting bits of water or as in a drop of mercury that forms a cohesive ball) (John W. M. Bush (May 2004). Surface tension is defined as the tensile force acting on the surface of a liquid in contact with a gas or on the surface between two immiscible liquids such that contact surface behaves like a membrane under tension.

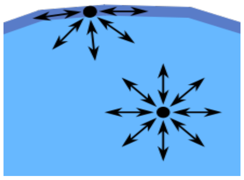


Fig2. 3

Surface tension is caused by cohesion (the attraction of molecules to like molecules). Since the molecules on the surface of the liquid are not surrounded by like molecules on all sides, they are *more attracted* to their neighbours on the surface (Harvey E. (1948).

Applying Newtonian physics to the forces that arise due to surface tension accurately predicts many liquids behaviour. Applying thermodynamics to those very same forces further predicts other more subtle liquid behaviours.

Surface tension has the dimension of force per unit length, or energy per unit area. The two are equivalent—but when referring to energy per unit of area, people use the term surface energy—which is a more general term in the sense that it applies also to solids and not just liquids.

The cohesive forces among the liquid molecules are responsible for the phenomenon known as surface tension. In the bulk of the liquid, each molecule is pulled equally in every direction by neighbouring liquid molecules, resulting in a net force of zero. The molecules at the surface do not have other like molecules on all sides of them and consequently they cohere more strongly to those directly associated with them on the surface. This forms a surface "film" which makes it more difficult to move an object through the surface than to move it when it is completely submerged.

Surface tension is responsible for the shape of liquid droplets. Although easily deformed, droplets of water tend to be pulled into a spherical shape by the cohesive forces of the surface layer. The spherical shape minimizes the necessary "wall tension" of the surface layer according to Laplace's law.

Another way to view it is that a molecule in contact with a neighbour is in a lower state of energy than if it was not in contact with a neighbour. The interior molecules all have as many neighbours as they can possibly have. But the boundary molecules have fewer neighbours than interior molecules and are therefore in a higher state of energy. For the liquid to minimize its energy state, it must minimize its number of boundary molecules and must therefore minimize its surface area (Walter J. (1962)).

As a result of surface area minimization, a surface will assume the smoothest shape it can (mathematical proof that "smooth" shapes minimize surface area relies on use of the Euler–Lagrange equation). Since any curvature in the surface shape results in greater area, a higher energy will also result. Consequently the surface will push back against any curvature in much the same way as a ball pushed uphill will push back to minimize its gravitational potential energy("Sessile Drop Method". Dataphysics. http://www.dataphysics.de/english/messmeth_sessil.htm. Retrieved 2007-09-08).

2.2.1 Effects of Surface Tension

Fig2. 4

Water beading on a leaf

Fig 2.5

Water dripping from a tap

Fig 2.6

Water Striders

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

- Beading of rain water on the surface of a waxed automobile. Water adheres iakly to wax and strongly to itself, so water clusters into drops. Surface tension gives them their near-spherical shape, because a sphere has the smallest possible surface area to volume ratio.

- Formation of drops occurs when a mass of liquid is stretched. The animation shows water adhering to the faucet gaining mass until it is stretched to a point where the surface tension can no longer bind it to the faucet. It then separates and surface tension forms the drop into a sphere. If a stream of water were running from the faucet, the stream would break up into drops during its fall. Gravity stretches the stream, then surface tension pinches it into spheres (John W. M. Bush (May 2004)).

- Flotation of objects denser than water occurs when the object is non wettable and its weight is small enough to be borne by the forces arising from surface tension (Harvey E. (1948).

- Separation of oil and water is caused by a tension in the surface between dissimilar liquids. This type of surface tension is called "interface tension", but its physics are the same.

- Tears of wine is the formation of drops and rivulets on the side of a glass containing an alcoholic beverage. Its cause is a complex interaction between the differing surface tensions of water and ethanol.

Surface tension is visible in other common phenomena, especially when certain substances, surfactants, are used to decrease it:

- Soap bubbles have very large surface areas with very little mass. Bubbles in pure water are unstable. The addition of surfactants, however, can have a stabilizing effect on the bubbles. Notice that surfactants actually reduce the surface tension of water by a factor of three or more.

- Emulsions are a type of solution in which surface tension plays a role. Tiny fragments of oil suspended in pure water will spontaneously assemble themselves into much larger masses. But the presence of a surfactant provides a decrease in surface tension, which permits stability of minute droplets of oil in the bulk of water (or vice versa).
  Water striders are a common nuisance that skims on surface tension.

- Water striders use surface tension to walk on the surface of a pond—hydrophobic setae on the tarsi keep the insect afloat while an apical hydrophilic claw penetrates the surface, allowing it to "grip" the water. The surface of the water behaves like an elastic film: the insect's feet cause indentations in the water's surface, increasing its surface area. This represents an increase in potential energy through the surface tension of the water equal to the loss of potential energy of the insect's lowered centre of mass (John W. M. Bush (May 2004).
  It is wonderful the way the free surface of a liquid seems to be covered by a thin film in tension that

makes drops spherical, jets cylindrical, and climbs up the wall of a container. Soap films are a related wonder, forming iridescent spheres so light they float in the air, and thick foams when agitated. The way it is presented in school physics often reinforces this view, though the film has properties unlike those of a material substance. Surface tension causes capillary waves, which are the surface ripples that form around the impacts of drops on water surfaces, and sometimes occur with strong subsurface currents flowing to the water surface. The apparent elasticity caused by surface tension drives the waves.

- Capillary action: Due to interplay of the forces of adhesion and surface tension, water exhibits capillary action whereby water rises into a narrow tube against the force of gravity. Water adheres to the inside wall of the tube and surface tension tends to straighten the surface causing a surface rise and more water is pulled up through cohesion. The process continues as the water flows up the tube until there is enough water such that gravity balances the adhesive force.
- Surface tension and capillary action are important in biology. For example, when water is carried through xylem up stems in plants, the strong intermolecular attractions (cohesion) hold the water column together and adhesive properties maintain the water attachment to the xylem and prevent tension rupture caused by transpiration pull.

Capillary waves were studied by Faraday in 1831, who termed them crispations. Scott Russell observed capillary waves made by an obstacle in flowing water in 1844. These are called stationary waves, but are different from the usual stationary waves formed by wave trains moving in opposite directions. Their velocities are fixed by the velocity of the stream and the angle of their wavefronts. The stream velocity must be greater than 23 cm/s (1/2 mph) for such waves to form, since this is their minimum phase velocity. Capillary waves form on the upstream side, gravity waves on the downstream.

2.2.2 Basic Physics of Surface Tension

2.2.2.1 Analysis of a Floating Needle

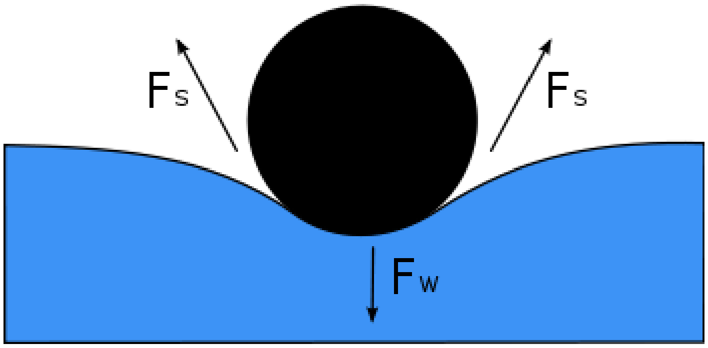


Fig2. 7

Diagram shows, in cross-section, a needle floating on the surface of water. Its weight, F_w, depresses the surface, and is balanced by the surface tension forces on either side, F_s, which are each parallel to the water's surface at the points where it contacts the needle. Notice that the horizontal components of the two F_s arrows point in opposite directions, so they cancel each other, but the vertical components point in the same direction and therefore add up (Harvey E. (1948) to balance F_w.

Surface tension, represented by the symbol γ is defined as the force along a line of unit length, where the force is parallel to the surface but perpendicular to the line. One way to picture this is to imagine a flat soap film bounded on one side by a taut thread of length, L. The thread will be pulled toward the interior of the film by a force equal to $2\gamma L$ (the factor of 2 is because the soap film has two sides, hence two surfaces).[4] Surface tension is therefore measured in forces per unit length. Its SI unit is newton per metre but the cgs unit of dyne per cm is also used. One dyn/cm corresponds to 0.001 N/m (Harvey E. (1948).

An equivalent definition, one that is useful in thermodynamics, is work done per unit area. As such, in order to increase the surface area of a mass of liquid by an amount, δA, a quantity of work, $\gamma \delta A$, is needed (Adam, Neil Kensington (1941). This work is stored as potential energy. Consequently surface tension can be also measured in SI system as joules per square metre and in the cgs system as ergs per cm^2. Since mechanical systems try to find a state of minimum potential energy, a free droplet of liquid naturally assumes a spherical shape, which has the minimum surface area for a given volume.

2.2.2.2 Surface Curvature and Pressure

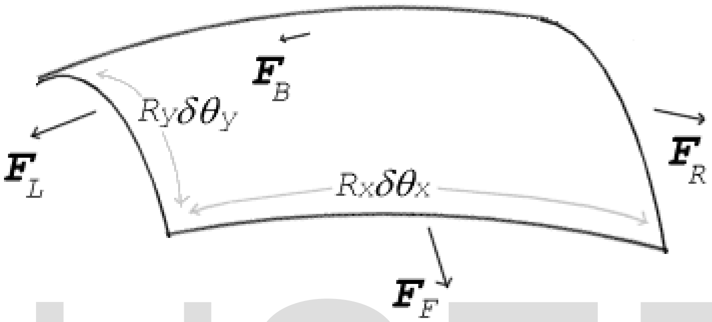


Fig.2 8

Surface tension forces acting on a tiny (differential) patch of surface. $\delta\theta_x$ and $\delta\theta_y$ indicate the amount of bend over the dimensions of the patch. Balancing the tension forces with pressure leads to the Young–Laplace equation

1. If no force acts normal to a tensioned surface, the surface must remain flat. But if the pressure on one side of the surface differs from pressure on the other side, the pressure difference times surface area results in a normal force. In order for the surface tension forces to cancel the force due to pressure, the surface must be curved. The diagram shows how surface curvature of a tiny patch of surface leads to a net component of surface tension forces acting normal to the centre of the patch. When all the forces are balanced, the resulting equation is known as the Young–Laplace equation (Addison Isley 1955).

$$\Delta p = \gamma \left(\frac{1}{R_x} + \frac{1}{R_y} \right) \qquad \text{..(3)}$$

where:

- Δp is the pressure difference.
- γ is surface tension.
- R_x and R_y are radii of curvature in each of the axes that are parallel to the surface.

The quantity in parentheses on the right hand side is in fact (twice) the mean curvature of the surface (depending on normalisation).

Solutions to this equation determine the shape of water drops, puddles, menisci, soap bubbles, and all other shapes determined by surface tension (such as the shape of the impressions that a water strider's feet make on the surface of a pond).

The table below shows how the internal pressure of a water droplet increases with decreasing radius. For not very small drops the effect is subtle, but the pressure difference becomes enormous when the drop sizes approach the molecular size. (In the limit of a single molecule the concept becomes meaningless.)

TABLE 1

Δp for water drops of different radii at STP				
Droplet radius	1 mm	0.1 mm	1 mm	10 nm
Δp (atm)	0.0014	0.0144	1.436	143.6

1. To find the shape of the minimal surface bounded by some arbitrary shaped frame using strictly mathematical means can be a daunting task. Yet by fashioning the frame out of wire and dipping it in

soap-solution, a locally minimal surface will appear in the resulting soap-film within seconds (Addison Isley 1955).

The reason for this is that the pressure difference across a fluid interface is proportional to the mean curvature, as seen in the Young-Laplace equation. For an open soap film, the pressure difference is zero, hence the mean curvature is zero, and minimal surfaces have the property of zero mean curvature.

2.3.2.3 Contact Angles

1. The surface of any liquid is an interface between that liquid and some other medium. The top surface of a pond, for example, is an interface between the pond water and the air. Surface tension, then, is not a property of the liquid alone, but a property of the liquid's interface with another medium. If a liquid is in a container, then besides the liquid/air interface at its top surface, there is also an interface between the liquid and the walls of the container. The surface tension between the liquid and air is usually different (greater than) its surface tension with the walls of a container. And where the two surfaces meet, their geometry must be such that all forces balance (Pierre-Gilles de Gennes; Françoise Brochard-Wyart; David Quéré (2002).

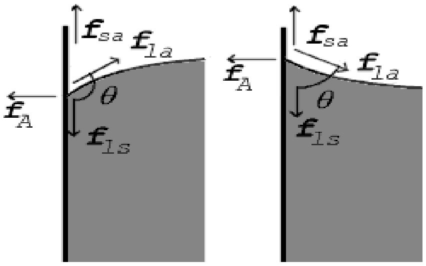


Fig 2.9

Where the two surfaces meet, they form a contact angle, θ, which is the angle the tangent to the surface makes with the solid surface. The diagram to the right shows two examples. Tension forces are shown for the liquid-air interface, the liquid-solid interface, and the solid-air interface. The example on the left is where the difference between the liquid-solid and solid-air surface tension, $\gamma_{\mathrm{ls}}-\gamma_{\mathrm{sa}}$, is less than the liquid-air surface tension, γ_{la}, but is nevertheless positive, that is

$$\gamma_{\mathrm{la}} > \gamma_{\mathrm{ls}} - \gamma_{\mathrm{sa}} > 0 \qquad \text{...(4)}$$

In the diagram, both the vertical and horizontal forces must cancel exactly at the contact point. The horizontal component of f_{la} is cancelled by the adhesive force, f_{A}(Addison Isley 1955).

$$f_{\mathrm{A}} = f_{\mathrm{la}} \sin\theta \qquad \text{..(5)}$$

The more telling balance of forces, though, is in the vertical direction. The vertical component of f_{la} must exactly cancel the force, f_{ls}(Addison Isley 1955).

$$f_{\mathrm{ls}} - f_{\mathrm{sa}} = -f_{\mathrm{la}} \cos\theta \qquad \text{..(6)}$$

TABLE 2

Liquid	**Solid**	**Contact angle**
water	soda-lime glass lead glass fused quartz	0°
ethanol		
diethyl ether		
carbon tetrachloride		

glycerol		
acetic acid		
water	paraffin wax	107°
	Silver	90°
methyl iodide	soda-lime glass	29°
	lead glass	30°
	fused quartz	33°
mercury	soda-lime glass	140°
Some liquid-solid contact angles[http//wikipedia.org.surface tension.]		

Since the forces are in direct proportion to their respective surface tensions, i also have. (David Quéré (2002).

$$\gamma_{ls} - \gamma_{sa} = -\gamma_{la} \cos\theta \text{...(7)}$$

where

- γ_{ls} is the liquid-solid surface tension,
- γ_{la} is the liquid-air surface tension,
- γ_{sa} is the solid-air surface tension,
- θ is the contact angle, where a concave meniscus has contact angle less than 90° and a convex meniscus has contact angle of greater than 90°(Addison Isley 1955).

This means that although the difference between the liquid-solid and solid-air surface tension, $\gamma_{\mathrm{ls}} - \gamma_{\mathrm{sa}}$, is difficult to measure directly, it can be inferred from the easily measured contact angle, θ, if the liquid-air surface tension, γ_{la}, is known.

This same relationship exists in the diagram on the right. But in this case i see that because the contact angle is less than 90°, the liquid-solid/solid-air surface tension difference must be negative:

$$\gamma_{\mathrm{la}} > 0 > \gamma_{\mathrm{ls}} - \gamma_{\mathrm{sa}} \text{...} (4)$$

Special Contact Angles:

Observe that in the special case of a water-silver interface where the contact angle is equal to 90°, the liquid-solid/solid-air surface tension difference is exactly zero.

Another special case is where the contact angle is exactly 180°. Water with specially prepared Teflon approaches this (David Quéré (2002). Contact angle of 180° occurs when the liquid-solid surface tension is exactly equal to the liquid-air surface tension.

$$\gamma_{\mathrm{la}} = \gamma_{\mathrm{ls}} - \gamma_{\mathrm{sa}} > 0 \qquad \theta = 180^\circ \text{...} (9)$$

2.2.3 Methods of Measuring Surface Tension

2.2.3.1 Use of Goniometer

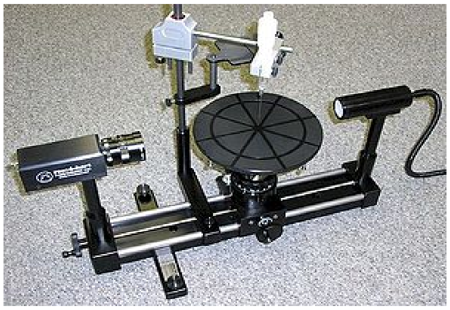


Fig 2.10

Surface tension can be measured using the pendant drop method on a goniometer.

Because surface tension manifests itself in various effects, it offers a number of paths to its measurement. Which method is optimal depends upon the nature of the liquid being measured, the conditions under which its tension is to be measured, and the stability of its surface when it is deformed.

2.2.3.2 By Capillary Action

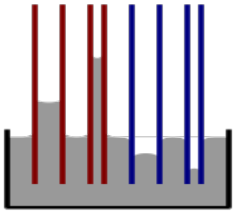


Fig2.11

Illustration of capillary rise and fall. Red=contact angle less than 90°; blue=contact angle greater than 90°

If a tube is sufficiently narrow and the liquid adhesion to its walls is sufficiently strong, surface tension can draw liquid up the tube in a phenomenon known as capillary action. The height the column is lifted to is given by: $\int ls$(Addison Isley 1955).

$$h = \frac{2\gamma_{\text{la}}\cos\theta}{\rho g r} \qquad \text{...(10)}$$

where

- h is the height the liquid is lifted,
- γ_{la} is the liquid-air surface tension,
- ρ is the density of the liquid,
- r is the radius of the capillary,
- g is the acceleration due to gravity,
- θ is the angle of contact described above. If θ is greater than 90°, as with mercury in a glass container, the liquid will be depressed rather than lifted.

2.2.3.3 Puddles on a Surface

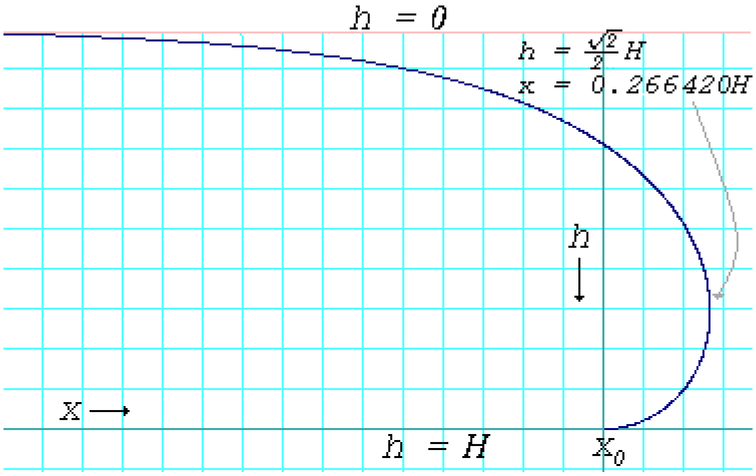


Fig 2.12

Profile curve of the edge of a puddle where the contact angle is 180°. The curve is given by the formula: $x - x_0 = \frac{1}{2}H\cosh^{-1}\left(\frac{H}{h}\right) - H\sqrt{1-\frac{h^2}{H^2}}$ where $H = 2\sqrt{\frac{\gamma}{g\rho}}$

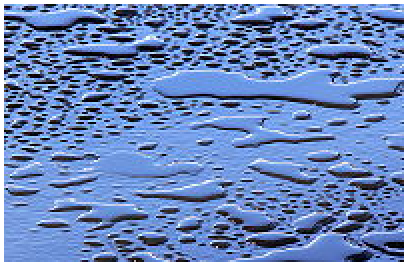


Fig 2.13

Small puddles of water on a smooth clean surface have perceptible thickness.

Pouring mercury onto a horizontal flat sheet of glass results in a puddle that has a perceptible thickness. (Do not try this except under a fume hood. Mercury vapour is a toxic hazard.) The puddle will spread out only to the point where it is a little under half a centimetre thick, and no thinner. Again this is due to the action of mercury's strong surface tension. The liquid mass flattens out because that brings as much of the mercury to as low a level as possible. But the surface tension, at the same time, is acting to reduce the total surface area. The result is the compromise of a puddle of a nearly fixed thickness.

The same surface tension demonstration can be done with water, but only on a surface made of a substance that the water does not adhere to. Wax is such a substance. Water poured onto a smooth, flat, horizontal wax surface, say a waxed sheet of glass, will behave similarly to the mercury poured onto glass.

The thickness of a puddle of liquid on a surface whose contact angle is 180° is given by (David Quéré (2002)).

$$h = 2\sqrt{\frac{\gamma}{g\rho}} \qquad \text{...(11)}$$

where

h is the depth of the puddle in centimeters or meters.

γ is the surface tension of the liquid in dynes per centimeter or newtons per meter.

g is the acceleration due to gravity and is equal to 980 cm/s^2 or 9.8 m/s^2

ρ is the density of the liquid in grams per cubic centimeter or kilograms per cubic meter.

Fig2.14

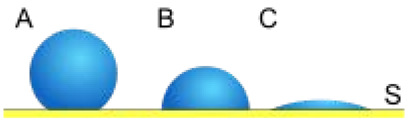


Illustration of how loir contact angle leads to reduction of puddle depth

In reality, the thicknesses of the puddles will be slightly less than what is predicted by the above formula because very few surfaces have a contact angle of 180° with any liquid. When the contact angle is less than 180°, the thickness is given by David Quéré (2002).

$$h = \sqrt{\frac{2\gamma_{\mathrm{la}}\left(1-\cos\theta\right)}{g\rho}}. \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

For mercury on glass, $\gamma_{\mathrm{Hg}} = 487\ \frac{\mathrm{dyn}}{\mathrm{cm}}$, $\rho_{\mathrm{Hg}} = 13.5\ \frac{\mathrm{g}}{\mathrm{cm}^3}$, and θ=140°, which gives $h_{\mathrm{Hg}} = 0.36\ \mathrm{cm}$. For water on paraffin at 25 °C, $\gamma_{\mathrm{H_2O}} = 72\ \frac{\mathrm{dyn}}{\mathrm{cm}}$, $\rho_{\mathrm{H_2O}} = 1.0\ \frac{\mathrm{g}}{\mathrm{cm}^3}$, and θ=107°which gives $h_{\mathrm{H_2O}} = 0.44\ \mathrm{cm}$.

The formula also predicts that when the contact angle is 0°, the liquid will spread out into a micro-thin layer over the surface. Such a surface is said to be fully wettable by the liquid.

Surface tension is dependent on temperature. For that reason, when a value is given for the surface tension of an interface, temperature must be explicitly stated. The general trend is that surface tension decreases with the increase of temperature, reaching a value of 0 at the critical temperature.

2.3 ADHESION

Adhesion is any attraction process between dissimilar molecular species that can potentially bring them in "direct contact" By contrast, cohesion takes place between similar molecules.

Adhesion is the tendency of dissimilar particles and/or surfaces to cling to one another (cohesion refers to the tendency of similar or identical particles/surfaces to cling to one another). The forces that cause adhesion and cohesion can be divided into several different types. The intermolecular forces responsible for the function of various kinds of stickers and sticky tape fall into the categories of chemical adhesion, dispersive adhesion, and diffusive adhesion. In addition to the cumulative magnitudes of these intermolecular forces, there are certain emergent mechanical effects that will also be discussed at the end of the article.

2.3.1 A Brief Explanation of Surface Energy

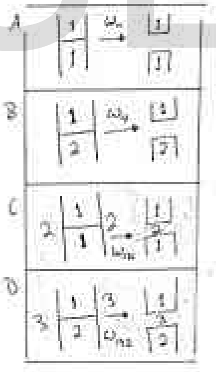


Fig 2.15

Fig2.15, Diagram of various cases of cleavage, with each unique species labeled. **A**-$\gamma = (1/2)W_{11}$ **B**-$W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$ **C**-$\gamma_{12} = (1/2)W_{121} = (1/2)W_{212}$ **D**-$W_{12} + W_{33} - W_{13} - W_{23} = W_{132}$.

Surface energy is conventionally defined as the work that is required to build a unit area of a particular surface. Another way to view the surface energy is to relate it to the work required to cleave a bulk sample, creating two surfaces. If the new surfaces are identical, the surface energy γ of each surface is equal to half the work of cleavage, W: $\gamma = (1/2)W_{11}$

If the surfaces are unequal, the Young-Dupré equation applies: $W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}$ where γ_1 and γ_2 are the surface energies of the two new surfaces, and γ_{12} is the interfacial tension.

1. I can also use this methodology to discuss cleavage that happens in another medium: $\gamma_{12} = (1/2)W_{121} = (1/2)W_{212}$. These two energy quantities refer to the energy that is needed to cleave one species into two pieces while it is contained in a medium of the other species. Likewise for a three species system: $\gamma_{13} + \gamma_{23} - \gamma_{12} = W_{12} + W_{33} - W_{13} - W_{23} = W_{132}$, where W_{132} is the energy of cleaving species 1 from species 2 in a medium of species 3(J. N. Israelachvili, New York, 1985).
2. A basic understanding of the terminology of cleavage energy, surface energy, and surface tension is very helpful for understanding the physical state and the events that happen at a given surface, but as discussed below, the theory of these variables also yields some interesting effects that concern the practicality of adhesive surfaces in relation to their surrounding (Y. Y. Huang, (2005).

2.3.2 MECHANISM OF ADHESION

Fig. 2.16

Cohesion causes water to form drops, surface tension causes them to be nearly spherical, and adhesion keeps the drops in place.

Fig 2.17

Water droplets are flatter on a Hibiscus flower which shows better adhesion.

Five mechanisms of adhesion have been proposed to explain why one material sticks to another:

2.3.2.1 Mechanical Adhesion

Adhesive materials fill the voids or pores of the surfaces and hold surfaces together by interlocking. Sewing forms a large scale mechanical bond, velcro forms one on a medium scale, and some textile adhesives form one at a small scale.

2.3.2.2 Chemical Adhesion

Two materials may form a compound at the join. The strongest joins are where atoms of the two materials swap (ionic bonding) or share (covalent bonding) outer electrons. A weaker bond is formed if a Hydrogen atom in one molecule is attracted to an atom of Nitrogen, Oxygen, or Fluorine in another molecule, a phenomenon called Hydrogen bonding.

Chemical adhesion occurs when the surface atoms of two separate surfaces form ionic, covalent, or hydrogen bonds. The engineering principle behind chemical adhesion in this sense is fairly straight forward: if surface molecules can bond, then the surfaces will be bonded together by a network of these bonds. It bears mentioning that these attractive ionic and covalent forces are effective over only very small distances – less than a nanometer. This means in general not only that surfaces with the potential for chemical bonding need to be brought very close together, but also that these bonds are fairly brittle, since the surfaces then need to be *kept* close together. (K. Kendall (1994)).

2.3.2.3 Dispersive Adhesion

In dispersive adhesion, also known as physisorption, two materials are held together by van der Waals forces: the attraction between two molecules, each of which has regions of slight positive and negative charge. In the simple case, such molecules are therefore Polar with respect to average charge density, although in larger or more complex molecules, there may be multiple "poles" or regions of greater positive or negative charge. These positive and negative poles may be a permanent property of a molecule (Keesom forces) or a transient effect which can occur in any molecule, as the random movement of electrons within the molecules may result in a temporary concentration of electrons in one region (London forces).

In surface science, the term "adhesion" almost always refers to dispersive adhesion. In a typical solid-liquid-gas system (such as a drop of liquid on a solid surrounded by air) the contact angle is used to quantify adhesiveness. In the cases where the contact angle is low, more adhesion is present. This is due to a larger surface area between the liquid and solid and results in higher surface energy. The work of adhesion explains the interactive force between the liquid and solid phases and the Young-Dupree equation is used to calculate the Work of Adhesion. The contact angle of the three-phase system is a function not only of dispersive adhesion (interaction between the molecules in the liquid and the molecules in the solid) but also cohesion (interaction between the liquid molecules themselves). Strong adhesion and weak cohesion results in a high degree of wetting, a lyophilic condition with low measured contact angles. Conversely, weak adhesion and strong cohesion results in lyophobic conditions with high measured contact angles and poor wetting.

2.3.2.4 London Dispersion

These forces are particularly useful for the function of adhesive devices, because they don't require either surface to have any permanent polarity. They were described in the 1930s by Fritz London, and have been observed by many researchers. Dispersive forces are a consequence of statistical quantum mechanics. London theorized that attractive forces between molecules that cannot be explained by ionic or covalent interaction can be caused by polar moments within molecules. Multipoles could account for attraction between molecules having permanent multi pole moments that participate in electrostatic interaction. However, experimental data showed that many of the compounds observed to experience van der Waals forces had no multi poles at all. London suggested that momentary dipoles are induced purely by virtue of molecules being in proximity to one another. By solving the quantum mechanical system of two electrons as harmonic oscillators at some finite distance from one another, being displaced about their respective rest positions and interacting with each others fields, London showed that the energy of this system is given by:

$$E = 3h\nu - \frac{3}{4}\frac{(h\nu\ \alpha^{2})}{R^{6}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

While the first term is simply the zero-point energy, the negative second term describes an attractive force between neighboring oscillators. The same argument can also be extended to a large number of coupled oscillators, and thus skirts issues that would negate the large scale attractive effects of permanent dipoles; cancelling through symmetry, in particular. The additive nature of the dispersion effect has another useful consequence. Consider a single such dispersive dipole, referred to as the origin dipole. Since any origin dipole is inherently oriented so as to be attracted to the adjacent dipoles it induces, while the other, more distant dipoles are not correlated with the original dipole by any phase relation (thus on average contributing nothing), there is a net attractive force in a bulk of such particles. Since i are discussing identical particles, this is called cohesive force (Y. Y. Huang (2005).

When discussing adhesion, this theory needs to be converted into terms relating to surfaces. If there is a net attractive energy of cohesion in a bulk of similar molecules, then cleaving this bulk to produce two surfaces will yield surfaces with a dispersive surface energy, since the form of the energy remain the same. This theory provides a basis for the existence of van der Waals forces at the surface, which exist between any molecules having electrons. These forces are easily observed through the spontaneous jumping of smooth surfaces into contact. Smooth surfaces of mica, gold, various polymers and solid gelatine solutions do not stay apart when their separating becomes small enough – on the order of 1-10 nm. The equation describing these attractions was predicted in the 1930s by De Boer and Hamaker (K. Kendall (1994)).

$$\frac{P}{area} = \frac{-A}{(24\pi\ z^3)} \quad \text{..(14)}$$

Where P is the force (negative for attraction), z is the separation distance, and A is a material specific constant called the Hamaker constant.

Two stages of PDMS microstructure collapses due to van der Waals attractions. The PDMS stamp is indicated by the hatched region, and the substrate is indicated by the shaded region. A) The PDMS stamp is placed on a substrate with the "roof" elevated. B) Van der Waals attractions make roof collapse energetically favorable for PDMS stamp.

1. The effect is also apparent in experiments where a Polydimethylsiloxane (PDMS) stamp is made with small periodic post structures. The surface with the posts is placed face down on a smooth surface, such that the surface area in between each post is elevated above the smooth surface, like a roof supported by columns. Because of these attractive dispersive forces between the PDMS and the smooth substrate, the elevated surface – or “roof” – collapses down onto the substrate without any external force aside from the van der Waals attraction (Y. Y. Huang, (2005)).

Simple smooth polymer surfaces – without any microstructures – are commonly used for these dispersive adhesive properties. Decals and stickers that adhere to glass without using any chemical adhesives are fairly common as toys and decorations and useful as removable labels because they do not rapidly lose their adhesive properties, as do sticky tapes that use adhesive chemical compounds.

It is important to note that these forces also act over very small distances. 99% of the work necessary to break van der Waals bonds is done once surfaces are pulled more than a nanometer apart (K. Kendall (1994)).

. As a result of this limited motion in both the van der Waals and ionic/covalent bonding situations, practical effectiveness of adhesion due to either or both of these interactions leaves much to be desired. Once a crack is initiated, it propagates easily along the interface because of the brittle nature of the interfacial bonds (B. Z. Newby, (1995).

As an additional consequence, increasing surface area often does little to enhance the strength of the adhesion in this situation. This follows from the aforementioned crack failure – the stress at the interface is not uniformly distributed, but rather concentrated at the area of failure (K. Kendall (1994)).

2.3.2.5 Electrostatic Adhesion

Some conducting materials may pass electrons to form a difference in electrical charge at the join. This results in a structure similar to a capacitor and creates an attractive electrostatic force between the materials.

2.3.2.6 Diffusive Adhesion

Some materials may merge at the joint by diffusion. This may occur when the molecules of both materials are mobile and soluble in each other. This would be particularly effective with polymer chains where one end of the molecule diffuses into the other material. It is also the mechanism involved in sintering. When metal or ceramic powders are pressed together and heated, atoms diffuse from one particle to the next. This joins the particles into one.

Diffusive forces are somewhat like mechanical tethering at the molecular level. Diffusive bonding occurs when species from one surface penetrate into an adjacent surface while still being bound to the phase of their surface of origin. One instructive example is that of polymer-on-polymer surfaces. Diffusive bonding in polymer-on-polymer surfaces is the result of sections of polymer chains from one surface interdigitating with those of an adjacent surface. The freedom of movement of the polymers ha s a strong effect on their ability to interdigitate, and hence, on diffusive bonding. For example, cross-linked polymers are less capable of diffusion and interdigitation because they are bonded together at many points of contact, and are not free to twist into the adjacent surface. Uncross linked polymers, on the other hand are freer to wander into the adjacent phase by extending tails and loops across the interface.

Another circumstance under which diffusive bonding occurs is “scission”. Chain scission is the cutting up of polymer chains, resulting in a higher concentration of distal tails. The heightened concentration of these chain ends gives rise to a heightened concentration of polymer tails extending across the interface. Scission is easily achieved by ultraviolet irradiation in the presence of oxygen gas, which suggests that adhesive devices employing diffusive bonding actually benefit from prolonged exposure to heat/light and air. The longer such a device is exposed to these conditions, the more tails are scissed and branch out across the interface.

1. Once across the interface, the tails and loops form whatever bonds are favorable. In the case of polymer-on-polymer surfaces, this means more van der Waals forces. While these may be brittle, they

are quite strong when a large network of these bonds is formed. The outermost layer of each surface plays a crucial role in the adhesive properties of such interfaces, as even a tiny amount of interdigitation - as little as one or two tails of 1.25 angstrom length - can increase the van der Waals bonds by an order of magnitude (N. Maeda, (2002).

2.3.2 EFFECTS OF ADHESION

The strength of the adhesion between two materials depends on which of the above mechanisms occur between the two materials, and the surface area over which the two materials contact. Materials that it against each other tend to have a larger contact area than those that do not. Wetting depends on the surface energy of the materials.

Low surface energy materials such as polyethylene, polypropylene, polytetrafluoroethylene, and Delrin are difficult to bond without special surface preparation.

In concert with the primary surface forces described above, there are several circumstantial effects in play. While the forces themselves each contribute to the magnitude of the adhesion between the surfaces, the following play a crucial role in the overall strength and reliability of an adhesive device.

2.3.2.1 Stringing

Stringing is perhaps the most crucial of these effects, and is often seen on adhesive tapes. Stringing occurs when a separation of two surfaces is beginning and molecules at the interface bridge out across the gap, rather than cracking like the interface itself. The most significant consequence of this effect is the restraint of the crack.

By providing the otherwise brittle interfacial bonds with some flexibility, the molecules that are stringing across the gap can stop the crack from propagating (K. Kendall (1994)).

. Another way to understand this phenomenon is by comparing it to the stress concentration at the point of failure mentioned earlier. Since the stress is now spread out over some area, the stress at any given point has less of a chance of overwhelming the total adhesive force between the surfaces. If failure does occur at an interface containing a viscoelastic adhesive agent, and a crack does propagate, it happens by a gradual process called "fingering", rather than a rapid, brittle fracture (B. Z. Newby, (1995). Stringing can apply to both the diffusive bonding regime and the chemical bonding regime. The strings of molecules bridging across the gap would either be the molecules that had earlier diffused across the interface or the viscoelastic adhesive, provided that there was a significant volume of it at the interface.

2.3.2.2 Hysteresis

Hysteresis, in this case, refers to the restructuring of the adhesive interface over some period of time, with the result being that the work needed to separate two surfaces is greater than the work that was gained by bringing them together ($W > \gamma_1 + \gamma_2$). For the most part, this is a phenomenon associated with diffusive bonding. The more time is given for a pair of surfaces exhibiting diffusive bonding to restructure, the more diffusion will occur, the stronger the adhesion will become. The aforementioned reaction of certain polymer-on-polymer surfaces to ultraviolet radiation and oxygen gas is an instance of hysteresis, but it will also happen over time without those factors.

In addition to being able to observe hysteresis by determining if $W > \gamma_1 + \gamma_2$ is true, one can also find evidence of it by performing "stop-start" measurements. In these experiments, two surfaces slide against one another continuously and occasionally stopped for some measured amount of time. Results from experiments on polymer-on-polymer surfaces show that if the stopping time is short enough, resumption of smooth sliding is easy. If, however, the stopping time exceeds some limit, there is an initial increase of resistance to motion, indicating that the stopping time was sufficient for the surfaces to restructure (N. Maeda, (2002).

2.3.2.4 Wetting and Adsorption

I can also characterize some atmospheric effects on the functionality of adhesive devices by following the theory of surface energy and interfacial tension. I know that $\gamma_{12} = (1/2)W_{121} = (1/2)\, W_{212}$ (figure 2). If γ_{12} is high, then each species finds it favourable to cohere while in contact with a foreign species, rather than dissociate and mix with the other. If this is true, then it follows that when the interfacial tension is high, the force of adhesion is weak, since each species does not find it favourable to bond to the other. Since i know that the interfacial tension of a liquid and a solid is directly related to the liquids wet ability (relative to the solid), i can also extrapolate that cohesion increases in non-wetting liquids, and decreases in wetting liquids. One example that verifies this is polydimethyl siloxane rubber, which has a work of self-adhesion of 43.6 mJ/m^2 in air, 74 mJ/m^2 in water (a non wetting liquid) and 6 mJ/m^2 in methanol (a wetting liquid).

This argument can be extended to the idea that when a surface is in a medium with which binding is favourable, it will be less likely to adhere to another surface, since the medium is taking up the potential sites on the surface that would otherwise be available to adhere to another surface. Naturally this applies very strongly to wetting liquids, but also to gas molecules that could adsorb onto the surface in question, thereby occupying potential adhesion sites. This last point is actually fairly intuitive: Leaving an adhesive exposed to air too long gets it dirty, and its adhesive strength will decrease. I can also observe this experimentally: When mica is cleaved in air, its cleavage energy, W_{121} or $W_{mica/air/mica}$, is smaller than the cleavage energy in vacuum, $W_{mica/vac/mica}$, by a factor of 13(K. Kendall (1994)).

CHAPTER THREE

3.0 MATERIALS AND METHOD

Experiments on capillarity had to be carried out with varied apparatus sizes and materials so as to obtain necessary data for proper investigation, analysis and evaluation of the observations made from the experiments. In this project, capillarity was demonstrated using glass tubes (capillary tubes), beakers and capillary mediums (liquids). In order to investigate adequately, capillarity and the effect of capillary radius on capillary rise, i had to use several diameters of capillary tubes and three different capillary liquids (materials).

3.1 MATERIALS

The basic materials used for this project work are the capillary liquids, and they are listed below;

i. Water

ii. Kerosene

iii. Diesel

3.1.1 Nature of Water for This Project Work

Water is available in Owerri, Imo State of Nigeria where this project was executed. However, the water used for this project is distilled water.

3.1.1.1 Source of distilled water for the project work

The distilled water used for this project was obtained from a laboratory equipment shop, vitrex laboratory equipments which is located at 12 Mbaise road, Owerri, Imo State. The water of course is free from inorganic and organic solutes. The presence of these solutes in water can alter the chemical composition of water and eventually weaken or strengthen the resulting intermolecular forces acting in the water. The presence of suspended particles in the water is prohibited and was avoided because they can also affect the experiment by altering the resulting surface tension in water.

3.1.1.2 Storage of the Distilled Water

The distilled water used for this project was stored in a well cocked plastic container in a store room. It was stored at room temperature and kept from direct heat, to ensure that the temperature of the distilled water is always within the range of room temperatures. The container was labeled for certainty, and to avoid mistaking the container or its content for another.

3.1.2 Nature of Kerosene Used for the Project Work

The kerosene is of high purity and quality (grade). It is of worldwide standard quality as specified by OPEC.

3.1.2.1 Source of the Kerosene

The kerosene used for this project work was obtained from a trusted petroleum company, precisely speaking; it was obtained from NNPC Depot at Ihiagwa in Owerri, Imo State, Nigeria. The reason for this was to maintain standards and to avoid the use of mixed (impure) or low grade kerosene for the project. I ensured that i obtained the required kerosene once and at a time from a particular supply unit (tank) at NNPC Depot Ihiagwa, in Owerri, Imo State, Nigeria. The reason for this was to avoid any unforeseen variation in the quality and grade of kerosene used for the project work.

3.1.2.2 Storage of the Kerosene

The kerosene used for this project was stored in a well cocked plastic container, in a store room. It was stored at room temperature and kept from direct heat, to ensure that the temperature of the kerosene is always within the range of room temperatures. The container was labeled for certainty, and to avoid mistaking the container or its content for another.

3.1.3 Nature of Diesel used for this Project Work

The diesel used for this project work was of high purity and grade. It is of worldwide standard qualities as specified by OPEC.

3.1.3.1 Source of the Diesel

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3.1.3.2 Storage of the Diesel

The diesel used for this project work was stored in a well cocked plastic container in a store room. It was stored at 20m temperature and from direct heat, so as to ensure that the temperatures of the diesel always within the range of room temperature. The container was labeled for certainty and to avoid mistaking the container or its content with another

3.2 METHOD

3.2.1 Experiment (1) to Demonstrate Capillary Using Distilled Water

This was the first experiment that was conducted because water is a universal solvent and is least prone to cause interference of the capillary fluids through handling them.

3.2.1.1 Aim of Experiment (1)

The experiment was aimed at demonstrating and investigating capillarity by the observation and analysis of the data obtained from the experiment and to evaluate the effects of diameter of capillary tube on capillary rise.

3.2.1.2 Apparatus

Beakers: Contains or holds the bulk of water from which the capillary risen water emerges.

A four (4) liters plastic container: Used to obtain and store the entire (bulk) of the distilled water used for the project.

Glass capillary tubes of diameters 1.0mm, 1.5mm and 2.0mm: They were used to enable or effect the capillary rise of the distilled water. When capillary action occurs, the distilled water rises into the capillary tube.

Transparent rule: A transparent rule that measures not more than one foot was used to measure the capillary rise.

Hand towel: A hand towel was used to dry up unwanted wetness of any of the apparatus and the hand.

A table (wooden): provided the platform on which the experiments were conducted.

3.2.1.3 Procedure

- The beaker was filled, almost to the brim with distilled water.
- For each of the capillary tubes, i placed an open end in contact with the surface of the water in the beaker and measured the resulting capillary rise in each case.

- I repeated step 2 three times, evaluated and recorded the average capillary rise.
- I Plotted graphs of average capillary rise against radius of capillary tubes used and I obtained the slope.
- I substituted the corresponding values of average capillary rise and radius of capillary tube into the formula $\gamma_w = (176RH)^2$.
- I compared the values of γ_w for all the tubes and derived a conclusion.
- I stated observations made and evaluated/investigated them.
- Deductions were made and hypotheses were postulated considering the variation in the values of capillary rise obtained for the various capillary tube radiuses and other relevant parameters.
- Based on such hypothesis, mathematical formulas were derived for analysis of capillary action, relating to capillary rise, radius of capillary tube and other relevant parameters.

3.2.1.4 Precautions

- I ensured that the laboratory where the experiment was conducted was equipped with at least the necessary apparatus as listed earlier.
- The windows and doors were closed and fans were switched off during the experiment to avoid disturbance by wind, since such can alter the readings obtained in the experiment.
- Vibrations or sources of vibration within or on the platform for the experiment were avoided.
- Movement within the laboratory was restricted so as to avoid unwarranted accidents.
- Apparatus used for this experiment were used only for this experiment.

3.2.2 Experiment (II) to Demonstrate Capillary Using Kerosene

This is the second experiment, and its title is as stated above.

3.2.2.1 Aim of Experiment (II)

The experiment was aimed at demonstrating and investigating capillarity of kerosene by the observation and analysis of the data obtained from the experiment. It was also aimed at evaluating the effects of radius of capillary tube on capillary rise.

3.2.2.2 Apparatus

Beakers: This was used to contain or hold the bulk of kerosene, from which the capillary risen kerosene emerges.

A 4 liters plastic container: The container was used to obtain and store the bulk of kerosene used for the project.

Glass capillary tubes of diameters 1.0mm, 1.5mm and 2.0mm: They were used to enable or effect the capillary rise of the kerosene. When capillarity occurs, the kerosene rises into the capillary tube.

Transparent rule: A transparent rule that measures not more than one foot was used to measure the capillary rise.

A hand towel: A hand towel was used to clean up unwanted wetness with kerosene of the hand or any of the apparatus.

A wooden table: This provided the platform on which the experiments were conducted.

3.2.2.3 Procedure

- The beaker was filled almost to the brim with kerosene.
- For each of the capillary tubes, i placed an Open end in contact with the surface of the kerosene in the beaker and measured the resulting capillary rise.
- I repeated step 2 three times, calculated and recorded the average capillary rise.
- I plotted graphs of capillary rise against the radius of capillary tubes used and obtained the slope.
- I substituted the corresponding values of capillary rise (average) and radius of capillary tube into the formula $\gamma_k = (159RH)^2$.

- I compared the values of γ_k for all the sizes of capillary tubes and gave a conclusion.
- I stated all observations made from the experiment and evaluated/investigated them.
- Deductions were made and hypotheses were postulated considering the variations in the values of capillary rise obtained for the various capillary tube radius used.
- Based on such hypothesis, mathematical formulas were derived for analysis of capillary action relating to capillary rise, radius of capillary tube and other relevant parameters.

3.2.2.4 Precautions

- I ensured that the laboratory where the experiment was conducted was equipped with at least the necessary apparatus stated earlier.
- The windows and doors were closed and fans were switched off during the experiment to avoid disturbance by wind, since such can alter the readings obtained from the experiment.
- Vibrations or sources of vibration, within or on the platform for the experiment were avoided.
- Movement within the laboratory was avoided so as to avoid unwarranted accidents.
- All the apparatus used for this experiment were only used for it.

3.2.3 Experiment (III) to Demonstrate Capillary Using Diesel Oil

This is the third experiment in this project and the title is as stated above.

3.2.3.1 Aim of Experiment (III)

The experiment was aimed at investigating capillary with diesel oil by observation and analysis of the data obtained from the experiment and to evaluate the effects of radius of capillary tube on capillary rise.

3.2.3.2 Apparatus

Beakers: They were used to contain or hold the bulk of diesel from which the capillary risen diesel emerges.

A 4 liters plastic container: This was used to obtain and store the entire (bulk) of the diesel used for this project.

Glass capillary tubes of diameters 1.0mm, 1.5mm and 2.0mm: They were used to enable or effect the capillary rise of the diesel. When capillarity occurs, the diesel rises into the capillary tube.

Transparent rule: A transparent rule that measures not more than one foot was used to measure the capillary rise.

Hand towel: A hand towel was used to clean up unwanted wetness with diesel, of any apparatus and the hand.

A wooden table: This provided the platform on which the experiments were conducted.

3.2.3.3 Procedure

- The beaker was filled almost to the brim with diesel.
- For each of the capillary tubes, i placed an open end in contact with the surface of the diesel in the beaker and measured the resulting capillary rise in each case.
- I repeated step 2 three times, calculated and recorded the average capillary rise.
- I plotted graphs of capillary rise against radius of capillary tube and obtained the slope.
- I substituted the corresponding values of capillary rise and radius capillary tube into the formula $\gamma_d = (162RH)^2$.
- I compared the values of γ_d for all the tubes and derived a conclusion.
- I stated all observations made from the experiment and investigated them.
- Deductions were made and hypotheses were postulated considering the variations in the values of capillary rise obtained for the various capillary tube radiuses.
- Based on such hypothesis, mathematical formulas were derived for analysis of capillary action relating to capillary rise, radius of capillary tube and other relevant parameters.

3.2.3.4 Precautions

- I ensured that the laboratory where the experiment was conducted was equipped with at least the necessary apparatus stated earlier.
- The windows and doors were closed and fans were switched off during the experiment to avoid disturbance by wind, since such can alter the readings obtained in the experiment.
- Vibrations or sources of vibration within or on the platform for the experiment were avoided.
- Movement within the laboratory was restricted to avoid accidents.
- I ensured that the glass tubes were clean.

3.3 CONCLUSION

Compare all the observations, deducting and mathematical expressions obtained from all the experiments conducted in this project and make general conclusions from the foregoing

CHAPTER FOUR

DATA PRESENTATION, ANALYSIS AND DISCUSION

4.1 Observations Made From Experiment (I)

- When i placed an open end of a capillary tube in contact with the surface of water, the water rose into the capillary tube up to a height (capillary rise).
- I also noticed that when i removed the capillary tube from the surface of water, it yet retains same amount of rise of water which of course is the capillary rise.
- When i used different sizes of capillary tube, i realized that the resulting capillary rise varied with different radius of capillary tube.
- When i immersed the capillary tube in water and withdrawn at once with caution, i noticed a retrained rise of water in the capillary tube which was obviously greater than the capillary rise, that tube normally holds.

- When i brought the capillary tube back in contact with the surface of water, part of the retained water discharges and the rise reduces to the corresponding capillary rise of water for that tube.

Table 3

D(mm)	**R(mm)**	**Capillary rises(H) in (mm)**			**Average Capillary rise (H_{avg}) in (mm)**
1.0	0.50	27	27	26	26.67
1.5	0.75	18	18	17	17.67
2.0	1.00	14	13	13	13.33

4.2 Analysis of Data In Table 3

From the data obtained in the above table, it can be seen that increase in the capillary tube radius results in decrease in the resulting capillary rise.

The radius of capillary tube is inversely proportional to the capillary rise.

k_w is a constant hereby called the specific capillary rise of water at room temperature.

R = the radius of capillary tube or capillary radius

H = Corresponding Capillary rise

$R \alpha 1/H$, $R=k_w/H$ and $RH = k_w$

$$0.5 = k_w / 26.67$$

$$k_w = 0.5 * 26.67 = 13.33 \qquad \text{Hence: } k_w = 13.33 \ldots\ldots\ldots\ldots(15)$$

k_w is a constant i called the specific capillary rise of water.

Taking a deductive approach to the variation in capillary rise with respect to the radius of the capillary tube, we can refer the causative (resultant) force of capillarity to the law of conservation of energy which state that energy can never be created nor destroyed but converted from one form to another(Principles of Physics by

Nelson). Work is expressed mathematically as the product of force and Distance travelled, so the resulting intermolecular force from the capillarity assembly drives a column of water up its hydrologic level to a distance H (capillary rise). Hence, work is done in each case of capillary tube radius and can be expressed mathematically thus: $W = H * \sum\Upsilon^{*}_{w}$

Where H is the capillary rise and $\sum\Upsilon^{*}_{w}$,is the resultant of the intermolecular forces that act within the liquid (water), air, solid (glass tube) interface. The forces are as follows:

- The adhesion of water to the glass tube,
- The adhesion (cohesion) of water to itself,
- The adhesion of water to air,
- Gravity.

These forces counteract each other and the resultant drives a column of water through the capillary tube up its hydrologic level to a distance H (capillary rise). Let the resultant intermolecular energy within the liquid (water), air, solid (interface) be Υ_w, hence it is equivalent to the potential energy of the capillary rise. (Law of conservation of energy),

Mathematically; $\Upsilon_w = mgH$……………………………………(16)

$$\Upsilon_w = e_w \, vgH$$

Using a cylindrical capillary tube with water

$$\Upsilon_w = e_w(\prod R^2H)gH$$

$$= e_w \prod R^2H^2g$$

Substituting the values of g and ∏ (For $g = 9.8m/s^{2}$, And $\prod = 3.142$)

$$\Upsilon_w = 31e_w \, (RH)^2$$

For density of water, $e_w = 1000kg/m^3$

$$\text{Thus, } \Upsilon_w = 31000 \, (RH)^2$$

$$\Upsilon_w = (176RH)^2 \text{……………………………………(17)}$$

Table 4

$D_{(mm)}$	**$R_{(mm)}$**	**Capillary Rises $H_{(mm)}$**			**$H_{(avg)}$**	**$(176RH_{avg})^2$**	**$(176RH_{avg})^2_{(J)}$**
1.0	0.50	27	27	26	26.67	5508221	5.508×10^{-6}
1.5	0.75	18	18	17	17.67	5440276	5.440×10^{-6}
2.0	1.00	14	13	13	13.33	5504091	5.504×10^{-6}

4.3 Analysis of Data in Table 4

From the table above, it can be seen that the energy causing the capillary rise (resultant intermolecular energy) of water at room temperature in various sizes of capillary tube is constant

Hence $\Upsilon_w = MgH = 5.5x\ 10^{-6}$ J………………………..(18)

The resultant intermolecular energy, i.e the potential energy of the capillary risen water at a constant temperature in a particular kind of capillary tube materials is constant

Mathematically: $MgH. = M_1G.H_1 = M_{1.5}gH_{1.5} = M_2gH_2$……………………………..(19)

Where $M_1G.H_1 = M_{1.5}gH_{1.5} = M_2gH_2$ are the potential energies of the capillary risen liquid in capillary tube of diameter 1mm, 1.5mm and 2.0mm respectively.

$$e_w = M_1/V_1 = M_{1.5}/V_{1.5} = M_2/V_2$$

Therefore; $M_1gH_1 = M_2gH_2$

Hence $e_w\ V_1\ g\ H_1 = e_w\ V_2\ g\ H_2$

$$V_1H_1 = V_2H_2$$

For a cylindrical capillary tube volume $V = \prod R^2H$

Hence: $\prod R_1{}^2H_1H_1 = \prod R^2{}_2H_2H_2$

$\prod R_1{}^2H_1{}^2 = \prod R_2{}^2H_2{}^2$

$R_1H_1 = R_2H_2$

:- $R_1/R_2 = H_2/H_1$…………………………………….(20)

This implies that the radius of capillary tube determines or affects the capillary rise. Hence, the smaller the radius, the higher the rise.

This also confirms the validity of the deductions and formula which says or expresses the potential energy of the capillary rise in a particular kind of capillary tube material and at a constant temperature to be constant.

Since $R\ \alpha\ 1/H$ from the experiment conducted and

$R = 13.33/H$ ……………………………………….(15)

And as deduced lately, that $R_2/H_1 = R_1/H_2$ **……………………………..(20)**

Thus, the hypothesis is hereby ascertained and satisfied.

It was also observed that the capillary tubes were capable of holding or retaining a rise of water greater than the capillary rise it can normally hold at that temperature.

Table 5

$R_{(mm)}$	$H_{(mm)}$			$H_{f(mm)}$			H(avg)	H_f(avg)	$H_{f(avg)}/H_{(avg)}$
0.50	27	27	26	41	40	36	26.67	39.00	1.46
0.75	18	17	18	28	25	23	17.67	25.33	1.43
1.00	14	13	13	21	18	20	13.33	17.07	1.470

H represents capillary Rise.

H_f represents Ebukapillary rise. (i.e False Capillary rise)

4.4 Analysis of Data In Table 5

From the above data, it can be seen that when immersed and isolated from water, the capillary tube retains a rise of water about 1.45 times the capillary rise it can normally hold at that temperature. This rise is a false rise, and i called it *Ebukapillary rise*. 1.45 is a constant which is the ratio of *Ebukapillary rise* to the Capillary rise and i called it *Ebukapillary constant*.

Capillarity in water occurs only when the adhesion of water to solid (in this case, the sides of a glass tube) it greater than the resulting (cohesion of the water) adhesion of water to itself. In other words, the forces that act to pull a column of water up the capillary tube are as follows;

❖ The adhesion of water to glass tube

❖ The adhesion of water to air. This acts to increase

❖ The surface area of water at that temperature The forces that act to resist the rise are thus:

❖ The cohesive or resultant surface tension of water owing to air.

❖ Gravity

However, the potential energy of the stored water is equal to the resulting adhesive energy, so that gravity impedes the rise by limiting it to a point where it experiences equilibrium.

Hence; the potential energy of the capillary risen water in a glass tube is constant at constant temperature and is equal to the resulting intermolecular energy which causes the rise. This can be stated mathematically thus;

$MgH = \Upsilon_w = A_{wG} + A_{WA} - A_{WW}$..(21)

Where Υ_w = resulting intermolecular energy

A_{wG} = Adhesive energy of water to glass

A_{WA} = adhesive energy of water to air

A_{WW} = Cohesion/Adhesive energy of water to water When the capillary tube was immersed in water and removed at once (with caution), an *Ebukapillary rise* (false capillary rise) was noticed and it is 1.45 times the normal capillary rise that capillary tube can cause.

Hence, the energy due to the *Ebukapillary rise*

$1.45\Upsilon_w$ can be expressed thus:

$1.45\Upsilon_w = A_{wG} - A_{WA} + A_{WW}$…………………………………..(22)

Let $(A_{WW} - A_{WA}) = C_{WW}$ (the resulting surface tension energy of water)………………………..(23)

Substituting (23) in (21);

Hence $\Upsilon_w = A_{WG} - C_{WW}$ ______ (24)

Substituting (23) in (22);

$1.45\Upsilon_w = A_{WG} + C_{WW}$ _____ (25)

Subtracting (24) from (25)

$1.45\Upsilon_w - \Upsilon_w = A_{WG} + C_{WW} - A_{WG} + C_{WW}$

$0.45\Upsilon_w = 2C_{WW}$

$0.225\Upsilon_w = C_{WW}$ ____ (26)

Substituting equation (26) in (24)

$\Upsilon_w = A_{WG} - 0.255\Upsilon_w$

$A_{WG} = 1.225\Upsilon_w$ ______(27)

$\Upsilon_w = 5.5 \text{ x } 10^{-6}$KJ…………………………(18)

Substituting (18) in (27)

:- $A_{WG} = 1.225\Upsilon_w$

$= 1.225 \text{ x } 5.5 \text{ x } 10^{-6}$

$= 6.74 \text{ x}1\ 0^{-6}$J………………………………….(28)

Substituting (18) in (26)

$C_{ww} = 0.225 \text{ x } 5.5\text{x}10^{-6}$

$C_{ww} = 1.24 \text{ x } 10^{-6}$J………………………………(29)

C_{ww} is the surface Energy of water (the resultant intermolecular energy between water and air). Hence the surface tension of water (Υ_w') at this temperature can be obtained by dividing C_{ww} by the specific capillary rise of water ($k_w = 13.33\text{mm}^2$) at same room temperature.

Mathematically,

$\Upsilon_w' = C_{ww}/ k_w$…………………………..(30)

Substituting (29) and (15) in (30)

$=1.24 \text{ x } 10^{-6}/ 13.33 \text{ x } 10^{-6}$

$\Upsilon_{w}' = 0.093$N/m

This value is actually close to the theoretical value of 0.078N/m, hence the formula is valid. The variation can be attributed to variations in physical (temperature, density etc), material or methodology.

4.5 Observations Made From Experiment (II)

- When i placed an open end of a capillary tube in contact with the surface of kerosene, the kerosene rose into the capillary tube up to a height (capillary rise)
- I also noticed that when i removed the capillary tube from the surface of kerosene, it yet retained some amount or rise of kerosene, which of course is the capillary rise
- When i used different sizes of capillary tube, i realized that the resulting capillary rise varied with different radius of capillary tubes.
- When i immersed the capillary tubes in kerosene and withdrew it, at once with caution, i noticed a retained rise of kerosene in the capillary tube which was obviously held.
- When i brought the capillary tube back in contact with the surface of kerosene, part of the retained water discharges and the rise reduced to the corresponding capillary rise of the tubes.

Table 6

D$_{(mm)}$	**R**$_{(mm)}$	**Capillary(H) rise**$_{(mm)}$			**Average Cap Rise H**$_{(avg)(mm)}$
1.0	0.50	13	12	13	12.67
1.5	0.75	9	8	8	8.37
2.0	1.00	6	6	7	6.33

4.5.1 ANALYSIS OF DATA: TABLE 6

From the data obtained in the above table, it can be seen that increase in the capillary tube radius results in decrease in the resulting capillary rise. The radius of the capillary tube (R)is therefore inversely proportional to the capillary rise (H).

Mathematically: $R \alpha 1/H$

$R = K_k/H$, $RH = K_k$

When $R = 1$, $1 = K_k/6.33$

$K_k = 6.33$…………….(31) *K_k is a constant i hereby called the specific capillary rise of kerosene.*

Taking a deductive approach to the variation in capillary rise with the radius of capillary tube, i can refer the causative (resultant) force of capillary to the law of conservation of energy which states that energy can never be created nor destroyed but converted from one form to another. Work is expressed mathematically as force * distance covers so the resulting intermolecular force from the capillarity assembly drives a column of kerosene up its hydrologic level to a distance H (capillary rise). Hence, work is done and can be expressed in each case of capillary tube radius as;

$W = H * \sum\Upsilon^*_k$

Where W is the work done, it is the capillary rise and $\sum\Upsilon^*_k$ is the resultant of the intermolecular forces that acts within the kerosene, air and glass tube interface. The forces are as follows:

- The adhesion of kerosene to the glass tube,
- The adhesion (cohesion) of kerosene to itself,
- The adhesion of kerosene to air,
- Gravity.

These forces counteract each other and the resultant drives a column of kerosene into the capillary tube (up its hydrologic level) to a distance H (capillary rise) where it experiences equilibrium. Let the resultant intermolecular energy be Υ_k, hence it is equivalent to the potential energy of the capillary rise (law of conservation of energy).

Mathematically: $\Upsilon_k = MgH$…………………………(15)

$\Upsilon_k = MgH$

$\Upsilon_k = e_k VgH$

Using a cylindrical capillary tube

$$\Upsilon_k = e_k (\prod R^2 H)\, gH$$

$$= e_k \prod g\, R^2 H^2$$

Substituting the values of g and ∏

$$\Upsilon_k = 31\, e_k\, (RH)^2$$

For density of kerosene, $e_k = 815 kg/m^3$

Thus $\Upsilon_k = 25265\, (RH)^2$

$$\Upsilon k = (159RH)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(32)$$

Table 7

D$_{(mm)}$	**R$_{(mm)}$**	**Capillary rise H$_{(mm)}$**			**Havg$_{(mm)}$**	**$(159RH)^2$(J)**
1.0	0.50	13	12	13	12.67	$1.014\text{x}10^{-6}$
1.5	0.75	9	8	8	8.73	$1.000\ \text{x}10^{-6}$
2.0	1.00	6	6	7	6.33	$1.013\text{x}10^{-6}$

4.5.2 Analysis of Data Table 7

From the above table, it can be seen that the energy causing the capillary rise (resultant intermolecular energy) of kerosene at room temperature in various sizes of capillary tube is constant.

Hence $\Upsilon_k = MgH = 1.01 \text{ x } 10^{-6} J \ldots\ldots\ldots\ldots\ldots\ldots\ldots..(33)$

The resultant intermolecular energy, i.e the potential energy of the capillary risen kerosene at a constant temperature in a particular kind of capillary tube material is constant.

Mathematically: $\Upsilon_{k=}\ MgH = M_1gH_1 = M_{1.5}gH_{1.5} = M_2gH_2$…………………………(19)

Density, $e = M/v$

For kerosene as the capillary fluid , density of kerosene, $e_k = M_1/V_1 = M_{1.5}/V_{1.5} = M_2/V_2$

Hence, $\Upsilon_k = M_1gH = M_2gH_2$

$e_k V_1gH_1 = e_k V_2gH_2$

$V_1H_1 = V_2H_2$

For a cylindrical capillary tube where R = Capillary radius and H = Capillary rise

$\prod R^2{}_1H_1H_1 = \prod R^2{}_2H_2H_2$

$\prod R^2{}_1 1H_1{}^2 = \prod R_2{}^2H_2{}^2$

$R_1H_1 = R_2H_2$

:- $R_1/R_2 = H_2/H_1$…………………………………(20)

This implies that the radius of the capillary tube determines or is proportional to the capillary rise. Hence, the smaller the radius, the higher the rise. This also confirms the validity of the deductions and formula which says or expresses the potential energy of a capillary risen (kerosene) liquid in a particular kind of capillary tube material and at a constant temperature to be constant since R α 1/H from the experiment i conducted and

$R H = K_k = 6.33$…………………………………..(31)

Agrees with $R_2/R_1 = H_1/H_2$ as deduced latterly, then the

Hypothesis is certain and satisfied.

It was also observed that the capillary tubes were capable of holding or retaining a rise of kerosene greater than the capillary rise, it can normally hold at that temperature.

Table 8

R $_{(mm)}$	**Capillary (H)rise** $_{(mm)}$	**H_f** **Ebukapillary rise** $_{(mm)}$	**H_{avg}**	**H_{favg}**	**H_{favg}/H_{avg}**

0.50	13	12	13	20	20	18	12.67	18.67	1.47
0.75	9	8	8	13	12	12	8.33	12.37	1.48
1.00	6	6	7	9	9	10	6.33	9.33	1.47

4.5.3 Analysis of Data in Table 8

From the above data, it can be seen that when i immersed and isolated from kerosene, the capillary tube can hold or retain a rise of kerosene is about 1.47 * the capillary rise it can normally hold at that temperature. This rise is a false rise, and i called it *Ebukaapillary Rise*. 1.47 is approximately 1.5, but it is closer to 1.45, hence take Hf/A_{AV} for kerosene = 1.45.

1.45 is a constant which is the ratio of False Capillary rise to the capillary rise, and i called it *Ebukapillary Constant*.

Capillarity in kerosene occurs only when the adhesion of kerosene to a solid (in this case the sides of a glass tube) is greater than the resulting (cohesion of kerosene) adhesion of kerosene to itself. Thus, the forces that act to pull a column of kerosene up the glass capillary tube are as follows:-

- The adhesion of kerosene to the glass tube,
- The adhesion of kerosene to air. This acts to increase the surface area of kerosene at that temperature.

The forces that act to resist the rise are as follows:

- The cohesive or resultant surface tension of kerosene to air.
- Gravity.

However, the potential energy of the stored kerosene is equal to the resulting adhesive energy, so gravity impedes the rise by limiting it to a point where it experiences equilibrium. Hence the potential energy of the capillary risen kerosene is equal to the resulting intermolecular energy which causes the rise. This can be stated mathematically thus:

$MgH = \Upsilon_K = A_{kG} + A_{KA} - A_{KK}$…………………………………….(21)

Where Υ_k = resulting intermolecular energy

A_{KG} = Adhesive energy of kerosene to glass

A_{KA} = Adhesive energy of kerosene to air

A_{KK} = Adhesion/cohesive energy of kerosene to itself

Hence, the energy due to the Ebukapillary rise is $1.47\Upsilon_K$ and can be expressed thus

$1.47\Upsilon_K = A_{KG} - A_{KA} + A_{KK}$ ……………………………(22)

Let $(A_{KK} - A_{KA}) = C_{KK}$ ………………………………..(23) (the resulting surface tension energy of kerosene).

Substituting (23) in (21)

:- $\Upsilon_K = A_{KG} - C_{KK}$ ______(24)

Substituting (23) in (22)

$1.47\Upsilon_K = A_{KG} + C_{KK}$ _____ (34)

Subtracting equation (24) from (34)

$1.47\Upsilon_k - \Upsilon_K = A_{KG} + C_{KK} - A_{KG} + C_{KK}$

$0.47\Upsilon_K = 2\ C_{KK}$

$0.235\Upsilon_K = C_{KK}$ _____ (35)

Substituting (35) in (24)

$\Upsilon_K = A_{KG} - 0.235\ \Upsilon_K$

$1.235\Upsilon_K = A_{KG}$ _____ (36)

Substituting (36) in (24)

$\Upsilon_K = 1.235\Upsilon_K - C_{KK}$

$C_{KK} = 0.235\Upsilon_K$……………………..(35)

Substituting (33) in (35)

$C_{KK} = 0.235 \times 1.0 \times 10^{-6}$

$C_{KK} = 2.35\text{x}10^{-7}J$………………….(37)

$A_{KG} = 1.235\Upsilon_K$…………………………(36)

Substituting (33) in (36)

$A_{kG} = 1.235 * 1.0 * 10^{-6}$

$A_{kG} = 1.235 * 10^{-6}J$

C_{KK} is the surface Energy of kerosene (the resultant intermolecular energy between kerosene and air). Hence the surface tension of kerosene (Υ_K') at this temperature can be obtained by dividing C_{KK} by the specific capillary rise of kerosene ($k_k = 6.33mm^2$) at same room temperature.

Mathematically: $\Upsilon_K' = C_{KK} / k_k$…………………………..(38)

Substituting (31) and (27) in (38)

$$\Upsilon_K' = 2.35 \times 10^{-7} / 6.33 \times 10^{-6}$$

$$\Upsilon_K' = 0.037N/m$$

This value is actually close to the theoretical value of 0.03N/m, hence the formula is valid. The variation can be attributed to variations in physical (temperature, density etc), material or methodology.

4.6 Observation Made From Experiment (III)

- When i placed an open end of a glass capillary tube in contact with the surface of diesel, the diesel rose into the capillary tube, up to a height (capillary rise).
- I noticed also that when i removed the capillary tube from the surface of diesel, it yet retained same amount or rise of diesel, which of course is the capillary rise.
- When i used different sizes of capillary tube, i realized that the resulting capillary rise varied with different radius of capillary tube.
- When i immersed the capillary tube in diesel and withdrew it at once with caution, i noticed a retained rise of diesel in the capillary tube, which was obviously greater than the capillary rise that the tube normally holds.
- When i brought the capillary tube back in contact with the surface of diesel, part of the retained diesel discharged and the rise reduced to the corresponding capillary rise of the tube.

Table 9

D(mm)	R(mm)	Capillary rises (mm)			Average Capillary rise (mm)
1.0	0.50	14	13	13	13.33
1.5	0.75	10	9	9	9.33
2.0	1.00	7	6	7	6.67

4.6.1 Analysis of Data in Table 9

From the above data in the above table, it can be seen that increase in the capillary tube radius results in decrease in the resulting capillary rise. The radius of the capillary tube is therefore inversely proportional to the capillary rise.

Mathematically: $R \alpha 1/H \quad R = K_D/H, RH = K_D$

When $R = 1, H = 6.67$

Hence, for $RH = K_D$

$1 \times 6.67 = K_D = 6.67$…………………………(39)

K_D is the specific capillary rise of Diesel oil. Thus it is the capillary rise of diesel per unit capillary radius at room temperature.

Taking a deductive approach to the variation in capillary rise with the radius of capillary tube, i can refer the causative (resultant) force of capillarity to the law of conservation of energy which states that energy cannot be created nor destroyed but converted from one form to another. Work is expressed mathematically as force * distance, so the resulting intermolecular force from the capillary arrangement drives a column of diesel up its hydrologic level to a distance (H) (capillary rise). Hence, work is done and can be expressed in each case of capillary tube radius as : $W = H \times \sum \Upsilon^{1}_{D}$

Where W is the work done, it is the capillary rise and $\sum\Upsilon^1_D$ is the resultant of the intermolecular forces that acts within the diesel, air and glass tube interface

The forces are as follows:-

- The adhesion of diesel to glass tube,
- The cohesion (adhesion) of diesel to itself,
- The adhesion of diesel to air.

These forces counteract each other and the resultant drives a column of diesel into the capillary tube (up its hydrologic level) to a distance H (capillary rise) where II experiences equilibrium. Let the resultant intermolecular energy be Υ_D, hence it is equivalent to the potential energy of the capillary rise (Law of conservation of energy).

Mathematically, $\Upsilon_D = MgH$……………………………(15)

$$\Upsilon_D = e_D VgH$$

Using a cylindrical capillary tube

$$\Upsilon_D = e_D (\prod gH^2R^2) \quad \text{where } e_D \text{ is the density of diesel.}$$

Substituting the values of g and ∏ (where $g = 9.8 m/s^2$ H is capillary rise, R is capillary radius and ∏ is 3.142)

$$\Upsilon_D = 31e_D (RH)$$

For diesel, $e_D = 850 kg/m^3$

Thus $\Upsilon_D = 26350 (RH)^2$

$$\Upsilon_D = (162RH)^2 \text{……………………………….}(40)$$

Table 10

D$_{(mm)}$	**R**$_{(mm)}$	**CapillaryRise H** $_{(mm)}$			**H**$_{AVG(mm)}$	**(162RH$_{AVG}$)** $^2{}_{(J)}$
1.0	0.50	14	13	13	13.33	$1.16x10^{-6}$

1.5	0.75	10	9	9	9.33	$1.28 \text{x} 10^{-6}$
2.0	1.00	7	6	7	6.67	$1.17 \text{x} 10^{-6}$

4.6.2 ANALYSIS OF DATA IN TABLE 10

From the above table, it can be seen that the energy causing the capillary rise (resultant intermolecular) of diesel at room temperature in various sizes of capillary tube is constant. Hence take Υ_D **=** $1.20 \text{ x } 10^{-6}{}_J$ room temperature

Mathematically: $MgH = \Upsilon_D = 1.2 \text{ x } 10^{-6}{}_J$ ……………………(41)

The resultant intermolecular energy, i.e the potential energy of the capillary risen diesel at a constant temperature in a particular kind of capillary tube material is constant

Mathematically: $\Upsilon_D = M_1gH_1 = M_{1.5}\, gH_{1.5} = M_2\, gH_2$ **……………………………..(19)**

Since $e_D = m/v$

$M_1/V_1 = M_{1.5}/V_{1.5} = M_2/V_2$

Hence, $M_1gH_1 = M_2gH_2$

$e_D\, V_1gH_1 = e_D\, V_2gH_2$

$V_1H_1 = V_2\, H_2$

Using cylindrical capillary tubes $R_1{}^2H_1)\, H_1 = (\prod R_2{}^2H_2)H_2$

$R_1{}^2H^{12} = R^2{}_2\, H_2{}^2$

$H_1R_1 = R_2H_2$

:- $R_1/R_2 = H_2/R_1$………………………..(20)

This implies that the radius of the capillary tube determines the capillary rise. Hence, the smaller the radius, the higher the rise. This also confirms the validity of the deductions and formula which says or expresses the potential energy of a capillary risen (diesel) liquid in a particular kind of capillary tube material and at a constant temperature to be constant.

Since R α 1/H from the experiments i conducted and R = 6.67/H agrees with $R_2/R_1 = H_1/H_2$ as deduced lately, then the hypothesis is hereby ascertained and satisfied.

it was also observed that the capillary tubes were capable of retaining a rise of diesel greater than the capillary rise, it can normally hold at that temperature.

Table 11

$R_{(mm)}$	Capillary rise (H) $_{(mm)}$			H_f rises			H_{avg}	H_{favg}	H_f/H
0.50	14	13	13	20	20	19	13.11	19.67	1.41
0.75	10	9	9	14	13	14	9.33	13.67	1.46
1.00	7	6	7	10	10	9	6.67	9.67	1.45

4.6.3 Analysis of Data in Table 11

From the data in table (III) III, it can be seen that when i immerged and isolated a capillary tube from diesel, the capillary tube could hold or retain a rise of diesel about 1.46, the capillary rise II can normally hold at that temperature. This rise is a false rise, and i called it *Ebukapillary rise* (Hf). 1.46 is approximately 1.5, but it is closer to 1.45, hence take Hf/H for diesel to be 1.45. Thus, 1.45 is a constant which is the ratio of *Ebukapillary rise* to Capillary rise of a liquid and i called it *Ebukapillary constant*.

Capillarity in (a liquid) diesel occurs only when the adhesion of diesel to a contacted solid (in this case the sides of a glass tube) is greater than the resulting cohesion of diesel to itself. In other worked, the forces that act to pull a column of diesel up the glass capillary tube are as follows;

- The adhesion of diesel to the glass tube.
- The adhesion of diesel to air. This acts to increase the surface area of diesel at room temperature.

The forces that act to resist the rise are thus;

- The cohesive or resultant surface tension of diesel to air.
- Gravity

However, the potential energy of the stored diesel is equal to the resulting adhesion energy of the stored diesel is equal to the resulting (adhesion energy), energy that causes capillary rise, so gravity only acts to impede the rise by limiting it to a point where the diesel (liquid) experiences equilibrium. Hence, the potential energy of the capillary risen diesel is equal to the resulting intermolecular energy that causes the rise. This can be stated mathematically thus;

$MgH = \gamma_D = A_{DG} + A_{DA} - A_{DD}$…………………………..(21)

Where; γ_D = resulting intermolecular energy of the diesel glass tube, air interface.

A_{DG} = Adhesion energy of diesel to glass

A_{DA} = Adhesion energy of diesel to air

A_{DD} = Adhesion/cohesion energy of diesel to itself

Hence, the energy due to the False Capillary rise is 1.46 γ_D and can be expressed thus;

$1.46\ \gamma_D = A_{DG} + A_{DD} - A_{DA}$……………………………..(42)

Let $(A_{DD} - A_{DA}) = C_{DD}$…………………(23) (the resulting surface tension energy of diesel in air).

Substituting (23) in (21)

Therefore, $\gamma_D = A_{DG} - C_{DD}$ …………………………… (24)

Substituting (23) in (42)

$1.46\ \gamma_D = A_{DG} + C_{DD}$…………………… (43)

Subtracting (24) from (43)

$1.46\ \gamma_D - \gamma_D = A_{DG} + C_{DD} - A_{DG} + C_{DD}$

$0.46\ \gamma_D = 2\ C_{DD}$

$0.23\ \gamma_D = C_{DD}$……………………………….. (44)

Substituting equation (44) in (24)

$\gamma_D = A_{DG} - 0.23\gamma_D$

$1.23\ \gamma_D = A_{DG}$ …………………………………… (45)

$\gamma_D = 1.25 \times 10^{-6}$J………………….(41)

Substituting (41) in (44)

C_{DD}= 0.23 x 1.25 x 10^{-6}

= 2.87 x 10^{-7}J…………………….(46)

Substituting (41) in (45)

$A_{DG} = 1.23\ \gamma_D$

= 1.23 X 1.25 x 10^{-6}

A_{DG} = 1.54 x 10^{-6}J…………………………(47)

C_{DD} is the surface Energy of Diesel oil (the resultant intermolecular energy between Diesel oil and air). Hence the surface tension of Diesel oil (Υ_K') at this temperature can be obtained by dividing C_{DD} by the specific capillary rise of Diesel oil (k_D = 6.67mm^2) at same room temperature.

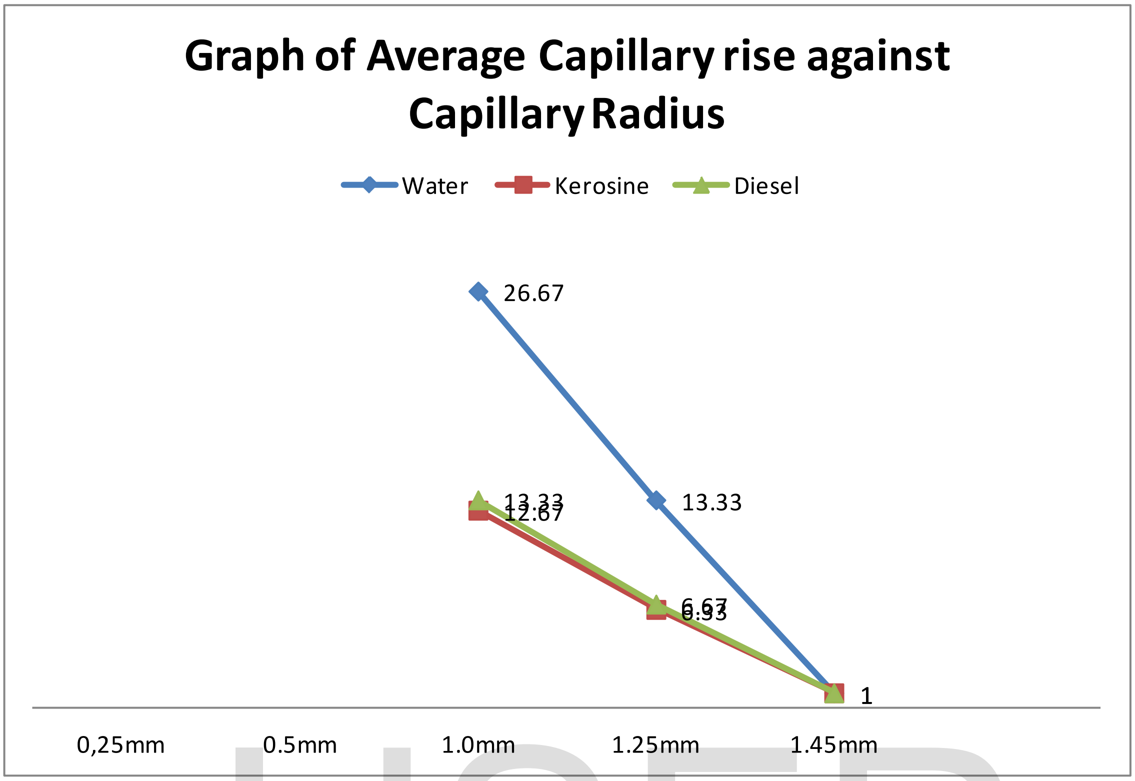
Mathematically: $\Upsilon_D' = C_{DD} / k_D$…………………………..(48)

Substituting (42) and (46) in (48)

Υ_D' =2.87 x 10^{-7}/ 6.67 x 10^{-6}

Υ_D'= 0.043N/m

This value is actually close to the theoretical value of 0.033N/m, hence the formula is valid. The variation can be attributed to variations in physical (temperature, density etc), material or methodology.



Analysis of the Graph

This graph is not to scale, however when plot on paper, you will see that the best line of fit for all the three plots are the values corresponding to the 0.5mm capillary radius and 1.0mm capillary radius respectively.

The plot for kerosene and Diesel are too close such that they can be assumed to be the same. This is because their densities are too close.

The plot for kerosene or Diesel is farther from that of water. This is actually because their densities are not too close.

It is seen that liquids exhibit similar capillary rise if i use a capillary radius of 1.45mm.

Hence i deduced that at room temperature (the temperature at which the experiment was conducted), a glass capillary tube of radius 1.45mm will cause a rise of 1mm in all liquids, provided the density of the liquid is less than that of the capillary tube. In other word the *Specific Capillary Rise* of all liquids at a particular temperature and in a particular kind of capillary tube will only coincide or equal at a value of 1.45.

FINDINGS

The law of conservation of energy holds virtually in every aspect of science and i found out that the phenomenon of capillarity is not an exception.

Capillary rise of any liquid in a glass capillary tube is of constant potential energy regardless of the radius of the capillary tube used, provided temperature remains constant.

The radius of a capillary tube is inversely proportional to its corresponding capillary rise of a liquid.

At constant temperature, the product of capillary radius and corresponding capillary rise is constant for any liquid.

The higher the density of a liquid, the higher the specific capillary rise at a constant temperature.

Denser liquids give rise to a greater magnitude of capillary rise.

A capillary tube is capable of retaining a column of liquid about 1.45 times greater than its corresponding capillary rise.

The potential energy in an Ebukapillary rise is about 1.45 times greater than the potential energy of the corresponding Capillary rise.

4.7 CONCLUSION

The H_f/H values for water diesel and kerosene are 1.45, 1.46 and 1.47 respectively. These values are too close and are hereby taken as constant for all liquids (that exhibit capillary rising). The values are approximately 1.5 but are closer to 1.45. Hence let the Ebukapillary constant for all the liquids be taken as 1.45.

Hence;

$\gamma_{**} = A_{*G} + A_{*A} - A_{**}$……………………….(21)

$1.45\ \gamma_{**} = A_{*G} + A_{**} - A_{*A}$………………….(22)

That can be rewritten as;

$\gamma_{**} = A_{*G} - C_{**}$…………………………….(24)

$1.45\ \gamma_{**} = A_{*G} + C_{**}$……………………….(25)

Where;

γ_{**} = resulting intermolecular energy of a capillary liquid

A_{*G} = the adhesion energy of the capillary liquid to glass.

C_{**} = the resulting cohesion energy of the capillary liquid to itself in the presence of air.

A_{**} = the adhesion energy of the capillary liquid to air.

$A_{*\ A}$ = the absolute adhesion energy of the capillary liquid to itself.

The rest of the formula derived In this project work are as follows;

Specific capillary rise of water (K_w) = 13.33………………………….(15)

Hence RH = 13.33 at room temperature.

Specific capillary rise of kerosene (K_K) = 6.33………………………(31)

Hence RH = 6.33 at room temperature.

Specific capillary rise of diesel (K_D) = 6.67…………………(39),

Hence, RH = 6.67 at room temperature.

At any temperature,

The resulting intermolecular energy in a Capillarity assembly is:

$\gamma_{**} = e_{**}31(RH)^2$.......................................(49)

Where e_{**} is the density of the capillary fluid, R is the capillary radius and H is the capillary rise.

At Room temperature,

The resulting intermolecular energy for water γ_w

$\gamma_w = (176RH)^2$……………………………(17)

The resulting intermolecular energy for kerosene, γ_k

$\gamma_k = (159RH)^2$…………………………..(32)

The resulting intermolecular energy for diesel, γ_D

$\gamma_D = (162RH)^2$…………………………..(40)

Hypothesis and deductions postulated from this project;

- The potential energy of a capillary risen liquid is constant at constant temperature.
- The resultant of the intermolecular energies in a capillary action or assembly is equal to the potential energy of the capillary risen liquid at constant temperature and materials.
- Increase in capillary radius results in decrease in the capillary rise.
- Increase in density of liquid results in increase in the resulting capillary rise.
- A capillary tube is capable of retaining an *Ebukapillary rise* (i.e a false capillary rise) of a liquid and which is about 1.45 times greater than the capillary rise it can normally cause at that temperature.
- The Phenomenon whereby at constant temperature, a capillary material is capable of holding a quantity of liquid greater than it's normal capillary retention is hereby called *Ebukapillarity*.
- The ratio of liquid retained due to Ebukapillaritry to that retained as a result of Capillarity is constantly 1.45 and this constant is hereby called *Ebukapillary Constant*.
- At constant temperature and material, the product of the capillary rise of a liquid and its capillary radius is constant and is hereby called the *Specific Capillary Rise* of the liquid at that temperature.
- At constant temperature and material, Specific Ebukapillary Rise is the uniform specific capillary rise of all liquids that exhibit capillary rising and it is constantly 1.45mm.

CHAPTER FIVE

5.0 SUMMARY AND RECOMMENDATIONS

From the forgoing, it can be summarized that capillarity occurs as long as the attraction of a liquid to a solid it contacts is different from the resulting attraction of the liquid to itself. An Ebukapillary rise (i.e a false capillary rise), occurs when an immersed capillary tube, which is filled or almost filled with the liquid it is immersed in, is gently isolated to stand in the capillary tube and surrounded only by air. I rephrased the statement thus;

Ebukapillarity results in a false capillary rise i called Ebukapillary rise. The ratio of Ebukapillary rise to the corresponding Capillary rise of any liquid is constant regardless the radius of the capillary tube, the nature of the liquid or temperature, provided the vicinity is air filled.

The law of conservation of energy states that energy can never be created nor destroyed but can be converted from one form to another. I found out that this law holds in virtually every aspect of science and the phenomenon of capillarity is not an exception. The capillary rise or depression of a liquid in a particular material of capillarity tube is of constant potential energy provided the temperature is constant. Capillary action or capillarity is only a mechanism that aids the conversion of the resulting cohesive force (Surface tension) or adhesive force (wetting) between the capillary tubes, liquid and air layer into potential energy. In nature, every system strives for equilibrium, which can or can never be reached.

The undisturbed surface or liquid resting in equilibrium with its container and atmospheric pressure happens to be disrupted/ disturbed by the surface of the capillary tube in contacts.

In order to annul this effect, a liquid column rises into the capillary tube, up to a height (capillary rise) where it experiences equilibrium again.

Work is expressed mathematically as the product of force and distance. So the resulting force from the capillary assembly drives a column of the liquid up or down its hydrologic level to a distance called the capillary rise and that is where the system experiences equilibrium again. For a particular liquid, and a particular capillary tube, the potential energy of the capillarity action is constant regardless of the radius of the capillary tube used, provided temperature remains constant.

5.2 RECOMMENDATIONS

An Increase in the temperature of liquid results in a decrease in its capillary rise and consequently potential energy of the capillary action.

The potential energy of a capillary action and the corresponding capillary rise in a particular liquid varies inversely with increase in temperature of the liquid.

Capillarity can possibly occur only in the presence of a liquid, and air.

Density is a determining factor of capillary rise but not viscosity.

The higher the density of a liquid, the higher the specific capillary rise at a temperature.

Denser liquids give rise to a greater magnitude of capillary rise.

A liquid will only exhibit capillary rise when it is in contact with a solid surface denser than it.

When a liquid is in contact with a liquid surface it is denser than, the liquid would exhibit capillary depression.

Ebukapillarity is seen to possibly occur only when there is a capillarity rise.

Regardless of temperature, the Ebukapillary constant remains about 1.45 for all capillary raised liquid in a capillary action.

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