A deliberation on the surface tension theory

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Abstract

It is shown that surface tension is not the reason causing minimization of the surface of a liquid pile. It is shown that there exists a pressure inside the liquid arising from the inward intermolecular resultant force on the surface molecules exerted by the liquid molecules adjacent to the surface. We call it as cohesion pressure. A method is presented for measuring the intermolecular attraction which will be also a means for testing the theory in comparison with the current theory of surface tension. It is proven that the surface tension is not what causes the horizontal wire sliding on the two limbs of a U-shaped wire to be in equilibrium in any position when a liquid film forms the area of the U-shaped wire. In a sure manner, incorrectness of the current relation $\Delta p = 4\gamma/R$, for the pressure difference between inside and outside of a bubble having radius R, and $\Delta p = 2\gamma/R$, for the one related to a solid drop having radius R, is proven. It is shown that the adhesion reduces the pressure inside the liquid, because a part of the liquid weight is sustained by the walls of the container. The mechanism of capillarity is discussed in detail in terms of intermolecular attraction and cohesion pressure. Dependence of rise altitude on depth of dipping and dependence of fall depth on depth of dipping are properties in capillarity; this is predicted by the theory presented in this paper and not by the theory of surface tension, and then can be a practical test for the theory.

1 Introduction

Surface tension in liquids is a very familiar subject in physics. Although in many of the sources discussing this phenomenon, to the existence of the resultant force of intermolecular attraction exerted inwardly on the molecules of the liquid surface has been pointed, no logical relation has been established between this inward attraction and external demonstrations which are attributed to the surface tension. In other words since in the first view it seems that these demonstrations can be justified by assuming a tension only on the liquid surfaces, the problem has been taken by the physicists as simple and solved, without being careful in the details of the reasonings presented for these justifications. In this paper, being careful about the details of the discussions, it is shown explicitly that the problem has not been solved as it is thought and also its solution is not so easy in some cases. In quite simple words it is shown that what is attributed to the tension between only the molecules on the liquid surface is in fact related to the tension between all the molecules, and because of the existence of measurable experimental parameters we cannot even, as an apparent form, attribute it to the surface tension.

2 Justifying the existent facts and experiments

2.1 Minimum surfaces

What distinguishes between solid, liquid and gas is the attraction force between the molecules. In solid this force is so strong that exertion of external forces cannot cause displacement of the molecules. In liquid this force is sufficiently weak that external forces can cause displacement of the molecules relative to each other, ie although there exists an attraction bond between two molecules, each of these two molecules due to the exertion of some force may give its location to some other molecule. In gas it can be said that there is not at all any attraction between the molecules. What is important for us here is that as we said in liquids there exists an attraction force between each two molecules. Such forces in liquid cause the molecules to assemble in the form of a pile. Consider a pile of liquid. Certainly this set of liquid molecules has an external surface. Consider a molecule of the liquid on this surface. Intermolecular attraction forces exerted on this molecule are only from the liquid molecules inside the pile (adjacent to it) and then it is pulled inwards. Each molecule of the surface has this situation. Therefore, all the molecules of the surface are pulled inwards and certainly each of them, if possible, will go inside the liquid. Displacement of a molecule from the surface towards the inside means decreasing of the surface and increasing of the thickness of the pile. The process of decreasing of the surface continues until the final possible minimum surface will be obtained.

The process of being minimized will exist for the liquid surface even when there are some limiting conditions for the liquid. So eg the liquid limited to the edges of a loop takes a plane form which has minimum surface in this state.

So we see that what causes liquid surfaces to be minimized is the attraction force between all the liquid molecules (normal to the surface) not one between the liquid surface molecules (parallel to the surface).

2.2 Cohesion pressure

It is clear that even when the pile of liquid gets the possible minimum surface, there exists yet the same inward intermolecular attraction resultant force exerted on the surface molecules by the liquid molecules adjacent to the surface. This inward normal force exerted on the liquid surface exerts a pressure on the liquid which will have a distribution throughout the liquid (just like a liquid pile set in the atmosphere which the air pressure affects it in the form of inward normal force exerted on its surface while this pressure is felt throughout the liquid). We call this pressure as cohesion pressure. It is in fact this pressure (beside the air pressure if the liquid is set in the atmosphere) that presses the pile and minimizes its surface.

Consider a liquid drop which on condition of nonexistence of the gravitational attraction and of nonexistence of the external gas pressure exerted on the drop surface (although this recent condition is not necessary) takes the form of a sphere (it is obvious that this form is obtained because it has the minimum surface). Consider a molecule of the liquid on the surface of this sphere. There exists some centerward force, normal to the surface, on this molecule due to the intermolecular attraction forces exerted on it from the inner molecules adjacent to it. Since this molecule is in equilibrium, necessarily there must also exist an equivalent but oppositely directed force on it. This force which is exerted outwardly on this molecule is arising from the cohesion pressure in the liquid of the drop.

We can also divide this sphere into two hemispheres by an imaginary meridional plane. Two equivalent but oppositely directed forces are exerted on the right hemisphere causing its equilibrium : the leftward force arising from the attraction between the molecules of the liquid in the separation surface of the two hemisphere (ie the meridional plane), and the rightward force arising from the cohesion pressure in this separation surface.

Cohesion pressure may be different in different points of a pile of liquid (just as the pressure arising from the weight of the liquid is not the same in different points of the liquid having different heights). To investigate this fact we consider two examples of unstable and stable states:

Consider the unstable state of the liquid pile of Fig. 1 supposing that there are no gravitational attraction and external gas pressure. Certainly the cohesion pressure in the protruding part is less than in other parts. This matter causes that although the same inward attraction force is exerted on a partial surface of the molecular layer forming the surface of this protruding part as on a partial surface of this layer forming the surface of other parts, but since the cohesion pressure under this layer in the protruding part is less than in other parts the outward force exerted on the partial surface of the layer in the protruding part is less than in other parts. Then the resultant force exerted on the partial surface of the layer is inward in the protruding part while it is almost zero in other parts. This causes that the layer is pulled inwards till a spherical shape is obtained for the pile.

Now consider stable state of a liquid drop which while there is no external gas pressure, is resting under the influence of its weight on a rigid surface which is not wetted by the liquid of the drop; see Fig. 2. We know that in each point on the surface of the drop, except that part in contact with the surface S, inward (resultant) force exerted on a partial surface (arising from the intermolecular attractions) is the same. Since each point of the drop is in equilibrium the outward force exerted on the partial surface must have the same magnitude as the inward. This outward force is arising from some pressure under the surface of the drop. This pressure is the sum of two pressures: the pressure arising from the weight of the liquid column above each point and the cohesion pressure. Since we know that the pressure arising from the liquid weight is increased by moving down on the surface from the top, we should inevitably conclude that the cohesion pressure is decreased in the liquid adjacent to the surface by moving down from the top, and in fact the form taken by the drop is for providing this necessary particular form of the cohesion pressure gradient.

Inward force exerted on the liquid surface in contact with the surface S includes both the inward force arising from the intermolecular attraction of the liquid molecules and the reaction (normal) force of the surface S. It is clear that this force must be canceled by the outward forces arising from the liquid weight and cohesion pressures, and since the weight pressure has not so much changed relative to the points of the liquid surface near to but not in contact with the surface S, we conclude that the cohesion pressure has been increased considerably relative to these points.

2.3 Measuring the intermolecular attraction

Consider a solid which the attraction force between a molecule of it and a molecule of a considered liquid is more than the attraction force between two molecules of the liquid. It is obvious that if this solid is dipped into the liquid, the molecules of the liquid will adhere to the body of the solid and wet it. If the intermolecular attraction between a solid molecule and a liquid molecule is less than one between two liquid molecules, the liquid will not wet the solid and won't remain adhered to it after pulling it out of the liquid. Let's make a plane ring from the solid of the first kind, which can be wetted by the liquid, and while its lower surface is in contact with the liquid hang it on the hook of a dynamometer. Now we try to detach it from the liquid surface by pulling it upwards. It is obvious that because of the intermolecular attraction, exertion of some force is necessary for this act. We read this force just in the moment that the ring is detached from the liquid. This force is sum of the attraction forces between the molecules of the liquid under the lower surface of the ring. This force is not sum of the intermolecular attraction forces between the liquid and solid, because as we said the solid is wetted by the liquid and then just in the moment of separation a thin layer of the liquid remains adhered to the lower surface of the ring causing the read force to be sum of the intermolecular attraction forces between the molecules of the layer and other liquid molecules adjacent to them. Suppose that this force is F and the area of the lower surface of the ring is A. In this manner a criterion for measuring the intermolecular attraction forces of the liquid molecules is obtained in the form of F/A which we show it by K. If the outer radius of the ring is R_2 and its inner radius is R_1, then obviously $A = \pi(R_2^2 - R_1^2)$ and then

$$F = KA = K\pi(R_2^2 - R_1^2). \tag{1}$$

Making R_1 equal to zero we expect that experimentally F to be proportional to the square of R_2, the disk radius.

2.4 Liquid film

Let a liquid film be formed between a U-shaped wire and a horizontal wire two ends of which are looped round the two limbs of the U-shaped wire. The horizontal wire tends to move upwards. Let's see what really the cause of this phenomenon is. Cross section of the horizontal wire and liquid film is shown in Fig. 3(a). Because of the kind of the horizontal wire, the liquid wets it and then adheres to almost entire upper half of the lateral surface of the horizontal wire, and by exerting intermolecular attraction between the molecules of the liquid and wire pulls it upwards. It is in fact the same inward intermolecular attraction force of the liquid, exerted on the liquid molecules in contact with the wire, that is transferred to the wire causing pulling it inwards (ie upwards), because the liquid molecules in contact with the wire are adhered to it. By weighting the horizontal wire down with some suitable weight, the wire will be kept in equilibrium (no longer being pulled upwards). It is clear that no matter what the thickness (t) of the film is, the contact surface of the liquid and wire remains constant (equal to half of the lateral surface of the wire), and then the horizontal wire will remain in equilibrium in any position it is set arbitrarily, because in any case the contact surface and thereby the total intermolecular attraction force between the liquid and wire will remain the same. Inattention to this fact has caused that it is supposed that the reason that the horizontal wire is in equilibrium in any position is that the upward force on the horizontal wire from the liquid film is exerted only by the surface tension of the two surfaces of the film, ie as we see in Fig. 3(b), this force is exerted only along the lines which their cross sections have been shown by a and b in the figure. It is obvious that change in the thickness of the film (t), does not alter the lengths of these lines.

It is proper to say at the end of this section that the liquid film does not exert only upward force on the horizontal wire. It exerts two smaller downward forces too, one being a part of the liquid (film) weight (while its other greater part is sustained by the U-shaped wire) and the other being the force arising from the cohesion pressure in the liquid.

2.5 Bubble

We saw that on condition of nonexistence of the gravitational attraction and external gas pressure, two equivalent but oppositely directed forces of intermolecular attraction and arising from the cohesion pressure are exerted on the right hemisphere of the previously mentioned solid drop. If this drop is set in an external gas pressure (eg atmosphere pressure) but yet with the condition of lack of the gravitational attraction, the balanced forces exerted on the right hemisphere are the leftward force arising from the external gas pressure exerted directly on the spherical surface of the hemisphere, the leftward force arising from the intermolecular attraction of the liquid molecules in the separation surface of the two hemispheres, and the rightward force arising from the pressure inside the liquid in the separation surface of the two hemispheres. This pressure is no longer only the cohesion pressure, but the external gas pressure exerted on the surface of the drop, which is felt inside the liquid drop, contributes to it too.

Let's in some manner blow into this solid drop and inserting gas into it form a spherical shell (ie bubble) as shown in Fig. 4. The forces exerted on the right half of this shell are the leftward force arising from the external gas pressure, p_2, exerted on the outer surface being equal to $p_2(\pi R_2^2)$, the leftward force arising from the intermolecular attraction between the liquid molecules in the surface $\pi R_2^2 - \pi R_1^2$ which considering the coefficient K introduced in Eq. (1) is equal to $K\pi(R_2^2 - R_1^2)$, the rightward force arising from the internal gas pressure, p_1, exerted on the inner surface being equal to $p_1(\pi R_1^2)$, and the rightward force arising from the pressure inside the liquid, p_i, exerted on the surface $\pi R_2^2 - \pi R_1^2$ (which is the separation surface of the two halves of the shell) being equal to $p_i\pi(R_2^2 - R_1^2)$. (this pressure (ie p_i) consists of three partial pressures: the cohesion pressure, the pressure arising from the external gas pressure exerted on the outer surface and transferred into the liquid, and the pressure arising from the internal gas pressure exerted on the inner surface and transferred into the liquid. It is important to notice that the cohesion pressure inside the liquid, as we saw in the discussions related to the figures 1 and 2, is not a constant parameter and making the spherical shell large or small decreases or increases.) Since this half is in equilibrium, we have

$$p_2(\pi R_2^2) + K\pi(R_2^2 - R_1^2) = p_1(\pi R_1^2) + p_i\pi(R_2^2 - R_1^2). \tag{2}$$

When p_1, p_2, and R_1 vanish, this relation results in the relation $K\pi R_2^2 = p_i\pi R_2^2$ in which p_i is only the cohesion pressure and the left side is the same leftward force arising from the intermolecular attraction, exerted on the right hemisphere of the drop mentioned at the beginning, and the right side is the same rightward force arising from the cohesion pressure, exerted on this hemisphere.

If we are able to measure p_i in some manner, considering that other parameters of Eq. (2) are directly or indirectly measurable easily, we can test the validity of this relation practically.

We can obtain the following relation for the gas pressure inside the bubble from Eq. (2) :

$$p_1 = (K + p_2 - p_i)(R_2/R_1)^2 + p_i - K,$$

from which we can conclude that if p_2 and K remain constant and assuming that the effect of the alterations of p_i is negligible in comparison with the alterations of $(R_2/R_1)^2$, then the larger the bubble, the lesser the pressure inside it, p_1, will be, because $(R_2/R_1)^2$ decreases more rapidly.

What we can see about the bubble in every current textbook discussing about surface tension (eg see "F. W. Sears, M. W. Zemansky, H. Young, University Physics, Addison-Wesley, 1987" and "Irving Herman Shames, Mechanics of Fluids, 4th printing, McGraw-Hill 1988") is that the balanced forces exerted on the right half of the spherical shell of the bubble are as follows (Fig. 5): the leftward force arising from the surface tension of the outer surface of the shell being equal to $2\pi R_2\gamma$, the leftward force arising from the surface tension of the inner surface of the shell being equal to $2\pi R_1\gamma$, the leftward force arising from the exterior gas pressure, p_2, being equal to $p_2(\pi R_2^2)$, and the rightward force arising from the interior gas pressure, p_1, being equal to $p_1(\pi R_1^2)$. Since this half is in equilibrium,

$$2\pi R_2\gamma + 2\pi R_1\gamma + p_2\pi R_2^2 = p_1\pi R_1^2 \Rightarrow \gamma = (p_1R_1^2 - p_2R_2^2)/(2(R_1+R_2)). \quad (3)$$

This relation is not true because when R_1 vanishes and the spherical shell is now in fact a solid drop having a spherical surface it yields a negative value for γ, and this is clearly irrational. The difficulty is arising, among others, from not considering the force arising from the pressure inside the liquid as one of the balanced forces.

Since in many bubbles R_1 and R_2 are very close together, they are considered almost equal to each other and consequently assuming that $R_1 = R_2 = R$, Eq. (3) appears in the form of $\gamma = (p_1 - p_2)R/4$ which yields

$$p_1 - p_2 = 4\gamma/R \quad (4)$$

which since has resulted from the main relation (3), has the same contradiction of inability to be generalized about a solid drop. And astonishing that instead of trying to find the existence cause of this contradiction in order to obviate it, a quite different reasoning is used for the particular state of a solid drop! In this reasoning only three forces exerted on a half of the drop is considered. Referring to Fig. 6, these forces are: the rightward force exerted on the separation surface of the two halves of the drop arising from the pressure inside the liquid, p_i, being equal to $p_i(\pi R^2)$ in which R is the radius of the sphere, the leftward force exerted on the spherical surface of this half arising from the gas pressure outside the liquid, p_2, being equal to $p_2(\pi R^2)$, and the leftward force arising from the surface tension of the drop surface, being equal to $2\pi R\gamma$. Since this half is in equilibrium, we conclude

$$p_i(\pi R^2) = p_2(\pi R^2) + 2\pi R\gamma \Rightarrow p_i - p_2 = 2\gamma/R. \quad (5)$$

It is not clear that while the pressure inside the liquid in this reasoning can exert a force that is considered as a balanced force, why it can not do so in the reasoning resulting in Eq. (3) (or (4))! These contradictions take the validity of the current relations (4) and (5) under question seriously.

3 Capillarity

3.1 Role of adhesion in pressure reduction

Consider a string of molecules of a liquid cohered to each other exerting intermolecular attraction on each other while the two end molecules are adhered to the walls of a fixed container exerting intermolecular attraction on the molecules of the walls. Middle part of this string bulges downwards due to the weight of the molecules. It is obvious that if the distance between the walls is increased, because of the more multiplicity of the molecules in the string increasing the weight of the string, it will bulge more, decreasing the height of its middle part. (The situation is similar to the cables carrying electricity which due to their weights bulge.)

Because of the intermolecular attraction between the molecules of an actual liquid, it comes approximately out of an ideal liquid and almost takes the state of a jellylike substance, ie because of the attraction between its molecules almost gets a state of continuity. (And this very gelatinous state causes that a lubricated needle set on the water surface causes alteration of the form of the water surface in such a manner that can bear it, just as a jelly can bear a weight on it by proper altering of its surface form. Therefore, there is no necessity to suppose an elastic membrane arising from the surface tension set upon the thin (watery) liquid under the membrane, which setting the needle on it, its form alters because of its elasticity and of the watery state below it.) This continuity state is the same we described above as strings of molecules cohered to each other. It is clear that if there exists an intermolecular attraction force between the liquid and the body of the container containing the liquid, this continuity will include the body, ie the situation will be so that some weight of our gelatinous liquid will be suspended from the walls of the container, just as the above-mentioned strings are suspended from the body. This means that a part of the liquid weight is borne by the walls of the container and the whole weight of the liquid is not exerted on the bottom of the container. In this manner we conclude that firstly the more the intermolecular attraction between the liquid and container is, the more percentage of the liquid weight is sustained by the walls of the container (notice that this percentage is sustained by the whole walls of the container in contact with the liquid, not only by the molecules along the contact line of liquid surface and the body; we can imagine that the liquid consists of many strings similar to the above-mentioned ones each end of which adhered to a point of the body), and secondly assuming the height of the liquid to remain constant, the more the diameter of the container is, the less percentage of the weight of the middle parts of the liquid is borne by the walls of the container. This means that we should expect that the more the adhesion force between the molecules of the liquid and container or the less the diameter of the container is the less the liquid pressure at the bottom of the container will be.

3.2 Effect of existence of adhesion

Suppose that the body of the tube of Fig. 7(a) is of such kind that the intermolecular attraction between a molecule of it and a molecule of the liquid in it is much more than the intermolecular attraction between two molecules of the liquid. Furthermore, let the bottom of the tube be of such kind that the intermolecular attraction between a molecule of it and a molecule of the liquid is just equal to one between two molecules of the liquid. Besides, suppose that welded on the upper opening of the tube to be a ring (shown by O in the figure) of such kind that its molecules do not attract the molecules of the liquid at all. We want to see what the form of a specified amount of the liquid poured in the tube is. Suppose that in the first instance the liquid has the level form of Fig. 7(b). Those molecules of the body of the tube which are immediately upper than the liquid level surface in Fig. 7(b) exert their powerful attraction force on the adjacent molecules of the liquid surface. Since this force is much more than the attraction force between the molecules of the liquid, these molecules are pulled towards the wall of the tube yielding Fig. 7(c). Because of the strong (although short-range) attraction between the molecules of the tube and liquid, this process continues till Fig. 7(f) is obtained in which the liquid molecules are no longer pulled towards the wall, because they have reached the ring O which do not exert any attraction force on the liquid molecules at all. (Certainly if this ring does not exist, the liquid molecules will be pulled out of the tube. This is the same process that occurs for the liquid helium which the intermolecular attraction between its molecules is much less than one between the molecules of it and its container (see Handbook of Physics by Condon and Odishaw, McGraw-Hill, 1967).)

What is quite obvious and no physicist can deny it is that in the final state that the liquid remains constant in the form of 7(f) the pressure at the bottom of the tube is much less than the pressure at this bottom if no (or at least much less) intermolecular attraction between the liquid and tube wall was to exist. Its reason is obviously that a great percentage of the liquid weight is sustained by the molecules of the tube wall which keep the liquid molecules adhered to themselves (as we said before, intermolecular attraction between the liquid molecules which causes approximate continuity of the liquid molecules causes a great percentage of the liquid weight to be suspended from, and in fact to be suspended by, the tube wall), therefore, the weight of the liquid will be no longer entirely exerted on the tube bottom causing much decreasing of the pressure compared to when there is no intermolecular attraction between the liquid and body. Another point being that as we saw and said before, this percentage of the liquid weight is borne by all the molecules of the tube wall being in contact with the liquid, not only by the molecules along the line of contact of the liquid surface with the tube wall (which is a circle under the ring O).

Of course the case of Fig. 7(f) is an ideal (but quite practical) one. For a more usual one in which the intermolecular attraction between a molecule of the liquid and a molecule of the body is not necessarily very much more than one between two molecules of the liquid, the process of Fig. 7 stops eg on Fig. 7(d), because now the intermolecular attraction between the liquid and body is only so much that does not allow sustaining the liquid weight adhered to the tube wall more than what can be seen in Fig. 7(d). It is obvious however that in the fixed state of Fig. 7(d) too, because of the same above-mentioned reason, the pressure at the bottom is less than what would be if there was no intermolecular attraction between the liquid and body.

There is another factor that decreases the pressure in the liquid. This factor is decrease of the cohesion pressure in the liquid of Fig. 7(d) (or 7(f)) compared to Fig. 7(b) because of the increase of the liquid surface (notice that as we have seen so far cohesion pressure in a pile of liquid decreases by increasing its surface).

3.3 Effect of nonexistence of adhesion

Now consider a tube quite similar to the tube of Fig. 7(a) with this only difference that its wall is of such kind that there is not at all any intermolecular attraction between it and the liquid of Fig. 7. Let's pour the same kind of liquid as in Fig. 7(b) into it. It is obvious that since there is not any intermolecular attraction bound between the liquid and body, upper surface of the liquid continues to the tube bottom in the form of a smooth curved surface; see Fig. 8(a). This means increase in the cohesion pressure in the liquid and consequently on the tube bottom, because this is no longer arising only from the inward intermolecular attraction resultant force exerted on the upper surface molecules (by the liquid molecules adjacent to this surface) but also from the inward intermolecular attraction resultant force exerted on the lateral surface molecules of the liquid column (by the liquid molecules adjacent to this surface) which have no attraction bond with the body. Then compared with when there exists intermolecular attraction between the liquid and body, the pressure on the bottom of the tube is increased.

The above-mentioned case is ideal (but quite practical). In the more usual case of Fig. 8(b) which there exists a weak intermolecular attraction between the tube and liquid, outward intermolecular attraction resultant force exerted on the liquid molecules in contact with the tube wall by the molecules of the tube wall adjacent to them is so much less than the inward intermolecular attraction resultant force exerted on these molecules by the adjacent inner molecules of the liquid that an additional cohesion pressure arising from this difference existing between the resultant forces exerted on the lateral surface molecules of the liquid is still felt inside the liquid. This additional cohesion pressure causes that the pressure inside the liquid and consequently on the tube bottom to be more than when the intermolecular attraction force between the liquid and body is sufficiently big.

There is another factor that increases the pressure on the bottom of the tube: Because of the nonexistence (or weakness) of the intermolecular attraction between the liquid and tube wall compared with when this attraction is sufficiently strong, no longer any percentage of the weight of the liquid column is sustained by the tube wall and all of this weight is exerted on the tube bottom increasing the pressure compared to when some of the weight is borne by the wall.

3.4 Open-bottom capillary tubes

Suppose that the heights of the liquid in the capillary tubes of Figures 7(d) and 8(b) are so much that in each tube the pressure in each point on the tube bottom is the same. Let's fill a big and deep container with the same liquid as in these tubes. We understood that the pressure at the bottom of the tube of Fig. 7(d) was slight and of Fig. 8(b) was excessive. We consider two points a and b inside the liquid of the container such that the pressure in the first point (a) is equal to the liquid pressure at the bottom of the tube of Fig. 7(d), and in the second point (b) is equal to the liquid pressure at the bottom of the tube of Fig. 8(b). Now we dip vertically the tubes of Fig. 7(d) and Fig. 8(b) into the container liquid to the extent that (the upper surface of) the bottom of the first tube and the point a are in the same level and (the upper surface of) the bottom of the second tube and the point b are also in the same level. It is obvious that if in this state we remove the bottoms of these tubes (connecting the liquid of the tubes with the liquid of the container), because of the equality of the internal and external pressures at the openings found by removing the bottoms of the tubes, the altitude and surface form of the liquid in the tubes will not change at all; see Fig. 9.

We should point out three points:

Firstly, the reasonings presented so far necessitate that form of the liquid surface of Figures 7(d) and 8(b) depends also on the amount of the liquid poured into these closed-bottom tubes, because in fact all the liquid molecules and all the molecules of that part of the tube in contact with the liquid are effective in forming the liquid surface, and by changing the liquid amount both of these two factors change in a manner that clearly does not necessitate unchanging of the liquid surface.

Secondly, if the intermolecular attraction between the tube and liquid in the closed-bottom tube of Fig. 7(d) is as much as allowing some of the liquid weight to be borne by the bottom of the tube (ie if the tube is not capillary very much), it will be obvious that when in Fig. 9 by removing the tube bottom in the point a in the container liquid we try to retain the altitude and surface form of the liquid inside the tube, the lower end of the tube (or the point a) will be always below the level of the liquid surface in the container. In principle we don't expect that in a tube which is sufficiently thick (such that some of the liquid weight is borne by its bottom) if the opened bottom of it is only in contact with the surface of the container liquid but has not dipped in it at all, the liquid to rise into the tube whatever the intermolecular attraction between the tube body and liquid may be much, while we expect that if in this state the tube is dipped a little into the container liquid, the liquid to rise into the tube such that its surface in the tube to be a little upper than the level of the liquid surface of the container. We call this property of the capillary tubes as dependence of rise altitude on depth of dipping. (In quite simple words and accepting a remote approximation if we suppose that while there exists a sufficiently strong intermolecular attraction between the tube body and the liquid the surface of the liquid in the tube is almost level (not curved), and besides we suppose that the tube body can bear only, eg, half of the weight of the liquid in the tube, then it will be obvious that if the depth of the dipping of the tube in the container liquid is h, the altitude of the rise of the liquid into the tube will be 2h relative to the lower end of the tube).

Thirdly, it is obvious that if the altitude of the liquid in the tube of Fig. 9(b) is increased, because of the increase in the lateral surface of the liquid column in the tube causing increase in the cohesion pressure (arising from the inward attraction of the liquid molecules of this surface) the pressure at the lower end of the tube will be increased causing the altitude of the liquid in the tube to decrease; ie we expect that the more the capillary tube is dipped into the container liquid, the lower the surface of the liquid in the tube is positioned (relative to the level of the liquid surface of the container). We call this property of the capillary tubes as dependence of fall depth on depth of dipping.

The above-mentioned two properties of the capillary tubes can not be predicted by the current theory of surface tension, and then experimental confirmation of the existence of these properties can be a strong support for the theory presented in this paper.

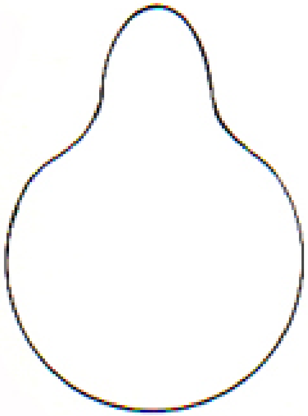
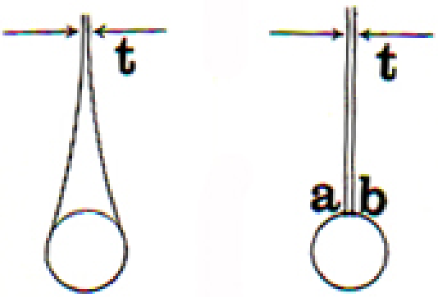


Fig. 1

Fig. 2



(a) (b)

Fig. 3

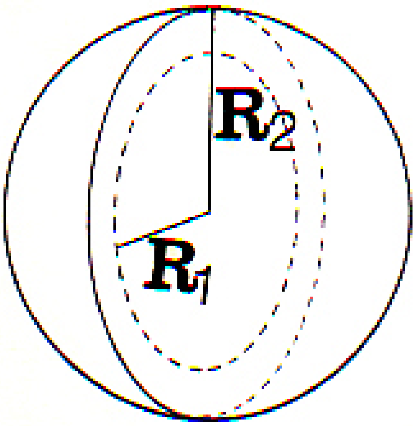


Fig. 4

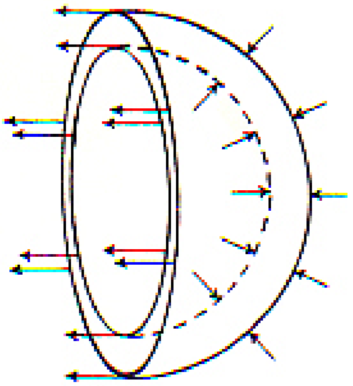


Fig. 5

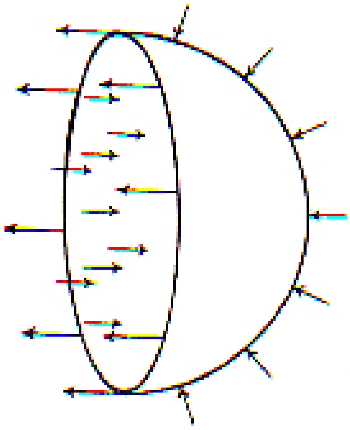


Fig. 6

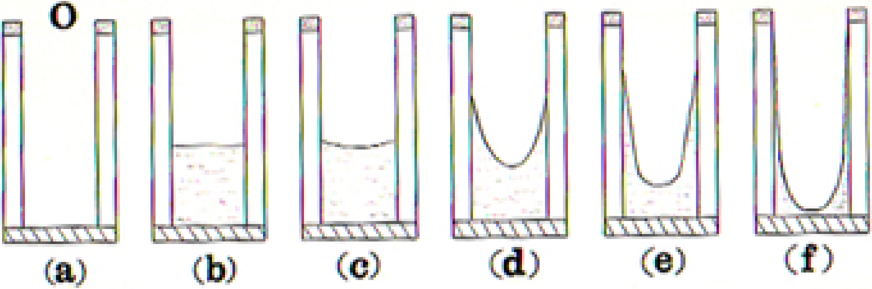


Fig. 7

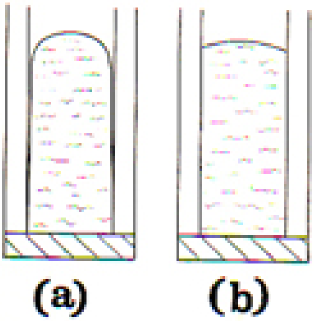


Fig. 8

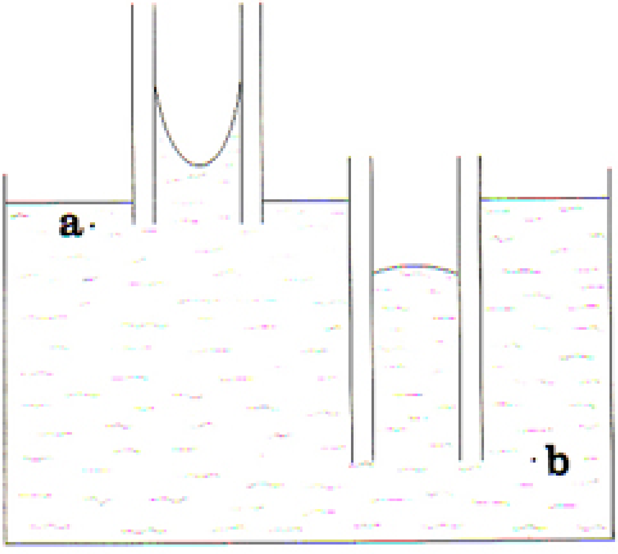


Fig. 9