SURFACE TENSION

Theory

The "Elastic Skin"

This laboratory is an investigation of some of the interesting properties of liquids that arise because of surface tension, an effect caused by molecular forces of attraction in the liquid. In the middle of a fluid neighbors on all sides of a molecule pull equally hard in all directions, but on the surfaces molecules are pulled into the bulk liquid. As a result, the surface tension makes the fluid behave as if it had an elastic skin.

The surface can be between a liquid and air, as with rain drops; or between two liquids, as with a dispersion of oil in water; or between a liquid and a solid surface, as with fluid drawn into a capillary. Some examples of phenomena associated with surface tension are the way water flowing slowly from a tap emerges as a succession of drops and not as a continuous stream, and the fact that a sewing needle with a density perhaps as much as ten times that of water, if placed carefully on a water surface, makes a small depression in the surface and rests there without sinking.

For molecules lying on a line on the surface the portions of surface on the two sides of the line exert pull on it, an effect that can be demonstrated with apparatus illustrated in Fig. (1). A wire ring has a loop of thread attached to it; when the ring and thread are dipped in a soap solution and removed, a thin film of liquid is formed in which the thread "floats" freely, as shown in part (a). If the film inside the loop of thread is punctured, the thread springs out into a circular shape as in part (b); the surface of the liquid pulls radially outward on it, as shown by the arrows. These same forces were acting even before the film was punctured, but then there was film on both sides of the thread, and the net force on a section of thread was zero.
Fig. (1) A wire ring with a flexible loop of thread, dipped in soap solution. (a) before and (b) after film inside the loop is punctured. Surface tension pulls the loop outward radially in all directions.

Another simple apparatus for demonstrating surface tension is shown in Fig. (2). A piece of wire is bent into a U shape and a second piece of wire is used as a slider. When the apparatus is dipped in a soap solution and removed, the slider is quickly pulled up to the top of the U (if its weight $w_1$ is not too great). The slider may be held in equilibrium by adding a second weight $w_2$. Surprisingly, the same total force $F = w_1 + w_2$ will hold the slider at rest in any position, regardless of the area of the liquid film, provided the film remains at constant temperature. That is, the force does not increase as the surface is stretched farther. This is very different from the elastic behavior of a sheet of rubber, for which the force required would be greater as the sheet was stretched.

Although a soap film like that in Figs. (1) and (2) is very thin, its thickness is still enormous compared with the size of a molecule. Hence we can consider a soap film as made up chiefly of bulk liquid, bounded by two surface layers a few molecules thick. When the slider in Fig. (2) is pulled down and the area of the film is increased, molecules formerly in the main body of the liquid move into the surface layers. That is, these layers are not "stretched"
as a rubber sheet would be; more surface is created by molecules moving from the bulk liquid.

![Diagram of a slide wire with forces and weights](image)

Fig. (2) The slide wire is pulled up by the force of surface tension, and down by its own weight $w_1$ and an additional weight $w_2$.

Let $L$ be the length of the wire slider. Since the film has two surfaces, the total length along which the surface force acts on the slider is $2L$. The surface tension $\gamma$ in the film is defined as the ratio of the surface force $F$ to the length $d$ (perpendicular to the force) along which the force acts:

$$\gamma = \frac{F}{d}.$$  

Hence, in the case, $d = 2L$ and

$$\gamma = \frac{F}{2L}.$$  

Note that although the term tension has previously been used in reference to a force, surface tension is a force per unit length. The SI unit of surface tension is the newton per meter (1 N·m⁻¹). This unit is not in common use; the usual unit is the cgs unit, the dyne per centimeter (dyne cm⁻¹). The conversion factor is

$$1 \text{ N m}^{-1} = 100 \text{ dyne cm}^{-1}.$$
Some typical values of surface tension are shown in Table I. Surface tension usually decreases as temperature increases; Table I shows this behavior for water.

Table I  Experimental Values of Surface Tension

<table>
<thead>
<tr>
<th>Liquid in Contact with Air</th>
<th>T, deg C</th>
<th>Surface tension, dyne·cm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benzene</td>
<td>20</td>
<td>28.9</td>
</tr>
<tr>
<td>Carbon tetrachloride</td>
<td>20</td>
<td>26.8</td>
</tr>
<tr>
<td>Ethyl alcohol</td>
<td>20</td>
<td>22.3</td>
</tr>
<tr>
<td>Glycerine</td>
<td>20</td>
<td>63.1</td>
</tr>
<tr>
<td>Mercury</td>
<td>20</td>
<td>465.0</td>
</tr>
<tr>
<td>Olive oil</td>
<td>20</td>
<td>32.0</td>
</tr>
<tr>
<td>Soap solution</td>
<td>20</td>
<td>25.0</td>
</tr>
<tr>
<td>Water</td>
<td>0</td>
<td>75.6</td>
</tr>
<tr>
<td>Water</td>
<td>20</td>
<td>72.8</td>
</tr>
<tr>
<td>Water</td>
<td>60</td>
<td>66.2</td>
</tr>
<tr>
<td>Water</td>
<td>100</td>
<td>58.9</td>
</tr>
<tr>
<td>Oxygen</td>
<td>-193</td>
<td>15.7</td>
</tr>
<tr>
<td>Neon</td>
<td>-247</td>
<td>5.15</td>
</tr>
<tr>
<td>Helium</td>
<td>-269</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Soap Bubbles

Surface tension causes a pressure difference between the inside and outside of a soap bubble or a liquid drop. A soap bubble consists of two spherical surface films very close together with a layer of liquid between. The molecules on the surface are so small compared to the film thickness that the film is really two surfaces sandwiched around a layer of bulk fluid. Surface tension causes the films to contract, but in so doing it compresses the inside air, increasing the interior pressure to a point that prevents further contraction. The liquid film will draw itself into a spherical bubble, minimizing the surface area. One way to calculate the pressure in the bubble is to set the force due to the pressure difference between the inside and the outside of the bubble, which is tending to push the bubble apart, equal to the force of the surface tension holding it together.
The bubble is imagined to be sliced in half; the pressure pushes directly out on each side, while the surface tension pulls it together along the circumference, as illustrated in Fig.(3). The pressure difference pushes horizontally on the projected area $\pi R^2$, not the total surface $2\pi R^2$, because the 'vertical' components of the force cancel out. The force exerted towards the left in figure, due to surface tension, is $2\gamma(2\pi R)$ where $2\pi R$ is the circumference, $\gamma$ is the surface tension, and the factor 2 is included to account for both surfaces. The force due to the pressure difference, $\Delta p$, is $\Delta p \cdot \pi R^2$. Setting these equal we have

$$\Delta p \cdot \pi R^2 = 2\gamma \cdot 2\pi R \text{ or}$$
$$\Delta p = \frac{4\gamma}{R} \text{ (soap bubble)} \quad (1)$$

For a liquid drop, which has only one surface film, the difference between pressure of the liquid and that of the outside air is half that for a soap bubble:

$$\Delta p = \frac{2\gamma}{R} \text{ (liquid drop)}$$

- Fig.(3) The two halves of a soap bubble are held together by the force of surface tension acting around an equatorial circumference, with a force $F = (2\gamma)(2\pi R)$; they are pushed apart by a pressure difference $\Delta p$ acting on the projected area of the equitorial surface $\pi R^2$ which exerts a force $\pi R^2\Delta p$. 
Capillarity

Thus far we have talked about surface films at the boundary between a liquid and a gas. Additional surface-tension effects occur when such a film meets a solid surface, such as the wall of a container, as shown in Fig.(4). In general, the liquid-gas surface curves as it approaches the solid surface, and the angle $\theta$ at which it meets the surface is called the contact angle. When the surface curves up, as with water and glass, $\theta$ is less than 90°, as shown in Fig.(4a); when it curves down, as with mercury and glass, $\theta$ is greater than 90°, as shown in Fig.(4b). The first case is characteristic of a liquid that tends to \textit{wet} or adhere to the solid surface; the second is characteristic of a nonwetting liquid.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig4.jpg}
\caption{Fig.(4) The surface of a liquid near a solid wall is curved up or down depending on whether or not the liquid wets the solid. Water, like the liquid on the left (a), wets a glass surface; mercury, like the liquid on the right (b), does not. The contact angle, $\theta$, between the solid wall and the liquid-vapor interface is indicated.}
\end{figure}

An important surface-tension phenomenon is the elevation or depression of the liquid in a narrow tube, as shown in Fig.(5). We call this effect capillarity; this term stems from the description
of such tubes as capillary, which means "hairlike." For a liquid such as water, which wets the tube with contact angle of less than 90° and the liquid rises until it reaches an equilibrium height $y$ as illustrated in Fig.(5a). This height is determined by the requirement that the total surface-tension force around the line where the liquid-gas surface meets the solid should just balance the extra weight of the liquid in the tube. The curved liquid surface is called a meniscus. Figure (5b) shows the situation with a non-wetting liquid such as mercury and a contact angle of greater than 90°. Again a meniscus forms, but the surface is depressed, pulled down by the surface-tension forces. In the case of the two fluids used in this laboratory, water and soap solution, the liquid is drawn up.

If the tube is no larger than a millimeter in diameter the curved surface at the top of the liquid column, the meniscus can be considered to be a section of a sphere. This spherical "bowl" is held up by the force of surface tension acting around the rim. The force pulls up and away at the angle $\theta$, being the contact angle between the meniscus and the tube.

Referring to Figs. (4a) and (5a), let $R$ be the radius of curvature of the meniscus, $r$ the radius of the tube, $\rho$ the liquid density, $h$ the height the meniscus above the outside level, and $\gamma$ the coefficient of surface tension. The total force is $2\pi r \gamma$, while the vertical component of this force is $2\pi r \gamma \sin(\theta)$. The weight of the fluid being held up by this force is $\pi r^2 \rho g$. Setting the force equal to the weight, we have:

$$\rho gh = \frac{2\gamma \sin(\theta)}{r}, \quad \text{or} \quad \gamma = \frac{\rho gh r}{2 \sin(\theta)}$$

(2)

Since $r = R \sin(\theta)$, this equation can also be written

$$\rho gh = \frac{2\gamma}{R}, \quad \text{or} \quad \gamma = \frac{\rho gh R}{2}$$

(3)
Fig. (5) Two examples of capillary effects when a small bore tube is immersed in a fluid. A fluid that wets the tube (e.g., water) will be drawn up, as in (a); a fluid which does not wet that tube (e.g., mercury) will be forced down by surface tension effects.

Capillarity is responsible for the rise of ink in blotting paper, the rise of melted wax in the wick of a candle, and many other everyday phenomena. It is also an essential part of many life processes. A familiar example is the rising of aqueous solutions from the roots of a plant to its foliage, due partly to capillarity and partly to osmotic pressure developed in the roots. In the higher animals, including humans, blood is pumped through the arteries and veins, but capillarity is still important in the smallest blood vessels, which indeed are called capillaries.

**Experiment**

In this laboratory three methods of measuring the surface tension are applied to two fluids, distilled water and soapy water. First, the surface tension is measured by measuring the pressure inside a bubble, using a water manometer. The surface tension can then be determined by measuring the rise of the fluid into a capillary. Finally, the surface tension can be measured directly
with a tensiometer, an instrument used for precision measurements of surface tension in medical and industrial laboratories. There are two models in the lab; one is of research quality, the other is made for student labs.

**The Tensiometer**

The tensiometer is basically just sensitive scale that measures the force required to pull a ring of wire (or another object, such as a glass slide) out of a fluid. The ring is pulled down by its weight and by the surface tension force of the fluid. Referring to Fig.(6), let \( C \) be the circumference of the wire ring. Since the film has two surfaces, the total length along which the surface force acts is \( 2C \). The surface tension is the film, \( \gamma \), is defined as the ratio of the surface force to the length along which the force acts. Hence, in this case,

\[
F = \frac{\gamma}{2C}
\]  

(4)  

In one version of the instrument, the ring is replaced be a glass slide. If the slide length is \( L \) and the thickness \( t \), the circumference \( C \) in the above formula is replaced by \( 2(L + t) \).

---

![Fig. (6) A cross-sectional view of a wire ring being lifted out of a soap solution. Surface tension in the film pulls the wire back into the bulk liquid. The Tensiometer measures the force (in addition to the weight of the ring) needed to pull the ring out.](image-url)
There are two tensiometers of each type, student and professional, available in the lab. The student model is for use with distilled water, the other for use with soap solution. They are kept separate, for only a tiny amount of soap can contaminate a large amount of water, lowering the surface tension considerably. Detailed instructions for the use of the tensiometers are supplied in a separate handout.

Fig.(7) A schematic diagram of a tensiometer. The liquid is raised over the ring, and then lowered. The surface tension force on the ring is calculated from the maximum deflection of the lever by calibration the torsion in the wire. See text for more detail.
The principles of operation of both models can be seen by referring to Fig.(7). A lever is clamped to a fine steel wire, and is held in position by the torsional stress in the wire. The torsion can be adjusted by the torsion-adjust knob. A ring (or other object) is suspended from the lever. A dish of liquid is raised to immerse the ring, and then lowered. As the liquid surface falls away the surface tension in the liquid pulls the ring down. The deflection of the lever at the moment before the ring pops loose measures the downward force of the surface tension. In the student tensiometer weights are hung on the ring to calibrate the deflection. On the professional model a calibrated torsion-adjust knob is turned to increase the tension to counteract the downward pull of the surface tension. In both cases the force F in Eq.(4) above is measured, and from it and the dimensions of the immersed object one can calculate the surface tension.

**Apparatus**

A frame of tubing and valves is provided for blowing soap bubbles at the end of a glass tube (with individual mouthpieces provided to prevent epidemics). A sensitive manometer is provided to measure the pressure inside a small bubble. There are capillaries, a measuring magnifier, and auxiliary beakers, tubing, corks, etc. for studying surface tension in bubbles and capillarity. Rulers and circle-hole templates are provided to measure the radii of bubbles. And there are four tensiometers for measuring the surface tension in soap-water solutions and pure water. Both versions of the apparatus are shown in Figs.(8) and (9).

**Procedure**

After gaining familiarity and proficiency with the soap bubble apparatus, observe qualitatively the following property of soap bubbles: If two spherical bubbles are connected, air flows from the smaller to the larger. Next, blow a small soap bubble and measure the pressure inside using the water manometer; then use the measured
Fig. (8) In this version of the apparatus bubbles have been blown separately on the two sides. When the valve connecting them is opened the air will flow from the smaller bubble to the larger, showing that it has the higher pressure inside.

Pressure and radius to calculate $\gamma$ from Eq. (1). A measurement of the pressure inside a water bubble is possible, but difficult, because the bubbles are so fragile. Try it to test your luck and dexterity, but don't waste a lot of time on it.
Fig. (9) In this version of the apparatus a sensitive manometer has been connected to one side to measure directly the pressure inside the bubble. The water level is located with no bubble (atmospheric pressure in each arm) and then with a bubble. The pressure is given by $\rho g \Delta h$, where $\rho$ is density of water and $\Delta h$ is the change in manometer level. The bubble radius can be estimated by holding a circle template up to it.
To make the pressure measurement with the manometer, first open the 'bubble side' of the manometer to the atmosphere, turn the micrometer and note the reading when the needle makes a visible dimple in the fluid surface. Close the two valves that isolate the 'bubble side' and blow a bubble. Close all valves, then open the valve connecting the bubble to the manometer. Wait for the liquid to come to equilibrium, and read the micrometer when the needle again just forms a dimple. Assuming that the cross section of both glass tubes is the same, the water level difference between the two sides, $\Delta h$, is twice the difference between the micrometer readings. The pressure in the bubble is $\rho g \Delta h$, where $\rho$ is the density of water.

Let both soap and pure water be drawn into the two capillaries provided. Measure the height, the capillary diameter, and the angle of contact using the magnifier as illustrated in Fig.(10). The angle can also be measured by a shadowing technique which will be demonstrated by the TA. Calculate $\gamma$ for both liquids from the measured height, diameter, and contact angle using Eq. (2).

![Contact Angle Diagram](image)

**Fig. (10)** The contact angle between fluid and capillary can be measured with a magnifier, or in the shadow of the tube projected on the wall.

Finally, measure the surface tension for both soap solution and pure water using the tensiometer. Follow the specific instructions that accompany each instrument.

**Date Analysis and Report**

Describe the measurements and tabulate your results. Compare the values of the surface tension measured by the three different methods. Discuss the sources of error and inaccuracy.