Paper Clip Suspended by Surface Tension on Water

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This intent of this image is to show that sometimes there is more to nature than just the basic rules of Archimedes' principle that governs whether or not an object will float. In the image it can be seen that a paper clip can float on water not by solely relying on the buoyancy force created by the weight of the displaced fluid, but instead by the surface tension created by the interface between two immiscible fluids. Additionally the image captures how the meniscus of the fluid bends the light creating interesting warped lines around the paper clip and even includes some diffraction creating a spectrum of colors.

Archimedes' principle states that there is an upward force acting on an object equal to the weight of the fluid displaced by that object [1]. What this means is that an object will float if it is less dense than the fluid it is submerged in. This appears to be violated by the metal paper clip floating on water because the paper clip is much denser than the water. This occurs because Archimedes' principle doesn't take into account surface tension forces that occur at the interface between two immiscible fluids.

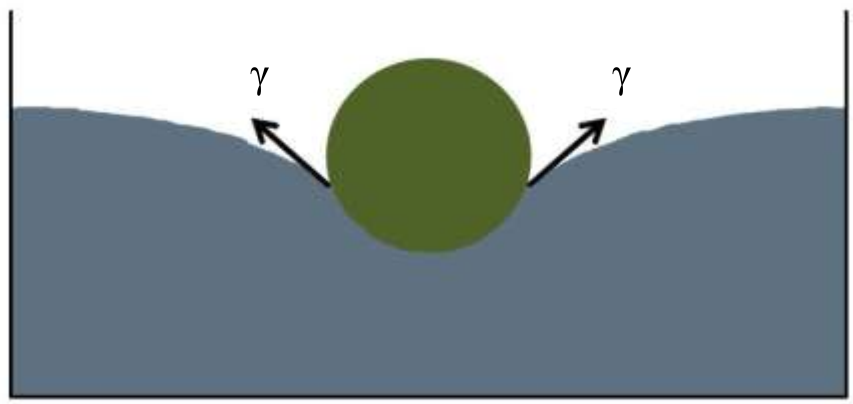

Figure 1: Cross section of a single rod of the paper clip floating on the water. The arrows denote the surface tension forces (γ) of the water that are keeping the paper clip afloat.

The surface tension force is created by cohesive forces in the fluid. A fluid particle inside the fluid attracted to other fluid particles all around it. However, particles at the surface do not have fluid particles all around, and hence they must be more attracted to the other particles on the surface than the ones below [2]. This creates a tension that tries to minimize the surface area of the fluid. This tension in turn can be used to aid in the flotation of materials denser than that of the fluid. Figure 1 shows the surface tension forces acting on a cross sectional area of a rod in a paper clip. The tension acts along the line of the surface of the fluid, creating both a horizontal force and a vertical force. The vertical force is equal to the weight of the fluid displaced by the meniscus [2]. This vertical force is then balanced by the weight of the paper clip.

As mentioned above the vertical surface tension is balanced by weight of the paper clip. The weight of the paper clip is a body force and surface tension is a surface force. Since these are two different types of forces it is important to understand which forces are more dominant in the problem. The Bond number is a dimensionless number that compares surface tension forces to body forces [3]. A low Bond number means that surface tension forces are more dominant than body forces. The Bond number can be calculated using the following formula:

$$\text{Equation 1:} \quad Bo = \frac{\Delta\rho \cdot g \cdot L^2}{\gamma} \text{ [3]}$$

where Bo is the Bond number, $\Delta\rho$ is the difference in densities between the two fluids, g is the gravitational force, L is the characteristic length (the radius of the paper clip rod in this case), and γ is the surface tension.

When the image was taken the air temperature was about 6° C, and it will be assumed that the temperature of the water was the same since the water was sitting in a glass surrounded by the air for quite some time before the image was taken. It will be assumed that the densities of water and air are 999.941 kg/m^3 and 1.2754 kg/m^3. Gravity will be assumed to be 9.81 m/s^2. The characteristic length scale is 0.25 mm or 0.00025 m.

To find the surface tension of water many studies have been done both theoretically and experimentally [4]. It has been shown that the surface tension of water is a function of temperature. The surface tension of water decreases as the temperature increases [5]. Although [4] and [5] do not entirely agree, they show comparable results that the surface tension varies from about 73 N/m (at 288 K) to 70 N/m (at 304 K) in a linear fashion [4][5]. It will be assumed that the surface tension for this experiment was about 75 N/m as the temperature was 6° C from extrapolating data from [4] and [5] to 279 K (6° C). Putting this all together the Bond number for this experiment was calculated to be about $8*10^{-6}$. Clearly the surface tension forces are much more dominant than the body forces. Hence the paper clip has no trouble floating on the water.

To visualize the surface tension fluid phenomenon a paper clip was suspended on top of tap water in a drinking glass. The paper clip had a 4.8 cm length by 1.1 cm width and weighed 1 gram. The diameter of a single rod of the paper clip was about 0.5 mm. The water came from a tap and nothing was added to or filtered out of the water. The water was contained in a drinking glass with a depth of about 7 cm. The diameter of the surface of the water was about 8 cm. In order to get enough light to capture the image without sacrificing the quality of the image it was shot outside on a cloudy day. Direct sunlight was avoided to reduce the harsh light and glare that it would produce. As mentioned before the temperature outside was about 6° C. Additionally the glass was placed in a box lined with white printer paper to setup a white backdrop. A tweezers was used to delicately place the paper clip on top of the water. Attempts were made to do this by hand, but this would break the surface tension resulting in the paper clip sinking to the bottom of the glass.

To capture the image much thought was put into how to shoot such a small object at close range. To achieve a crisp picture a large depth of field was desired. Hence a small aperture was used. As mentioned above in order to get enough light the image was shot outside. In the final cropped image the size of the field of view was about 5 cm wide by 3.8 cm high. The distance from the object to the lens was about 15 cm. The focal length of the lens was 8 mm. A small amount of optical zoom was used to get the correct composition in the image. In addition to this a digital camera was used. The original pixel width and height was 4000 by 3000, respectively. This was then cropped down to a final width and height of 2413 by 1810 pixels. The camera that was used was a Panasonic DMC-ZS7. It was set into its fully manual mode such that the exposure settings could all be manually adjusted independently. As mentioned before a small aperture was used to achieve the largest depth of field. This was done by setting the f-stop to f/6.3. Additionally a 200 ISO was used to reduce the granularity in the image. The exposure time was then adjusted manually until the desired exposure was achieved. In the final image an exposure time of 1/125 sec. was used. In order to reduce any motion blur from the camera both a tripod as well as the camera's image stabilization option. After the image was captured it was then imported to a computer where it was converted from a JPG to TIF file. It was then uploaded into GIMP where it was cropped to its final size. The next post processing item that was done was to change the contrast using the curves editor in GIMP. More contrast was added, but in a non-linear fashion. Some small blemishes were smeared out using GIMP's smudge tool.

As mentioned before this image reveals the nature of surface tension that exists between two immiscible fluids by capturing a paper clip "floating" on water. Unintentionally it also revealed some neat optical phenomenon as it shows some diffraction of light creating a spectrum of colors. I like the lines in the image that are distorted by the meniscus created by the surface tension of the water supporting the paper clip. I also like the crisp focus that was achieved in the image. In addition to this I had another image where the paper clip was horizontal. This image was boring as it was too symmetrical. Instead I chose this picture where the paper clip was at an angle giving the image more oddly shaped lines creating a more interesting image. What I disliked about the image was the lines that showed up from the bottom of the glass. If I were to do this again I would use a large glass casserole pan that would remove the lines from the bottom of the glass. I think that the surface tension phenomenon is clearly illustrated here with the paper clip being the central focus of the image balanced on the water. Additionally it would be interesting to further investigate this phenomenon with paper clips of different diameter sized rods as well as varying the temperature of the water to see when a paper clip could no longer be supported by the surface tension in the water.

References:

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