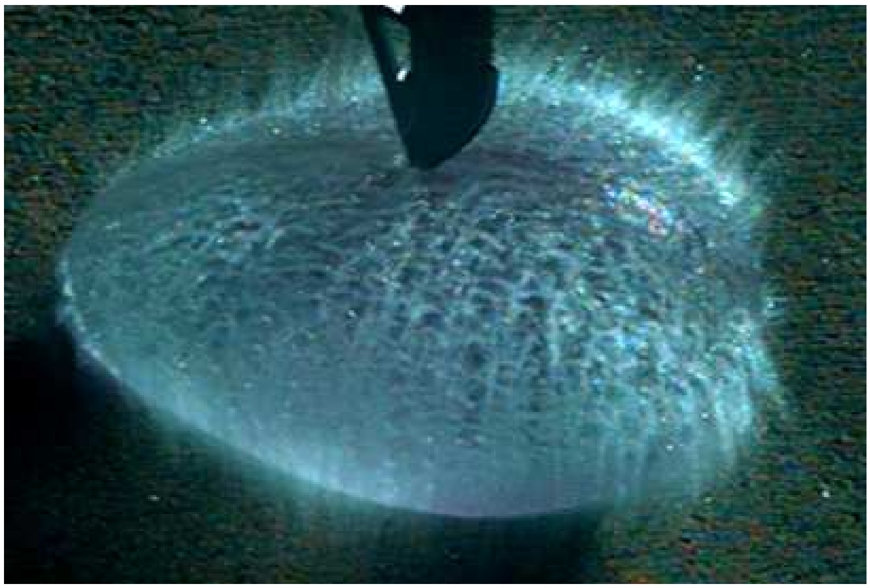
Capturing the Physics of a Popping Water Balloon



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I. Introduction
This image was taken as the first group project photograph in the Flow Visualization course in the Mechanical Engineering department at the University of Colorado at Boulder. The intent of this image was to capture a still moment which could not be seen freely by the naked eye. The object was chosen to be a water balloon popping, which ordinarily happens much too fast for anyone to see the exact physics of the phenomena displayed. The water balloon in this situation is modeled by an imploding membrane with viscous drag effects over a free surface, skin friction between the water and the balloon and surface tension in the water.

The image was chosen from a series of photographs taken at 300 frames per second and is the first image after the balloon was popped in which the entire balloon has left the water and yet the water remains free standing, with some visible attraction toward the balloon as it is about to collapse into a puddle. As the balloon tears across the surface of the water, the water first responded to the drag created by the balloon (also referred to as skin friction) and the surface tension that is common among water molecules before completely dispersing.

II. Methods
The experimental setup of this project included a balloon filled with water and a sharp knife on a clear sunny day. The setup is shown below in Figure 1.

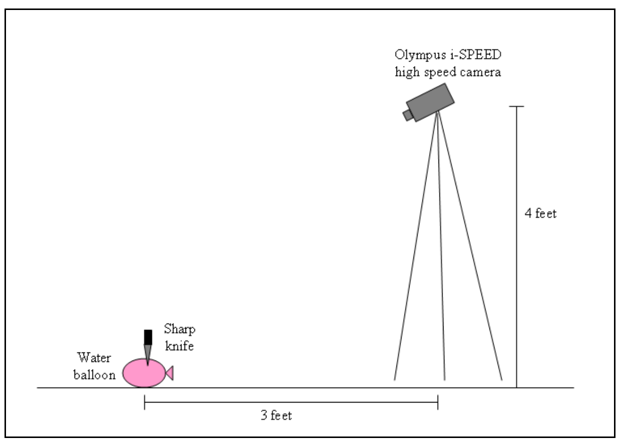

Figure 1. Experimental setup for capturing water balloon at high speed

As shown in the diagram, the camera was placed on a tripod about 3 feet horizontally and 4 feet vertically from the water balloon, resulting in an actual distance of 5 feet away from the camera. The field of view was about 2 feet high and 2 feet wide.

The camera used for this image was a digital high-speed Olympus i-SPEED set at 300 frames per second. The shutter speed was set to 1/200 second. Because the image was taken from a video, many of the camera characteristics were not properly recorded in the EXIF data. The only manipulations made in Adobe Premier and Photoshop were first extracting the image from an .avi movie file, then cropping it down to size and increasing contrast. Because the image has relatively low resolution and is displaying fluid moving very rapidly, one can assume that the spikes on the water ball are additionally affected by motion blur.

III. Flow Physics

Skin Friction

In this image, the water undergoes skin friction as it is separated from the balloon. Skin friction is parasitic drag which arises from the friction of the fluid against the "skin" of the object that is moving through it [3]. In this case, the skin of the object moves over it rather than through it, causing the same phenomenon of skin friction, but is less straight-forward in the calculation of the drag force. The force applied on the fluid due to skin friction follows the traditional drag equation, shown below in Equation 1 [3].

$$F_D = \frac{1}{2}\rho u^2 C_D A \qquad \text{(Eq. 1)}$$

In Equation 1, F_D is the force of the drag (in this case, the force caused by skin friction), ρ is the density of the fluid, u is the velocity of the object relative to the fluid, C_D is the drag coefficient and A is the reference area [3]. Note that the skin friction is caused by viscous drag in the boundary layer around the object and is proportional to the square of the velocity of the fluid. In this case, the velocity of the fluid can be taken as the relative velocity between the fluid and the balloon membrane.

The drag coefficient, C_D, in this situation will be modeled as that of a sphere because, while the water is not flowing over a sphere, the membrane is flowing over the surface of the sphere which has a similar behavior to that of a fluid flowing over a sphere. The drag coefficient of a sphere is 0.47 [4]. The density of water is 1000 kg/m^3 [1]. The velocity of the balloon tearing over the water was approximately 1 m/s. The radius of the balloon was about 5 cm, making the surface of the balloon 0.3 m^2. From these values, the force of skin friction is calculated using Equation 1 to be 70.5 N.

Surface Tension

Surface tension is a property of the surface of a liquid that causes the surface of a liquid to be attracted to another surface [2]. It is caused by the strong cohesion between the molecules [2]. Surface tension of a fluid, γ, is calculated using Equation 2, below. In Equation 2, F is the force exerted parallel to the surface of a fluid and L is the length of the line over which F acts [2].

$$\gamma = \frac{F}{L} \qquad \text{(Eq. 2)}$$

In this image, the surface tension is seen as the water on the surface is attracted to the balloon membrane and is realized by the spikes of water coming from the surface. Additionally, the surface tension is seen as the water is held briefly in a solid ball, demonstrating that the molecules are attracted to their like molecules. On the day this photograph was taken, the outside temperature was about 20ºC. The water inside the balloon can be assumed to have settled to the outside temperature due to Newton's Law of Cooling. At 20ºC, the surface tension of water is 72.88 mN/m [1]. Water has the highest surface tension of the non-metallic liquids.

IV. Conclusion

This image reveals that more happens in the world than simply what the eye can see. The engineer who created this image likes the contrast between the sharp knife and the smooth but detailed surface of the water. She also would have used more lighting and perhaps a more interesting background. She also wishes that the camera could have achieved better resolution while still achieving the detail portrayed in this image. Overall the image reveals what the engineer intended.

V. References

[1] Properties of Water – Wikipedia, the free encyclopedia. http://en.wikipedia.org/wiki/Properties_of_water

[2] Surface Tension. http://www3.interscience.wiley.com:8100/legacy/college/cutnell/0471151831/ste/ste.pdf

[3] Molecular dynamics simulation of the orthobaric densities and surface tension of water. http://jcp.aip.org/jcpsa6/v102/i11/p4574_s1?isAuthorized=no

[4] Parasitic drag – Wikipedia, the free encyclopedia. http://en.wikipedia.org/wiki/Parasitic_drag