Team Project 1 – Rising bubble With Recirculating Colored Wake
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Background:
This photograph was taken as the second team project assignment for the Flow Visualization course offered at the University of Colorado, Boulder campus. The intent of this image was to capture the flow phenomenon that occurs between a submerged water balloon filled with colored water as it is popped. This particular view was achieved using a Phantom high-speed camera from Vision Research. It captures a small, trapped air bubble in the balloon escaping and causing a jet to form.

Experimental Setup:
The setup of this experiment included a fish tank, a needle, tap water, water balloons, and food coloring. The fish tank was oriented such that the Phantom camera had a clear view. A white poster board was used as a backdrop for the image. Two North Star light fixtures were used for lighting.

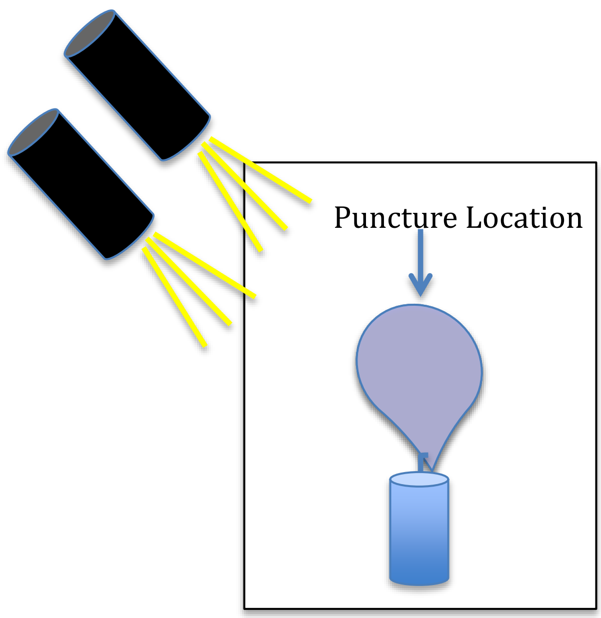

Figure 1 - Experimental Setup

In order for the video to capture the balloon skin unraveling from the colored water inside the balloon, we needed to estimate the time resolution that would be needed to clearly visualize the phenomenon. Based on other videos shot at about 6000 frames per second (fps) where the skin was not smoothly retracting, we were able to estimate the increase in frame rate. We determined that the frame rate needed to be at least an order of magnitude faster and settled on 20000 fps. The Phantom camera was able to capture 1 megapixel over the field of view at 20000 fps.

The lighting for this experiment needed to be very bright and the use of two North Star lights was necessary for good video clarity. The lighting was oriented such that the side of the balloon being shot (left side) was illuminated. We only had one opportunity to shoot the video and the settings were adjusted and optimized by the camera technician Mark Doerfler. The distance the picture was taken at was chosen based on what distance would allow the camera to capture the balloons. The field of vision on the original video was approximately 3 inches. The original video had some odd coloring and slightly distracting elements. I chose to take still frames from the video over the course of 100 frames to show the bubble travelling through the top of the colored water and creating a trail of food coloring. The photographs were then edited using Adobe Photoshop; only cropping of components I found distracting were deleted. The contrast, tone and coloring of the photos was then changed to better highlight the boundaries between the colored water and the clear water.

Results – Explanation of the Phenomenon:

The phenomenon that is highlighted in this photograph is the release of an air bubble from the balloon skin. As the bubble rises the colored water surrounding it is forced around the bubble's shape and ends up in the wake of the bubble. Due to the speed of the bubble the wake region is large and the vortex recirculation is strong enough to continually pull colored fluid behind the bubble. Estimation of bubble speed and Reynolds number is investigated below.

The flow analysis of the bubble through the water can be simplified using some common assumptions. First, by assuming the bubble to maintain a constant spherical shape we can change the reference frame of the flow. Instead of seeing the bubble travelling through the water at some speed, we can see the water travelling past the bubble at that same speed. Using this reference frame and the assumption of a spherical surface, we can apply the well-researched principles and phenomenon of flow over spherical objects to understand what is happening in this flow. Examples of this research includes papers by C. Piccolo, R. Arina and C. Cancelli[i] which discuss the interaction between the recirculating vortices formed behind spherical surfaces and the external flow. This example clearly explains that the vortices created in the wake region of the flow and how they recirculate the flow caught there. In the photograph the initial fluid behind the bubble (colored fluid) is quickly trapped behind the rising bubble and recirculates in the low-pressure zone. This phenomenon creates the visual of the jet following the trajectory of the bubble. S. Taneda was able to capture this phenomenon during his research[ii] with a larger sphere and small aluminum particles suspended within the water. This recirculation zone is clearly defined in Figure 2.


Figure 2 - Circulation Region (S. Taneda, 1956)

To estimate the bubble velocity, the balloon height was used as a size reference and the number of frames as a time reference. The balloon was approximately 6 inches tall and 4 inches wide. Based on the initial bubble size and its relation to the size of the balloon the bubble was estimated to be 1 mm in diameter. Over the course of the series of photographs the bubble's change in height was approximately 10 mm. The series of stills were taken over the length of 120 frames. Time was calculated using equation 1, velocity was calculated using equation 2, and Reynolds number was calculated using equation 3. The kinematic viscosity of water used is 8.9 x 10^-4 Pa.Sec.[iii]

$$Time_{elapsed} = \frac{number\ of\ frames}{number\ of\ frames\ per\ second} = \frac{120\ frames}{20000\ fps} = .006\ seconds \quad (1)$$

$$Velocity_{bubble} = \frac{distance\ travelled}{Time_{elapsed}} = \frac{.01\ m}{.006\ sec} = 1.67\ m/s \quad (2)$$

$$Re = \frac{Velocity_{bubble} \cdot D_{bubble} \cdot \rho_{water}}{\nu_{water}} = \frac{\left(1.67\frac{m}{s}\right)(.001\ m)(1000\frac{kg}{m^3})}{8.9\ x10^{-4}\ Pa \cdot sec} = 1876.4 \quad (3)$$

The flow of water is defined as laminar for Reynolds numbers less than 2100. This flow estimated by a Reynolds number of 1876.4, shows characteristics of laminar flow over a spherical object. Once the flow becomes turbulent, the recirculation region begins to act asymmetrically and forms Karmen Vortex Sheddings. Kravchenkoa and Moin discuss this phenomenon at a Reynolds number of 3900.[iv]

Discussion, Conclusion and Future Work:

Although this exact phenomenon was not expected when taking the video, it shows a very commonly studied and interesting phenomenon. The fact that this is the only location along the boundary layer that the dispersion of the colored dye travels so quickly is also testament to this phenomenon occurring. When watching the video the recirculation is visible near the lower part of the color trail; the blue dye circulates inwards and draws more blue dyed water up with the jet. This was a great phenomenon to capture along side the “unzipping” of the balloon skin. Future work could include purposefully increasing the amount of the air in the water balloon to see if the size of the bubble has a large effect on the dispersion of the colored water along the boundary. Another interesting possibility would consist of dropping food dye into water while a periodic array of bubbles are passing by to clearly see the effects on the descending dye.

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[i] Piccolo, Arina, Cancelli. *Fluid Exchange Between a Recirculation Region and the Perturbed External Flow. (2001)* Phys. Chem. Earth. Vol. 26 pp. 269-273.

[ii] S. Taneda. *Streamlined patterns visualized by suspending aluminum powder. (1956)* Physical Society of Japan.

[iii] Elert, Glen. *Viscosity (2010)* The Physics Hypertextbook. <http://physics.info/viscosity/> (Accessed March, 2011)

[iv] Kravchenko, Arthur & Moin Parviz. *Numerical studies of flow over a circular cylinder at ReD=3900 (2000)* Physics of Fluids. Vol. 12 Num. 2.