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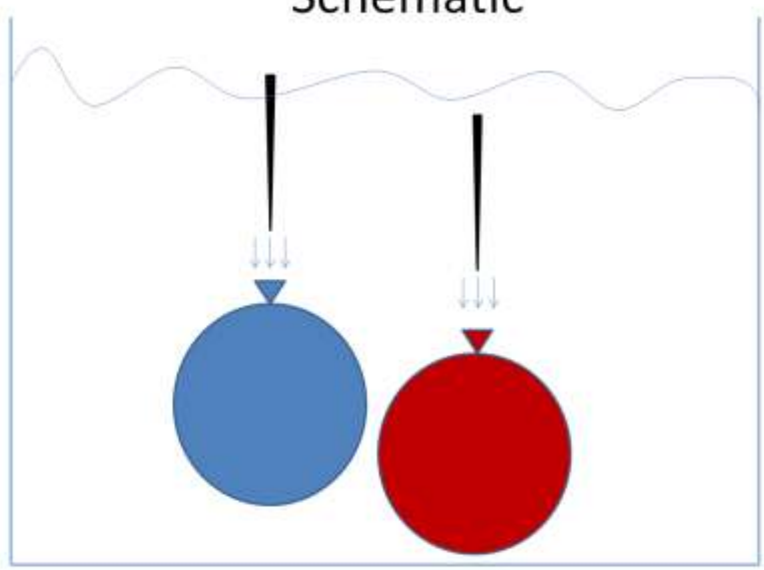
This image was produced as an assignment for a flow visualization class taken at the University of Colorado under Professor Hertzberg. The specific assignment was meant to exhibit the science behind fluid flow in a visually appealing manner. The particular video recorded was filmed by technicians visiting from Vision Research who were demonstrating their camera, the Phantom v710[1]. The experiment was set-up and orchestrated by a flow visualization team comprised of Stefan Berkower, Scott Christian-dold, Cory Fuhrmeister, Nathan Gust, and Logan Meyer. The team used the University of Colorado's Durning Lab to perform and record the demonstration. The team wanted to accentuate the incredible high-speed camera by exhibiting a process that happens very quickly and also involves the movement of gas relative to liquid. The team decided to focus on investigating the failure behavior of a burst air balloon underwater, and the resulting effect on both the air and water boundaries separated by the water membrane. (The footage can be easily viewed at http://www.youtube.com/watch?v=7nGVUjIITqo)



This demonstration utilized non expensive household materials in order to observe the characteristics of a membrane catastrophically failing and allowing the separated mediums to interact. Two regular size balloons, as seen in the schematic above, were filled with dyed water of red and green color. These balloons were tied off with knots and attached to weights using fishing line and then submerged underwater in a clear water tank. An operator then used sewing needles to pop the balloons simultaneously. The balloons were approximately 4 inches tall vertically and 3 inches wide at their widest point. Also the human thumbs visible in the picture give an accurate representation of

[1] http://www.visionresearch.com/Products/High-Speed-Cameras/v710/

scale for this demonstration. A high speed camera, specifically the Phantom v710, was used to record the resulting membrane fracture, membrane withdrawal, and the fluid movement that resulted from both the shear forces and the dispersion forces that caused the dyed and clear water to gradually mix. One of the most interesting aspects of the video is the method in which the balloon fractures. Both balloons when punctured, first failed linearly as the tear proceed in a straight-line directly down the side of the balloon as molecules in a lattice on a microscopic scale tore apart from each other causing rapid crack propagation. While the crack was continuing to propagate the tension stored in the flexible membrane pulled back on itself causing the entire membrane to 'unwrap' itself towards the opposite side of the balloon always following perfectly tangent to the boundary provided by the balloon. In the very final stages of the balloon unwrapping, the balloon can be observed to wrinkling up on itself as the balloon is coming together faster than the balloon can decrease its surface area. As a result of the balloon membrane 'unwrapping', shear forces are exerted on the water both inside the balloon and out that lie on the boundary layer which the deflating balloon is brushing against. Specifically wall shear forces in fluids are modeled by the equation:

$$\tau_{\mathrm{w}} \equiv \tau(y=0) = \mu \left.\frac{\partial u}{\partial y}\right|_{y=0} .$$

The shear forces are subject to μ, the dynamic viscosity of the fluid, u the velocity of the fluid along the boundary layer (in our case the movement is relative but still represents fluid moving in relation to a surface), and *y* which is the perpendicular distance to the boundary.

After the balloon has retracted, simple diffusion causes the dyed water and regular water to further mix. The specific rate at which the food coloring diffused is relatable by Fick's Law of diffusion which states:

$$J = -D\frac{\partial \phi}{\partial x}$$

Fick's first law relates the diffusive flux to the concentration field, by postulating that the flux goes from regions of high concentration to regions of low concentration, with a magnitude that is proportional to the concentration gradient (spatial derivative). In one (spatial) dimension, this is the equation stated above.

$$\frac{\partial \phi}{\partial t} = D\frac{\partial^2 \phi}{\partial x^2}$$

Fick's second Law predicts how diffusion causes the concentration gradient to change with time.

In this video, regular tap water was used both in the water balloons and in the water tank. Then general Kroger brand food coloring of colors red and blue were added to the water contained in the water balloons. The video was captured in the Durning Lab located at the University of Colorado. The lighting was supplied through the use of a 200 watt industrial light and the ambient light present in the Durning Lab. The image was front lit with a white background to capture as much detail as possible.

In this film, the field of view is approximately 20 inches across and the image was approximately 4 feet from the lens. The Camera used was a Phantom v710 capable of taking over 1 million frames per second. The raw video for this film was shot using approximately 20,000 frames per second and a 1 megapixel view. Adobe Premier was then used to reduce the frames present in the final video as well as provide the forward and backward speeding up and slowing down which is present in the final video. The final film was run at 25% speed forward initially, 50% speed backwards, and then 500% speed through the rest of the film.

This image reveals the microscopically science that is occurring every instant at a speed that is far too rapid to be observed by the naked eye. Specifically as seen in this video, a balloon popping is much more detailed than the instantaneous pop that the human eye observes in real time. In reality, the balloon is first fracturing linearly in accordance with it's molecular grain structure, and then is also being pulled all the way around the outside of the balloon by the elastic tension contained within the stretched material. After the fracture further fluid dynamics can be observed as the dyed water and clear water diffuse into each other and the previously exact shape of the balloon becomes more and more mixed. If possible in the future, I would find it interesting to investigate the reaction of the water to shear forces of materials other than latex. In all reality, I was expecting vortices to appear at the boundary as the balloon was retracted and was surprised that the boundary was relatively undisturbed. Perhaps other materials would cause greater friction between the liquid and the elastic material retracting?

References:

"Phantom V12.1." *Vision Research*. Web. 18 Mar. 2011. <http://www.visionresearch.com/Products/High-Speed-Cameras/v121/>.

Tiwari, Prashant, Steven P. Antal, and Michael Z. Podowski. "Modeling Shear-induced Diffusion Force in Particulate Flows." *Computers & Fluids* 38.4 (2009): 727-37. Print.

Ravindra Datta, Saurabh A. Vilekar, The continuum mechanical theory of multicomponent diffusion in fluid mixtures, Chemical Engineering Science, Volume 65, Issue 22, 15 November 2010, Pages 5976-5989, ISSN 0009-2509, DOI: 10.1016/j.ces.2010.08.022.
(http://www.sciencedirect.com/science/article/B6TFK-50W80XG-7/2/d39a2d58488855e70040fc98e105c79f)