# Flow Visualization
# MCEN 5228

**Assignment:** Team Project 1
**Presented To:** Dr. Jean Hertzberg
**Participants:** Ben Bishop
3/11/09

The Flow Visualization course taught by Dr. Jean Hertzberg at the University of Colorado in Boulder integrates the physics of fluids with fine art in hopes of capturing flow phenomena through photography. "Team Project 1" was the third assignment of the course. For the project, students worked together (or individually if desired – as chosen in this case) to artistically visualize a flow of their choice. I worked individually to capture the Kaye effect: a sudden instability caused by shear forces in fluids like shampoo when they are poured from small heights. Because little is known of the cause of this instability, and that this fluid flow is usually captured in streaming video format, my intent was to capture still images to reveal some of the unknowns behind the Kaye effect; providing a better understanding as to why it occurs.

In order to create the effect, shampoo was poured into an elongated funnel in order to create uniform flow properties. Flow from the bottle would create a "chugging" effect which would vary the width and the velocity of the resultant fluid stream, skewing the effects if any were produced. The funnel was suspended with a stand and clasp system that tightened with a wing-nut eleven inches from the stand base. This height ensured enough shear would be created in the falling shampoo for the Kaye effect to take place (found through personal experimentation). A white base on the stand reflected enough light so that only one halogen lamp was needed on conjunction with the camera flash to properly illuminate the field of view. The camera was set approximately 1.5 inches away to help enlarge the small-scale effect. Figure 1 is a schematic of the set-up.

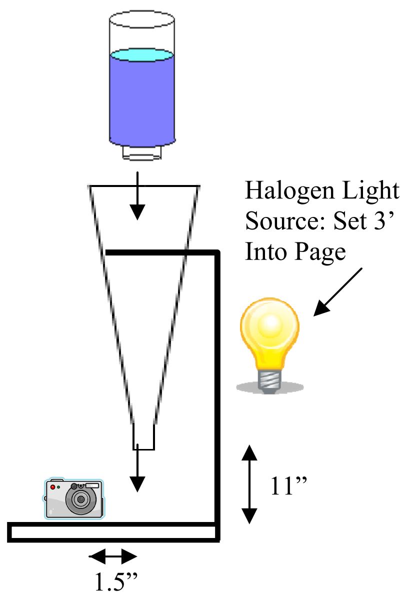



**Figure 1: Photographic Set-up for Team Project 1**

The stream of shampoo falling from the funnel was fast in comparison to the resultant expelled shampoo. Initially, the Reynolds number is 4,708 as it falls from the funnel, approximating the exit diameter to be 0.005 m, the dynamic viscosity (similar to ammonia from the high water content) to be 2.2E-4 N*s/m (Smits, 493), the velocity (calculated from the video frames) to be 0.373 m/s, and the density (calculated from the weight of 0.8 lb/bottle and a volume of 665 mL) to be 547.2 kg/cubic meter. In each session, the diameter of the jettison was larger than that of the falling fluid. The velocity, then, was smaller, following the continuity equation:

$$V_{in} R_{in}^2 = V_{out} R_{out}^2$$

where R is radius and V is velocity. The diameter of the expelled fluid was estimated to be 0.001 m larger than the falling shampoo. From the continuity equation, $V_{out}$ would be approximately 0.259 m/s. The resultant expelled fluid Reynolds number is 3,865. This is calculated from the equation for Reynolds number:

$$N_R = \frac{\rho V D}{\mu} \quad \text{(Smits, 29)}$$

where rho is density of the fluid, D is the descriptive diameter, V is the velocity, and mu is the dynamic viscosity of the fluid. At these speeds, the falling shampoo would have been able to move 0.187 mm within the frame the expelled fluid could move a distance of 0.130 mm, since the exposure time was 0.5 ms.

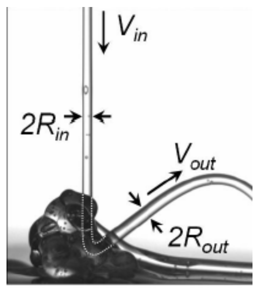
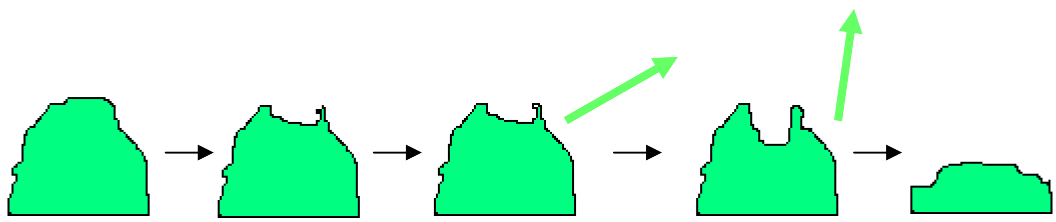



**Figure 2: Visualization of Continuity Equation at Work (Versluis, 18)**

The Kaye effect was discovered in 1963 by a British engineer named Alan Kaye. In trying to analyze the reasoning behind the sudden jettisoned fluid, Kaye simply concluded, "I can offer no explanation for this." His research sparked new pursuits in shear-thinning fluids, and we now know that changes in viscosity are the cause of the Kaye effect, previously unexplainable.

Changing viscosity is a property of non-Newtonian fluids in which there is a reversible structural break-down of materials due to flow-induced stress. Newtonian fluids, such as water or air, maintain the same viscous properties when placed under shear stress. Non-Newtonian fluids show opposite effects. Those that increase their viscous forces when shear is applied, such as silly-putty, are categorized as shear-thickening, while those the show reduced viscosity (blood, shampoo) are shear-thinning (Maisel). The latter effect can be seen everyday when the bottom of a catsup bottle is beat to expel the condiment. Catsup is a shear-thinning fluid and the exerted force causes a reduction in viscous properties, allowing it to flow from the bottle. The ability of the shampoo to begin highly viscous then reduce its viscous properties makes the Kaye effect possible. The falling shampoo creates a heap of highly-viscous fluid that is slow to dissipate. The rising mound of shampoo conflicts with the stream of shampoo falling from the funnel. Due to the interference, a dimple begins to form within the heap. As the dimple deepens, the falling force from the funneled-shampoo increases in magnitude, resulting in higher shear forces within the heaped-shampoo. These heighted shear forces cause the jettison of the lower-viscosity fluid; resultant of the non-Newtonian properties and increased forces. As the fluid ejects, the dimple depth increases, causing the jettison to rise in height from continuity and conservation of energy. Once the rising fluid comes into contact with the falling fluid and the heaped fluid is able to subside, the Kaye effect ends

(Versluis, 3-5). The following diagram and table summarize the Kaye effect sightings and their causes.



1 2 3 4 5

**Figure 3: Deformation of Heap Through Progression of Kaye Effect**

**Table 1: Summary of Kaye Effect**

| Step # | Visualized Effect | Cause |
|---|---|---|
| 1 | Heap forms | High viscosity of fluid |
| 2 | Dimple forms within heap | Force due to falling fluid |
| 3 | Fluid jettisoned | Increased shear forces from falling fluid decrease viscous properties of fluid within heap |
| 4 | Jettison arch increases | Conservation of energy, continuity |
| 5 | Heap subsides | Rising arch impacts falling fluid |

For the photograph, no special visualization technique was used; the fluid was shot in its natural state in nominal conditions. Four types of shampoo were purchased at the Safeway store off of Baseline Rd. in Boulder to simulate the different colors. They were all a product of Suave shampoos in their “naturals” selection. Fresh Mountain Strawberry created red, Daily Clarifying was clear, Juicy Green Apple was green, and Soothing Lavender Lilac made purple. The other materials, including the halogen lamp, funnel, stand, wooden base, and clean-up supplies, were all found in either Dr. Hertzberg’s laboratory or Dr. Scott Summers laboratory, both within the Stores and Labs hallway of the University of Colorado at Boulder. The halogen lamp used a 30 W bulb found at McGuckin’s Hardware off of Arapahoe Ave. in Boulder. This provided the lighting in conjunction with the flash from the camera. The Sony digital camera used comes equipped with a flash range of (0.2-7) m wide x (0.9 to 5.6) m tall and a Carl Zeiss Vairo-Tessar 10x zoom lens.

A digital Sony DSC-H10 was used to photograph the continuous fluid phenomenon at an average object distance of 1.8 inches over the four images; chosen as the best for each color of shampoo over a total of 607 images. This distance, possible using the Micro setting on the camera to enabling it to focus on close-up objects, created a field of view ranging from 3 inches for the red image to 6.5 inches for the clear, green, and purple images. The corresponding focal lengths for the images were 6.3 mm, 11.5 mm, 11.4 mm, and 11.5 mm, respectively. These settings coupled with and aperture value of f/3.5, a shutter speed of 0.5 ms, an f-stop value of f/9, and ISO speed ratings of 125 created the four original images. Each of the original images began with pixel dimensions of 3264 wide x 2448 high. These were later cropped in Adobe Photoshop to matching dimensions of 1821 pixels wide x 885 pixels high. Using Photoshop’s Curves function, each image of varying color had its contrast heightened in order to bring out the full color of the transparent fluid while darkening some of the shadows to prevent saturation in the image. In this fashion a full contrast range was achieved. Glare seen on the jettison streams from the camera flash were removed using the Clone Stamp feature. This, again, needed to be done on all four images. The images, now of finished quality and equivalent dimensions, were placed within a new sheet in Photoshop and aligned together manually; aligned in order best suited for the viewer to move their eye through the image following the discharge streams. For an extra aesthetic appeal, a black border was placed around the outside, at a width of 30 pixels, using the Fill function to heighten the contrast of the image from whatever the piece is mounted on. The resulting compiled image also had pixel dimensions of 1821 wide x 885 high.

Captured statically, this image reveals a little of the physics behind the Kaye effect. From the image one can see the continuous, random motion of the discharge streams resulting from the high shear stress built up in the heaped shampoo. The images serve to demonstrate the abstractness of this flow I geometry, even though the height itself can be controlled with the impact forces. I am very happy with the clarity of the photos since the camera needed to focus on objects constantly changing their distance from the lens, as well as the vividness of coloration brought out by the lighting. However, the clear image, specifically, seems to have some areas that are blurred by the motion and controlling the direction/geometry of the discharges might have creaded an image more aesthetically mixable. Captured well, the images spur new questions as to what controls the length and shape of the jettisoned stream. To answer this question, different non-Newtonian fluids could be utilized and the orientation of the base could be changed in order to control jettison direction.

**References**


1. Maisel, Merry. “Secrets of Shear Thinning.” http://www.tacc.utexas.edu. University of Texas at Austin. Texas Advanced Computing Center. 2008

2. Smits, Alexander J. A Physical Introduction to Fluid Mechanics. “Laminar and Turbulent Flow.” pg. 29. John Wiley & Sons, Inc. New York City, NY. 2000

3. Smits, Alexander J. A Physical Introduction to Fluid Mechanics. “Table C.9 Properties of Common Liquids at Atmospheric Pressure and 20°C” pg. 493. John Wiley & Sons, Inc. New York City, NY. 2000

4. Versluis, Michel et al. “Leaping Shampoo and the Stable Kaye Effect.” http://arxiv.org. pgs 3-18. University of Twente, Faculty of Science and Tech.