Unsteady Cascading Kaye Effect in a Shear Thinning Liquid

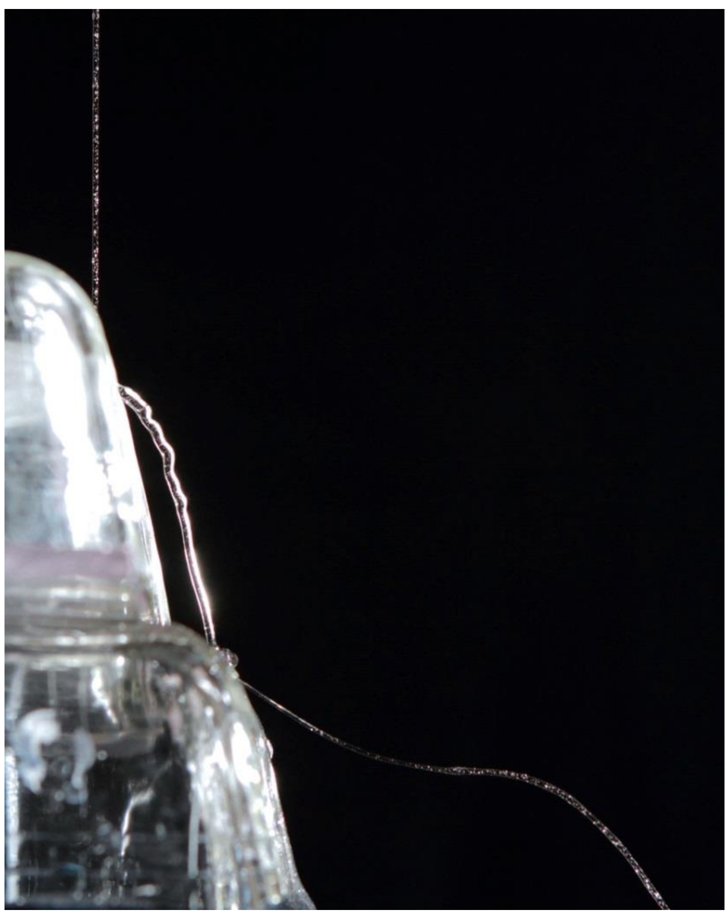
Joseph C Straccia

Teammates: Max Scrimgeour, Jeremy Parsons

MCEN5151: Flow Visualization

Mechanical Engineering

University of Colorado, Boulder



Objective

The objective of the “Team Second” assignment was to develop an idea for a flow visualization experiment, to collectively gather materials and design the experiment and then to photograph the results. The image should embody the essence of the art of flow visualization by striking a balance between revealing the physics of the flow and achieving an aesthetically appealing picture. In this assignment Team 10 set out to generate and photograph the Kaye effect in a shear thinning liquid.

Background

Fluid Rheology

In simple, true fluids like water and air the relationship between shear stress and strain rate is linear [1]. The parameter which relates these two quantities is called viscosity and it can be accurately approximated as a constant (at fixed pressure and temperature) for these Newtonian fluids. In complex fluids however, the relationship between shear stress and strain rate can be non-linear. For these so called Non-Newtonian fluids viscosity is a function of shear strain rate or strain rate history [2]. Two common types of Non-Newtonian fluids are shear thinning and shear thickening fluids. These complex fluids are usually mixtures, emulsions, slurries or suspensions [3]. For shear thinning fluids, also known as pseudo-plastic fluids, the viscosity of the fluid decreases as shear strain rate increases (Fig 1). For shear thickening fluids, also known as dilatant fluids, the viscosity of the fluid increases as shear strain rate increases (Fig 1) [2]. The dependency of viscosity on strain rate in these fluids leads to physical phenomena which may seem strange or unintuitive when compared with the behavior of the Newtonian fluids we are most accustomed to observing.

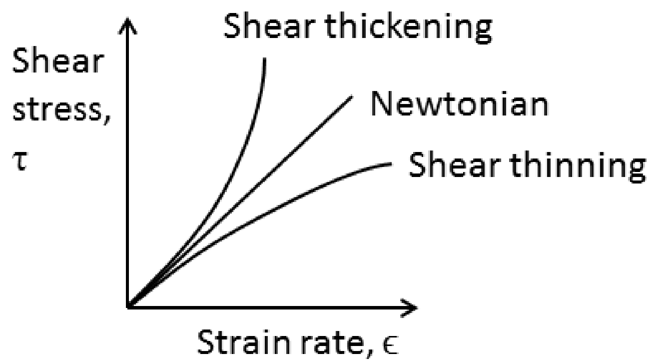


Figure 1: Viscous behavior of Newtonian and non-Newtonian fluids

Kaye Effect

The Kaye effect is the bending of a stream of shear thinning fluid that occurs when the stream impacts a pool or thin film of the same fluid. The effect was first noted by the eponymous Arthur Kaye in 1963 although Kaye did not present an explanation for the phenomenon [4]. Collyer and Fisher identified the effect to be limited to shear thinning fluids in 1976 although they also arrived at several other conclusions regarding the conditions under which the Kaye effect would occur that would later be disproven [5, 6]. A more complete understanding of how and when the Kaye effect occurs wasn’t revealed until 2006 with the work of Versluis et al [6]. Their team employed a number of techniques to study the Kaye effect including shooting high speed footage of streams of shear thinning fluid impinging on fluid pools or fluid film covered inclined surfaces, using total internal reflection to direct laser beams down the fluid stream and bouncing streams of the fluid off of suspended thin films of soap. They found that where the falling stream impinges on the pool of fluid a small cup forms in the pool. On the inside of this cup the stream-cup interface experiences high shear and therefore develops a low viscosity layer (i.e. shear thinned layer). If the height from which the stream is dropped is sufficiently large the kinetic energy of the impinging stream exceeds the viscous dissipation at the interface and so the stream 'slides' off the fluid cup and escapes as an outgoing stream with the remaining kinetic energy. Versluis et al. demonstrated that the effect is stable by maintaining it for several minutes on an inclined surface. They therefore argued that the term "bending" is a more appropriate representation of what happens to the stream than the descriptions "bouncing" or "reflection". By using different opacity fluids and directing laser beams down the impinging stream Versluis et al. also showed that the stream and pool of fluid remain distinct with no mixing occurring at the interface. In one of the experiments Versluis et al. even demonstrated a cascading Kaye Effect with multiple "bends" in the fluid stream from repeated impacts on an inclined surface. In this work we seek to produce a similar cascading Kaye effect with a somewhat modified experimental set-up.

Method

Experimental set-up

In this experiment Team 10 set out not only to demonstrate the Kaye effect but to show that after a 'bend' the stream would be reaccelerated by gravity and could bend a second time off of a lower surface. A generic clear liquid hand soap was chosen as the test fluid because hand soaps are an inexpensive and easily obtained shear thinning liquid.

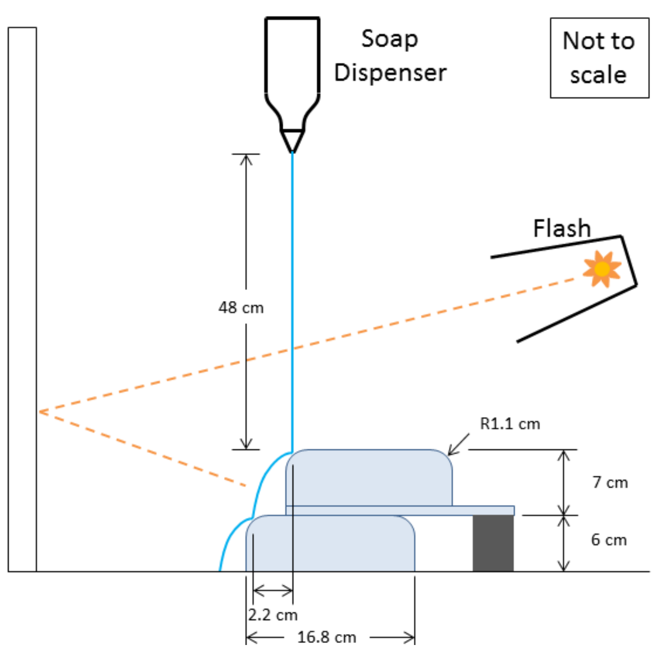


Figure 2: Side View of Experimental Set-up

In phase one the team experimented with generating the Kaye effect by altering three variables: the surface the stream would impinge on, the height above the surface to start the stream and the flow rate of the fluid. The surfaces tested were an included acrylic plate, the side of an acrylic cylinder and the chamfered corner of a glass dish. The rounded chamfer on the corner of the glass dish was found to be effective in generating the Kate effect bend because the stream was able to easily clear the surface of the dish due to the way the chamfer sloped away from the incident point. The glass dishes were also stackable with the addition of an acrylic sheet so that the team could attempt multiple bends in series. The height from which the fluid was dropped was ultimately set at 48 cm high and the flow rate used was roughly ~1.05L/hr.

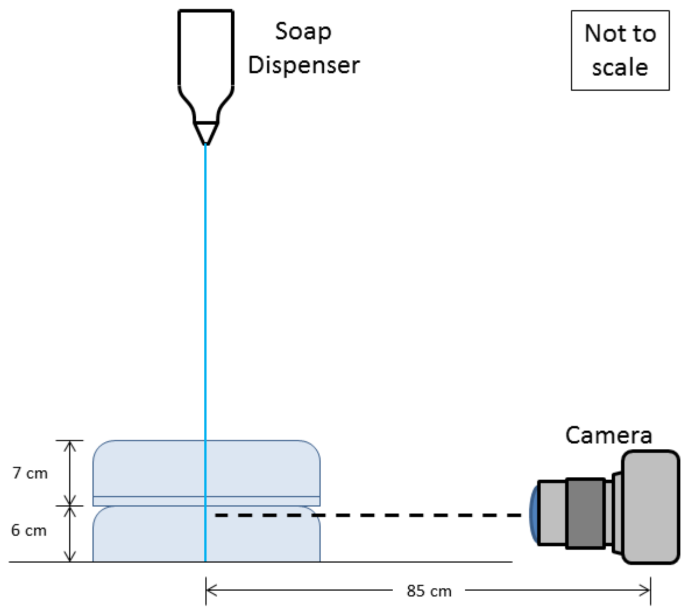


Figure 3: Front View of Experimental Set-up

To achieve the double Kaye effect bend one glass dish was placed on top of an identical glass dish with the edges offset by 2.2 cm and a 1cm thick piece of acrylic between them. A plastic sheet was put under the glass dishes extending out to where the fluid stream would impact the ground to collect the expended fluid. The camera was mounted on a tripod and placed to the side of glass dishes such that the lens axis was aligned with the edge of the lower glass dish. The imaging place of the camera was 85 cm from the point on the glass dish where the fluid stream would be incident. For lighting a flash was set up behind the experiment on a tripod pointing at the wall on the opposite side which was used to bounce the flash. A target object was placed at the location where the fluid stream would fall to focus the camera in the correct plane. Figure 2 and 3 provide a depiction of this setup.

Photo Settings

Photos were taken with a Canon 7D DSLR camera and 24-70mm F2.8 lens. The lens was adjusted to a zoom of 54mm. Lighting was provided by an off camera flash with the light bounced off of the wall onto the subject. The camera was in aperture priority mode and the file was written to RAW format.

Aperture was set to f/6.3 because that f-stop sits in the sharp range for the lens and provided enough depth of field for the scene. The ISO was set to 640 to keep the shutter speed sufficiently fast. The resulting shutter speed of 1/200 seconds was able to freeze the motion of the liquid stream. Focus was set manually in the plane of the liquid stream. A summary of the photo settings with additional details can be found in Table 1.

Focal Length	54mm
Shutter Speed	1/200s
Aperture	f/6.3
ISO	640
Autofocus	On
White balance	Auto
Gamut	sRGB
Format	RAW
Pixels WxH	2740x3425

Table 1: Photo settings

<u>Post processing</u>

The original image was shot in Canon RAW format. A TIF file was written out using Canon's raw file post processor. The image was then edited in Photoshop Elements 5.0. The image was first cropped into a portrait orientation. Then the image was flipped left to right so that the fluid was flowing from left to right. The lightning and contrast were adjusted over the whole image and the pink end of the acrylic sheet between the glass dishes was decreased in saturation to deemphasize that color. Finally the warmth of the whole image was shifted towards a cooler tone. An unedited version of the original photo can be found in Appendix A for reference.

Results

The cascading Kaye effect using a shear thinning liquid (hand soap) was successfully captured in this experiment (Fig. 4). The initial stream of falling fluid is fairly uniform in diameter and is completely vertical because no initial horizontal velocity component was added. Achieving the first Kaye effect bend on the chamfered edge was fairly easy and a steady deflection could be reliably maintained. Between the first and second edge the stream takes a ballistic path as gravity accelerates it through a parabolic arc. After the first bend however, the stream developed unsteadiness and tended to pool excessively on the second lip. This made initiation of the second bend in the stream much more difficult and when the Kaye effect did initiate on the second surface it was typically short lived. This unsteadiness is responsible for the multiple curvature path that the stream takes after the second bend because as the second bend formed and developed the angle at which the stream left the fluid pool varied with time. Within the stream a string of small bubbles were illuminated by the flash. These bubbles were introduced into the fluid when the expended liquid was returned to the soap reservoir for repetitions of the experiment. Bubbles are also visible in the experimental images taken by Versluis et al and their team actually used the bubbles in the high speed film to compute the stream velocity [6]. A similar calculation was not possible in this experiment because the camera used did not have the ability to trigger photos on a designated time interval for intervals less than a few seconds. Instead the velocity of the initial stream was estimated using kinematic equations.

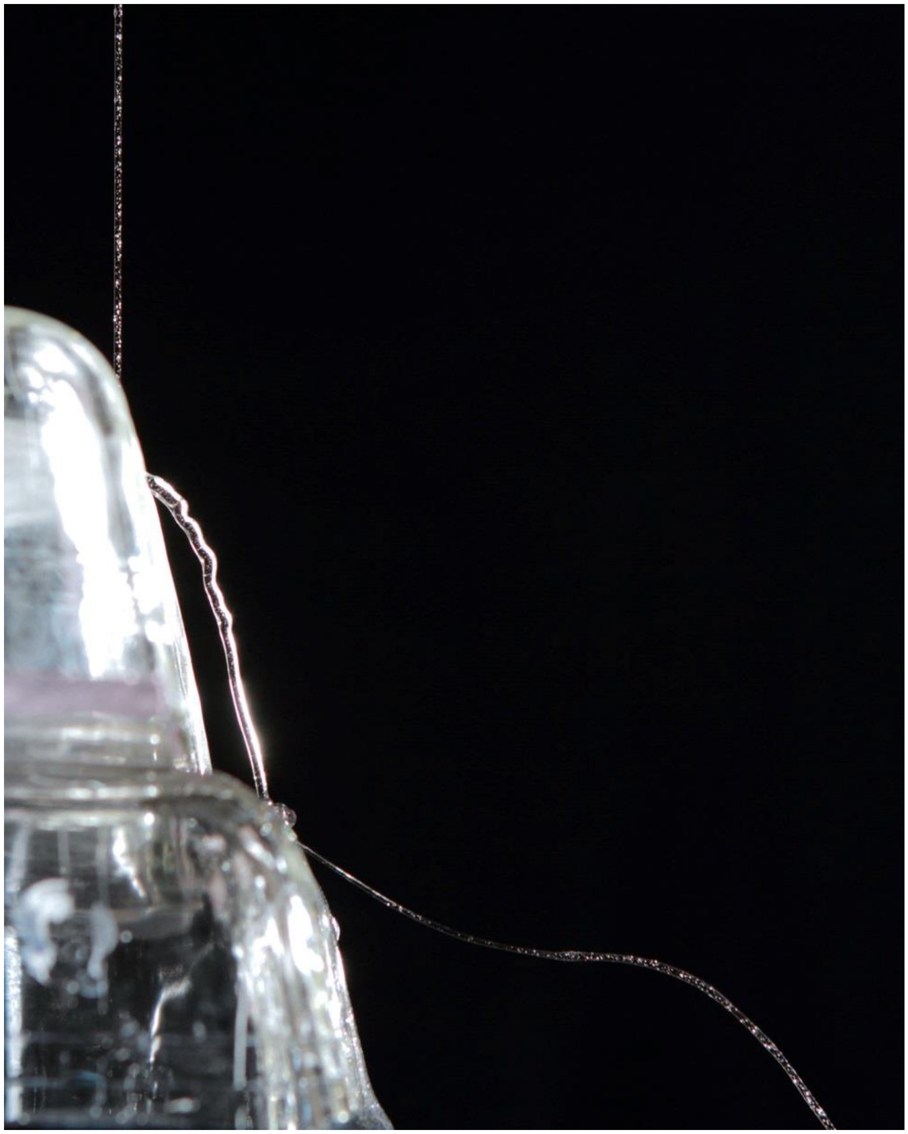


Figure 4: The Kaye effect in a stream of liquid hand soap

The velocity of the fluid stream at the first impact can be estimated using equation 1.

$$x = \frac{1}{2}at^2 + v_0 t + x_0 \tag{1}$$

We approximate the initial velocity v_0 as zero and compute the time of descent using equation 2.

$$t = \sqrt{\frac{2}{a}(x - x_0)} \tag{2}$$

For a 48cm fall with the stream accelerating at 9.81m/s^2 the time of descent is 0.313 seconds.

$$\mathrm{v} = at \tag{3}$$

During that descent time the fluid would accelerate from 0 to 3.07m/s by equation 3. This is probably an underestimate of the impact velocity because the fluid left the nozzle at a small non-zero velocity i.e. $v_0 \neq 0$. In theory the velocity of the stream after the first and second bend could also be computed by comparing the stream diameters and applying the continuity equation. Unfortunately, such an approach would assume a constant flow rate and steady behavior of the stream after each bend which is not true in this case.

The width of the fluid stream right before the first impact can be estimated by comparing its size in the frame with the relative size of other objects of known dimension. Using this approach the stream is 1.1mm in diameter before impact.

$$Q = \frac{\pi}{4} D^2 \mathrm{v} \tag{4}$$

The flow rate can be estimated using equation 4 and the approximate stream velocity and diameter. It is found to be roughly 1.05L/hr.

Conclusions

A cascading Kaye effect was successfully achieved using liquid hand soap dropped from a height of 48 cm onto the rounded chamfer of the edge of two glass dishes. Rough computations of velocity and flow rate were possible for the initial stream but the unsteadiness in the stream after the bends precluded velocity computations by continuity there. The bubbles which were unintentionally introduced into the stream during reservoir refilling could theoretically have been used to compute velocity vectors throughout the stream but this would have required more sophisticated high speed camera equipment.

The shear thinning fluid used in this experiment tended to pool excessively on the lips of the glass dishes and flow away very slowly. This led to the difficulty in generating the second bend and the stream unsteadiness after the bends. A fluid with a smaller low-shear viscosity would probably have been more effective. For example, teammate Peter Brunsgaard achieved better results using clear dish soap instead of thick hand soap. Versluis et al also used a separate reservoir to release a thin film of fluid with controlled thickness along the impact surface instead of depending on the falling stream to deposit the initial layer of fluid, as was done in this experiment [6]. Their approach appears to be a superior method although their impact surface was an inclined plate was constant slope so fluid pooling was less of an issue. These modifications to the experimental method used in this study are recommended for future work.

Acknowledgements

This experiment was conducted with Max Scrimgeour and Jeremy Parsons.

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship Program under Grant No. (DGE 1144083). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Literature Cited

[1] Cengal, Yunus A., and Cimbala, John M, "Fluid Mechanics: Fundamentals and Applications", The McGraw-Hill Companies, Inc., New York 2006.

[2] White, F. M., "Viscous Fluid Flow", 3rd Edition, McGraw-Hill, 2006.

[3] Panton, R. L., "Incompressible Flow", 3rd Edition, John Wiley & Sons, 2005.

[4] Kaye, A., "A bouncing liquid stream", Nature, 1963; 197 1001

[5] Collyer, A., Fischer, P. J., "The Kaye effect revisited", Nature, 1976; 261:682.

[6] Versluis, M., Blom, C., van der Meer, D., van der Weele, K., Lohse, D., "Leaping shampoo and the stable Kaye effect", J. of Statistical Mechanics: Theory and Experiment. 2006; 2006(07):P07007.

Appendix A: Unedited image