Get Wet Report

Figure 1: Rope coiling instability of honey on a horizontal surface

This image is my submission to the Get Wet assignment. This assignment constitutes my first foray into the field of flow visualization. The requirements for the assignment were straightforward. Students were to work individually in choosing a fluid flow phenomena and capturing it in a clear and artistic way using a visualization method of their choice. I began by identifying viscous mixing as the subject of my experimentation. After controlling and observing several preliminary flows using various viscous fluids, it quickly became apparent that the most intriguing of my flows involved the higher-viscosity fluids and particularly concerned the interaction between these fluids and dry, horizontal surfaces. My selected flow phenomenon is known in the world of fluid dynamics as "fluid rope coiling" or simply "coiling" [1]. The final image I submitted is a shot that captures the rope coiling effect of a stream of honey poured from a fixed point and at a constant rate onto a simple sheet of paper.

The apparatus used for this experiment included a horizontal surface of white printer paper, a vertical black backdrop, a blue headlamp, a bottle of chilled honey, and a Sony Cyber-Shot DSC-H55 digital camera. These items and their arrangement can be seen below in Figure 2. With regards to procedure, I began by focusing the camera and light source on a target location on the paper. I slowly poured a steady stream of honey from a height of 8 inches onto the specified spot taking care to hold the bottle stationary. The liquid rope coiling effect is best achieved with a constant stream of viscous fluid emitted from a set point. I took many images as the honey coils grew in order to capture a time lapse of the flow. After roughly 20 coil turns, I replaced the sheet of paper and repeated the process several times. The nicer images seemed to be the ones taken early in the flows before substantial mounds of honey accumulated. I should note I chilled the honey in a refrigerator to roughly 40°F. This increased its viscosity (more on this shortly), and the slower flow that resulted allowed me to capture better-focused images.

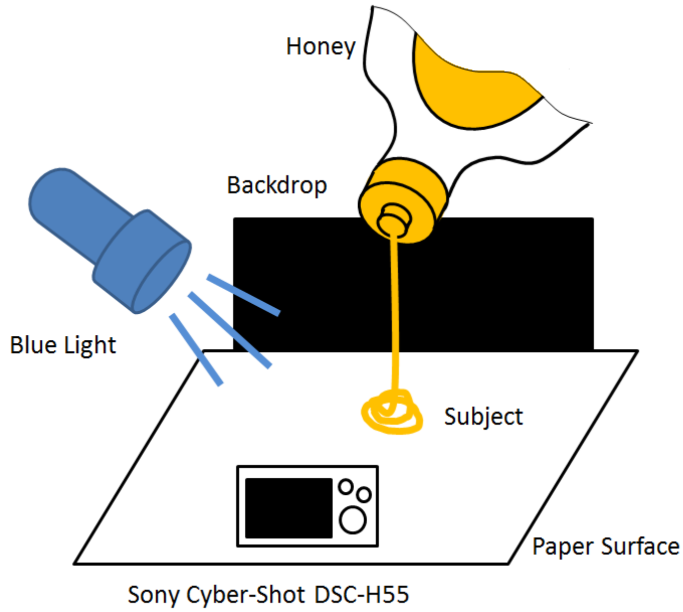

Figure 2: Diagram of experimental apparatus

The fluid phenomenon referred to as the "rope coiling" instability is like a fluids counterpart to solid beam buckling. Just as axial stresses in a vertical beam may exceed the buckling strength of the member and cause the beam to buckle, excessive axial stresses in viscous fluids can cause a similar effect [2]. Simply put, when a column of viscous fluid comes into contact with a flat, horizontal surface, the weight of that column will cause it to deform. Because of strong intermolecular forces that exist within very viscous fluids, the column will bow rather than splitting or splashing apart like inviscid fluids would. This initiates the coiling instability. Unlike solid buckling, however, these viscous fluid columns are very complicated to model as they deform not only by bending, but also by twisting, and stretching [3]. Many journal papers have been written on this subject, but here I will try to condense them to convey a simple and concise explanation.

According to L. Mahadevan's group, the parameters crucial to coiling presenting in a fluid "include the fluid density ρ, [dynamic] viscosity μ, the flow rate Q, gravity g, a characteristic filament radius r, and the height, h, over which the filament falls" [2]. These parameters govern both the radius R of the resulting coil and the frequency Ω of deposition. R and Ω are related by (1) where $\mu Ur/R^3$ represents the Newtonian viscous force per unit volume and $p\Omega^2 R$ represents the force per unit volume resulting from centripetal and Coriolis accelerations [2].

$$\mu Ur/R^3 \sim p\Omega^2 R \tag{1}$$

Mahadevan's paper explains that the relationship $U \sim \Omega R$ describes a constant filament radius coiling instability and $Ur^2 \sim Q$ describes vertical flow with axial stretching. The idea here is superposition. Each relationship represents part of what is happening and their combination with (1) yields a governing equation for viscous rope coiling (2) where $v = \mu/\rho$ is the kinematic viscosity [2].

$$\Omega \sim Q^{3/2} r^{7/2} v^{-1/2} \tag{2}$$

M. Maleki et al. have a slightly different perception, noting the existence of three different rope coiling regimes, namely the viscous, gravitational, and inertial regimes. Equation (3) shows Maleki's differentiation between models for each coiling regime [3].

$$\Omega_V = \frac{Q}{hr^2} \qquad \Omega_G = \left(\frac{gQ^3}{vr^8}\right)^{1/4} \qquad \Omega_I = \left(\frac{Q^4}{vr^{10}}\right)^{1/3} \tag{3}$$

As I said, I chilled the honey to increase its viscosity and achieve a slower flow. In his 1951 paper, Arthur K. Doolittle shows mathematically various models for the decrease in viscosity with increase in temperature for Newtonian liquids [4]. Their technicality exceeds the scope of this paper, but the relationship between temperature and fluid viscosity is a well-tested and accepted aspect of fluid dynamics. Kundu and Cohen assert in their text that in liquids the relationship between T and μ is inverse as I have observed in this experiment, but it must be noted that for gases, the relationship is proportional. At the molecular level, μ decreases with T in liquids because exciting the molecules of a liquid aides them in overcoming the attractive, intermolecular forces at play within. μ increases with T in gases because energizing gas molecules increases the number of random collisions and hinders fluid motion [5].

To reiterate that this is a slow-moving, highly laminar flow, I have approximated its Reynolds number. I assume the viscosity of honey at room temperature to be $\mu = 10\ kg/m \cdot s$ and that of honey chilled to 40°F (4.44°C) to be $\mu \approx 30\ kg/m \cdot s$. The density of honey is approximately $\rho = 1360\ kg/m^3$. For this flow, I estimate the velocity and characteristic diameter of the stream to have been $V \approx 0.08\ m/s$ and $D \approx 0.003\ m$ respectively. Calculation of the Re is shown in (4).

$$Re = \frac{inertial\ forces}{viscous\ forces} = \frac{\rho V D}{\mu} = \frac{(1360\frac{kg}{m^3})(0.08\frac{m}{s})(0.003\ m)}{20\ kg/m{\cdot}s} \approx 0.01 \qquad (4)$$

$Re = 0.1$ is an extremely low Reynolds number, denoting a flow well within the laminar regime. Because of the high viscosity of honey, an extremely high flow rate would be required to approach the transition to the turbulent regime. That honey flows slowly and in the laminar regime should come as no surprise to honey users.

Note that this image also demonstrates refraction, or the redirection of light passing through the honey coils. Refraction, however, is not the primary fluid phenomenon being showcased in the image, and its explanation is therefore beyond the scope of this paper.

Some fluids, like water and air, lack sufficient pigmentation to make flow visualization images apparent. Fluids like these are therefore often augmented with visualization aides like dyes or smokes. For this experiment, the viscous fluid chosen was honey which possesses a rich and beautiful gold color on its own. It was selected as much for this reason as it was for its viscous properties. Honey is a fantastic fluid for introducing color and contrast into a picture. In bulk, it shows off its rich color, but when drawn into thin streams, as I have done, it becomes quite transparent. The transmission of light through honey is subject to rather extreme refraction, and I used this to make the image pop. Rather than employing some additional visualization aid, I carefully manipulated my experimental environment causing the honey to showcase itself. I used a blue headlamp to light the subject from the left and top. The blue light imparted its color onto the white paper resulting in color contrast between the gold honey and blue surface. In addition, a black backdrop was placed behind and perpendicular to the paper surface. The tight coils of honey refract light at sharp enough angles to show the black background despite its absence from the frame of view. I believe these manipulations combined with the relative angles of the light source and camera allowed the image apparent flow visualization without additives like dyes.

My chosen photographic technique was color photography. I wanted to focus on manipulating the fluid flow, backdrops, and lighting. In an effort to be economical, I simply used my own point-and-shoot digital camera, a Sony Cyber-Shot DSC-H55. The field of view size of the original image was only 4in x 3in. The depth of field was nearly zero at the location of the subject as it was shot at a downward angle, the surface on which it rested serving also as its backdrop. There were roughly two inches between the lens and the honey. Reducing this distance further led to poor image focus due to the limitations of the camera. The original image was captured in 7 Megapixel (4320 x 3240 pixels) resolution. Using Photoshop Elements 8©, I cropped the image to 1992 x 1401 pixels, increased the contrast, and slightly altered the color curves to accentuate the blues and yellows. The most notable change I made was the exclusion of the honey stream as it was finishing as well as the shadow associated with it. These elements were unsightly, in poor focus, and did not add to observation of the coiling instability. Other camera settings for this image include a focal length of 4 mm, max aperture of 3.625, 1/20 second exposure time, and ISO-400 sensitivity. No flash was used.

Figure 3: Before and after comparison of image post-processing

Overall, I am happy with this image especially as my first conscious attempt at flow visualization. I believe the coiling instability is the star of the show, and this image does a good job showing it off. I am very pleased with the color variation and contrast I was able to capture as well as the crispness of the focus and the glass-like texture of the honey. However, this is not to say I am completely satisfied with my work. While I like the aesthetics of the asymmetrical coil produced, it does not demonstrate a perfect, symmetrical coiling instability like those documented in the referenced papers. This is almost certainly due to perturbations in the source of the honey. That is, I was only able to hold my hand so still. For future work, I would like to develop a rigid frame apparatus, possibly with a syringe pump, to administer a more constant and unwavering flow. I would also like to experiment more with the temperature dependency of fluid viscosity and how it plays into the coiling instability.

References

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