Liquid Rope Coiling Effect:

Assessing the Behavior of a Highly Viscous Fluid Jet

Terese Decker

Flow Visualization, Professor Jean Hertzberg

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I. Introduction

This image was captured as the *Get Wet* project in the graduate level Flow Visualization course offered in the Spring 2010 semester at the University of Colorado at Boulder, in which scientists and artists alike seek to discover the beauty of fluid flows that may otherwise be overlooked or considered for pure utility. The intent of this image was to document the instability observed from a jet of fluid with very high viscosity into a fluid of lesser viscosity. The behavior of this phenomenon is very complex and poses many physical uncertainties to an untrained eye. In order to understand the properties of the highly viscous fluid jet, the forces that govern a particular jet and its behavior will be investigated in great detail in this report.

II. Methods

In this demonstration, the fluid of high viscosity was honey which was dyed with red food coloring and the fluid of low viscosity was water. The honey was held one foot above the surface on which it impinged and was slowly poured into an eight ounce glass of water, as shown in Figure 1. The jet of honey was approximately one centimeter in diameter. The image was backlit with 15 Watts of diffused fluorescent light and top lit with 13 Watts of fluorescent light.

The experimental setup of capturing this image required an extra person to pour the honey, honey, red food coloring, water, proper lighting (as well as something to diffuse the light from the back) and a camera capable of rapid continuous shooting. First, about an eighth of a cup of honey was dyed red and an 8 ounce glass was filled with water in the engineer's kitchen. The camera was held on continuous shooting mode while the assistant poured the honey in a constant stream from one foot above the glass of water.

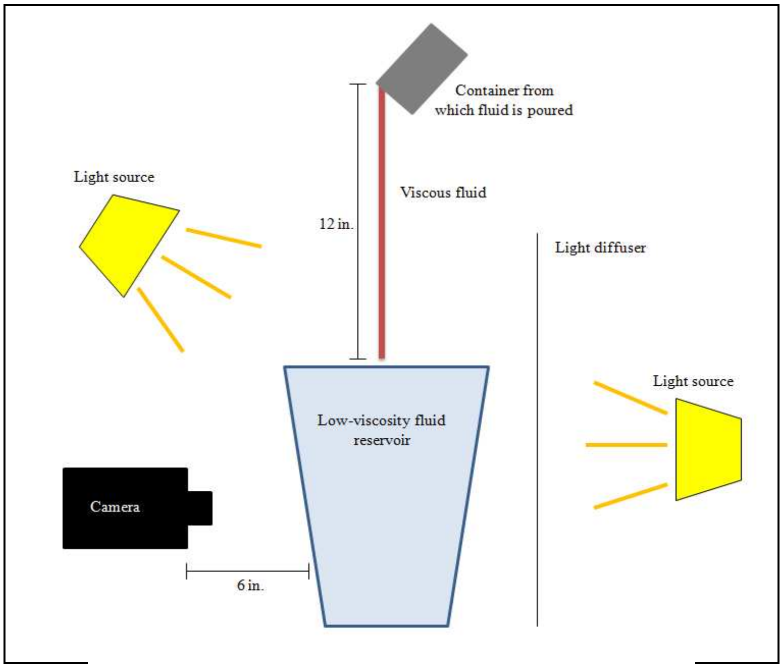

Figure 1. Schematic diagram of experimental setup

This image was captured using a digital Nikon D40 SLR camera. The original image was 3008 pixels wide by 2000 pixels high at a resolution of 300 dpi. The image was cropped and the resulting edited image was then 882 pixels wide by 1860 pixels high. When photographing the phenomenon, the camera was approximately 6 inches from the fluid reservoir. The focal length was 38 mm. The shutter speed was 10/1600 seconds, the f-stop value was f/6.3 and the ISO speed rating was 200. The maximum aperture value was f/4.7. The camera's flash did not fire. To edit the image, the engineer cropped the photo to capture the most interesting parts of the flow and increased the contrast, saturation and hue of the photo. She also used Photoshop's smudge tool to eliminate a slight glare towards the top of the image which was slightly distracting.

III. Analysis

When the honey was poured, it remained in a constant straight stream until it hit the surface of the water. Upon contact with the water, it began to wander in a seemingly chaotic form. This was the result of shear resistance, which is a tangential stress caused by fluid viscosity that takes place along a boundary of a flow in the tangential direction of local motion. This is common among fluids with a low Reynolds number.

The Reynolds number of a fluid flow is a dimensionless number which quantifies the relationship between the inertial forces and viscous forces of the flow. The Reynolds number can be calculated using common properties of the fluid,

$$Re = \frac{\rho V L}{\mu}$$

where μ is the dynamic viscosity in kg/m·s, ρ is the density of the fluid in kg/m^3, L is the traveled distance of the fluid in m and V is the mean fluid velocity in m/s. At room temperature, the dynamic viscosity of honey, μ, is on the order of 10 kg/m·s, which is approximately 10 times the viscosity of water [5]. Honey has a density, ρ, of about 1360 kg/m^3, which is about 36% more dense than water [4]. Using a length, L, equal to one foot (0.3048 m) and a mean fluid velocity of 0.5 m/s, the Reynolds number of honey is approximately 21, which is a low Reynolds number and indicates a laminar flow in which viscous forces dominate.

In this particular image, two different phenomena are demonstrated which are closely related – fluid buckling and a fluid rope coiling effect. The viscous stream falling through the fluid of lesser viscosity demonstrates a low Reynolds number instability often referred to as fluid buckling [2]. Additionally, fluid of high viscosity often undergoes the fluid rope coiling effect, which is seen at the bottom of the image where the viscous fluid, although dropped from the same location above the surface, lands in a coil configuration at the bottom of the less viscous fluid.

Fluid coiling is not completely understood yet by scientists. However, it is widely accepted that fluid buckling and coiling require a longitudinal compressive stress, like the buckling of an elastic column under a load [1]. It is also accepted that surface tension has a very small effect on the behavior of the fluid and can be neglected in the analysis of the flow [2].

The behavior demonstrated by the viscous fluid is such that it elongates as it falls, and exhibits a buckling instability as nears the surface. The buckling is the result of a competition between bending and axial compression, and causes the thread to loop itself into coils [1]. After much experimentation and exploration of these phenomena, it has been observed that the the liquid rope coiling effect causes the coils to pile up on the surface, forming a tall column and that the frequency of coiling exhibits a dependence on the fall height. In general, honey falling from a moderate height is driven mostly by gravitational forces [2].

IV. Conclusions

The image as a whole reveals the beauty in a very simple fluid flow which can be devised in anyone's kitchen. On a broader scale, this image represents the beauty in all natural phenomena in the world. The engineer is particularly fond of the color gradient in the background and the interesting path the viscous fluid takes on its the way down the glass, as well as the interesting rope coiling at the bottom. Although the fluid physics are adequately shown in this image, the engineer wishes that the original photograph had been better focused for the fluid phenomena to be more clearly realized. For future images, she would put more attention toward the camera settings in order to master the focus of the entire fluid flow, rather than just the rope coiling portion toward the bottom of the image which seems to be in the best focus in the image. The intent of this image was achieved for purposes of flow visualization, but these phenomena could definitely be explored further to demonstrate other aspects of low Reynolds number flows.

This concept could be further developed in a number of ways. First, it would be interesting to experiment with fluids of very high density as well as viscosity to see if the Rayleigh-Taylor instability occurs in conjunction with fluid buckling. Also, the fluid buckling would be interesting to observe with the exact same path of viscous fluid being poured onto a moving conveyer belt in order to freeze the phenomena for further investigation.

V. References

[1] Morris, S.W., et al. *The meandering instability of a viscous thread*. 07 Feb. 2010 <http://www.physics.utoronto.ca/nonlinear/preprints/MDRL_07.pdf>

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[3] Purcell, E.M. *Life at low Reynolds number*. 07 Feb. 2010. <http://www.hep.princeton.edu/~mcdonald/examples/fluids/purcell_ajp_45_3_77.pdf>

[4] Rainer Krell, (1996). *Value-Added Products from Beekeeping (Fao Agricultural Services Bulletin)*. Food & Agriculture Organization of the UN. ISBN 92-5-103819-8.

[5] "Viscosity." *The Physics Hypertextbook*. Web. 07 Feb. 2010. <http://physics.info/viscosity/>