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Assignment 1 Report
ARTF 5200
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Viscosity Dynamics and Liquid Rope Coiling

9/25/2021

Overview

This picture was taken with the intent of visualizing the behavior of a jet stream as it's flow changes mediums and it's viscosity is also changing. In order to achieve this, the fact that viscosity is temperature dependent was leveraged. Leah Selman assisted in the set up of the photograph, and poured the jet as the picture was taken.

The Flow

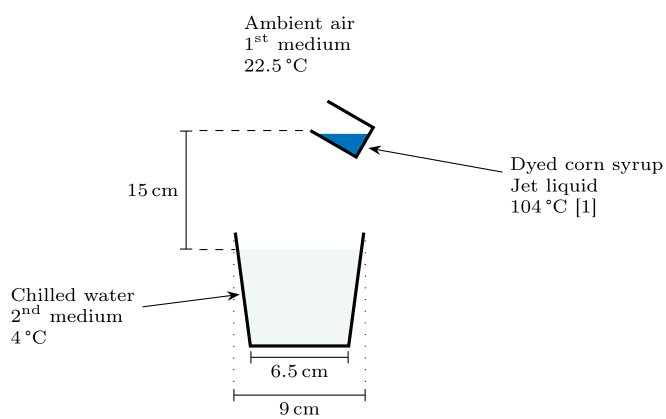

Figure 1: Diagram of the setup used for the picture. All values in this diagram are approximate [1].

A clear plastic cup was filled to about 85 % with cold tap water. The cup of water was stored in a standard refrigerator for approximately 10 min, reducing the water's temperature further. The cup was then placed in the predetermined location of the shot, which was already set up. As this was taking place, the jet fluid (corn syrup dyed with blue food coloring) was heated up in a microwave until it began bubbling (approximately 40 s). The jet fluid was then immediately removed from the microwave, and slowly poured into the cup of chilled water from a height of approximately 6 inches. A burst of pictures were taken as the jet entered the chilled water. A diagram of the setup can be seen in Fig (1).

We begin our analysis by first defining the states that our three fluids are in. We will assume that prior to prior to the jet's formation, all three fluids were perfectly homogeneous and had no time dependence. We justify this simplification because we are analyzing over a short time frame. Furthermore, we will neglect cooling that occurs while the jet is falling, as it will be much smaller than the cooling that is experienced as the jet hits the cold water.

To calculate the Reynolds Number of the jet as it hits the water, we first will determine it's velocity at that time.

$$\begin{aligned}
&\Delta x = \tfrac{1}{2}at^2 \\
\implies\quad &15\,\text{cm} = \tfrac{1}{2}\left(9.81\,\text{m/s}^2\right)t_{\text{entry}}^2 \\
\implies\quad &t_{\text{entry}} = \sqrt{\frac{2(0.15\,\text{m})}{9.81\,\text{m/s}^2}} \approx 0.175\,\text{s} \\
&\begin{cases} \Delta v = at \\ v_0 = 0 \end{cases} \\
\implies\quad &v_{\text{entry}} = \left(9.81\,\text{m/s}^2\right)t_{\text{entry}} \approx 1.72\,\text{m/s}
\end{aligned}$$

We will then approximate the viscosity of the corn syrup to be $0.2\,\text{Pa}\,\text{s}$ using tabulated data of temperature versus dynamic viscosity from "Determining the Activation Energy of Corn Syrup using the Arrhenius Equation," by Utkarsh Sharma [2]. Finally, we will use a density of $\rho = 1.33\,\text{g/mL}$ [3], and a characteristic length of $L = 15\,\text{cm}$. Although not used when calculating the Reynolds number, we will note that the jet has a diameter of approximately 2.5 mm, which was calculated using a known length, the diameter of the top of the cup (9 cm), and multiplying that by the pixel ratio of the jet to the top of the cup ($^{85}/_{3000}$).

$$\text{Re}_{\text{entry}} = \frac{\rho L v_{\text{entry}}}{\mu_{\text{entry}}} \approx \frac{\left(1330\,\text{kg/m}^3\right)\left(1.72\,\text{m/s}\right)\left(0.15\,\text{m}\right)}{0.2\,\text{kg/m}\,\text{s}} \approx 1715 \tag{1}$$

When the jet enters the water, the medium drastically changes, which has a significant effect on the flow of the jet. One of the more important effects, in this case, is that the rate at which heat is leaving the jet will increase due to the medium surrounding it having a decreased temperature and an increased thermal conductivity. Because the corn syrup is now rapidly cooling, it's viscosity is also rapidly changing [2]. Another important effect that the medium change causes is that now, there is a buoyant force pushing upwards on the jet due to the significantly increased density of the medium.

Because of the buoyant force, the acceleration of the jet rapidly decreases, allowing us to see the beginning of a phenomenon called *liquid rope coiling*, which is commonly seen in highly viscous fluids when their speed is significantly and abruptly reduced (e.g. hitting a solid surface). In reality, there are multiple different regimes of the liquid rope coiling effect, each of which has different governing equations, according to Habibi et al. [4]. In our case, it seems that as the jet travels further into the medium it transitions from an inertial regime to a viscous regime. This is due to the inertial forces acting on the jet decreasing as it slows down, while the viscous forces acting on the jet increase as the corn syrup's viscosity increases [4]. Due to the buoyant force opposing the gravitational force on the jet, gravity has a reduced impact on the flow's behavior.

Visualization Techniques

This image utilizes Wilton Gel Food Colors blue food coloring to make the corn syrup more visible. The lighting was obtained be shining both a sun lamp and a ring light onto a white poster board that was sitting behind the subject. A diagram of this can be seen in Fig (2). The ring light was producing white light.

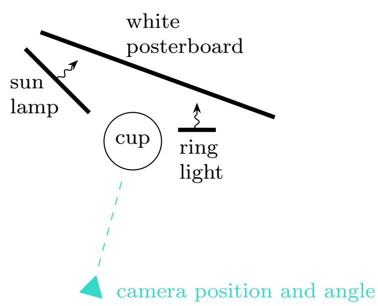

Figure 2: Birds eye view diagram of light setup including approximate location of camera lens during shooting. Diagram is not necessarily to scale.

Photographic Techniques

The picture was taken with a Canon EOS Rebel T6s using a Canon EF-S 18-135 mm lens. An aperture of f/8.0, an exposure of 1/2000, and an ISO of 6400 were used. The camera lens was approximately 1 ft from the subject while shooting. The original image, in lower resolution, can be seen in Fig (3) for context regarding initial image quality and field of view. Post processing for the photo primarily took place in Darktable, followed by cropping and conversion to portable networks graphic (PNG) in GIMP. Post processing leaned heavily on lens correction, adjusting white balance, bringing in the edges on the base curve, heavily modifying color zones, compensating with color correction, and increasing local contrast.

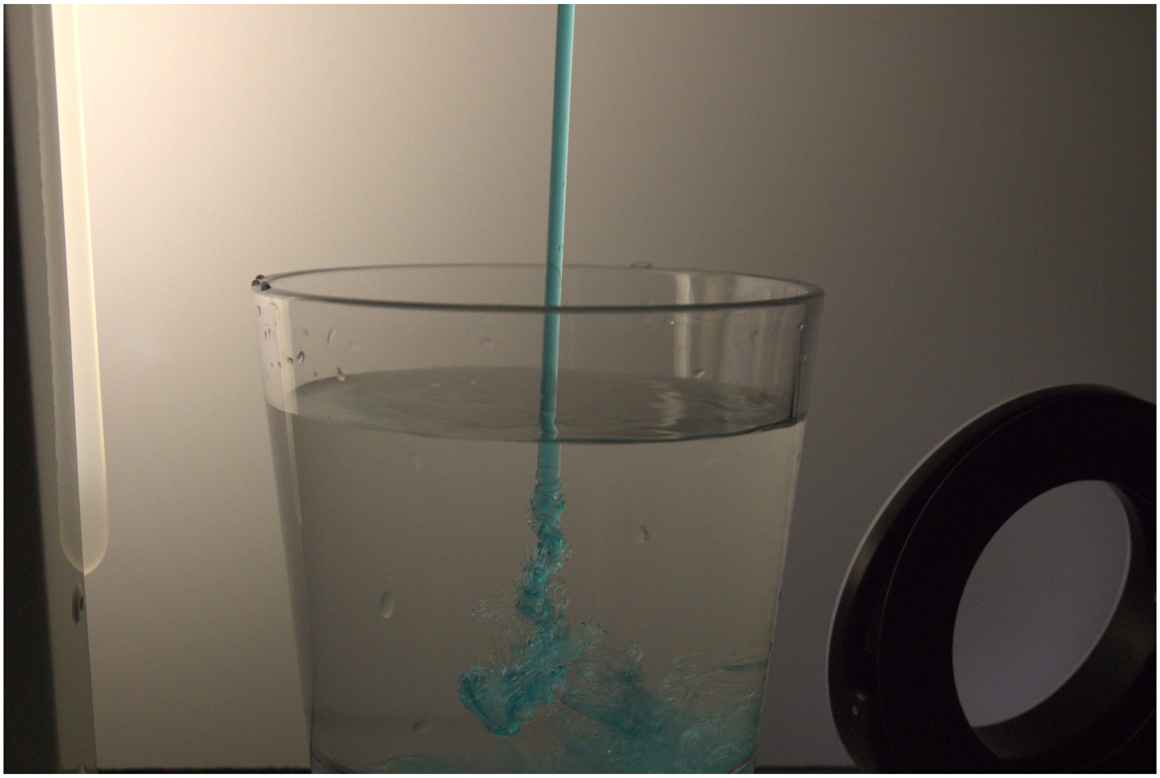

Figure 3: This was the original photo taken, unedited other than to reduce it's size for display purposes. The original image was 6024×4022 pixels.

Final Thoughts

This image shows an example of how a jet behaves when transitioning from a very low density fluid to a higher density fluid. Additionally, it reveals that liquid rope coiling can still occur while the jet is moving, whereas it is usually portrayed when the jet hits a solid surface. Finally, and most interestingly, it shows the effect that a non-constant viscosity has on liquid rope coiling. I am overall very pleased with the outcome of this picture, but the ISO setting is too high in my opinion, which almost makes the shot seem out of focus at the scale it is being viewed. I think that I was able to strike a good balance between flow clarity and making the colors *pop*, which was actually quite difficult to achieve. One idea for a future photograph exploring this phenomenon would be to switch the temperature differential around, meaning that the water would be approximately 95 °C (the boiling temperature for water in Boulder, Colorado) and the corn syrup would be chilled. This would mean that we would instead observe the flow of a jet whose viscosity is decreasing, rather than increasing.

References

[1] S. Phillips, "Candy - sugar syrup temperature chart," *CraftyBaking*, 2000. [Online]. Available: www.craftybaking.com/howto/candy-sugar-syrup-temperature-chart. [Accessed: 23-Sep-2021]

[2] U. Sharma, "Determining the activation energy of corn syrup using the Arrhenius Equation," *Queensland Academies*, July 2018.

[3] "What is the density of corn syrup?" *Reference*, 09-Apr-2020. [Online]. Available: www.reference.com/science/density-corn-syrup-86ad5d3ce78b63d4. [Accessed: 23-Sep-2021].

[4] M. Habibi, M. Maleki, R. Golestanian, N. M. Ribe, and D. Bonn, "Dynamics of liquid rope coiling," *Physical Review E*, vol. 74, no. 6, 2006.

NOTE: academic literature used are citation numbers 2 and 4.