GET WET

Blood Is Thicker Than Water

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Flow Visualization

MCEN 4151

Purpose

There is a common saying that goes, “blood is thicker than water.” The saying implies, of course, that family ties are stronger than friends. But what does it mean in terms of physics to be “thicker than water”? This flow visualization was intended to capture the physical properties that make blood thicker than water (surface tension, density, and viscosity) by photographing a drop of blood falling through water. The visualization was also intended to capture a beautiful image of a Worthington jet as the blood impacts the surface of the water.

Apparatus

The equipment for the setup included an eyedropper, a 4.25 in diameter martini glass, a green poster board as a backdrop, tap water, and a small amount of livestock blood provided by Arapahoe Meat Co. A small amount of EDTA (about 1 teaspoon per 100 mL) was added to the blood as an anticoagulant.

The eye dropper was used to drop uniform sized drops of the blood from various drop heights into a martini glass filled with tap water. The camera was held as close to the surface of the water as possible while still holding the location of impact in focus. The drop height in this photo was approximately 40 cm. The height of the Worthington jet is approximately 1.5 cm. The diameter of both the satellite droplet above the Worthington jet and the vortex right are about 0.2 cm.

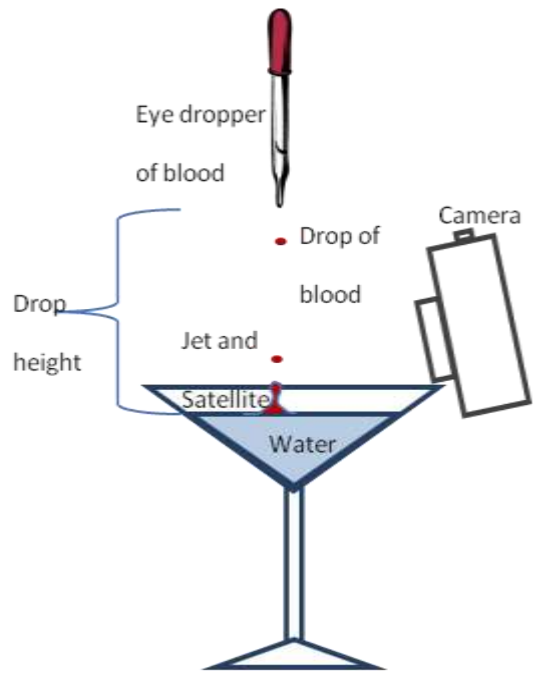

Figure 1: Apparatus

Flow Phenomena Observed

Varying drop heights produced different effects. The lower drop heights (less than about 15 cm) produced very distinct vortex rings and no jets. Higher drop heights (30-40 cm) produced distinct Worthington jets and vortices, although the vortices were not as pronounced at higher drop heights as they were at lower drop heights. The effects of different drop heights can be seen in Figure 1 on the right.

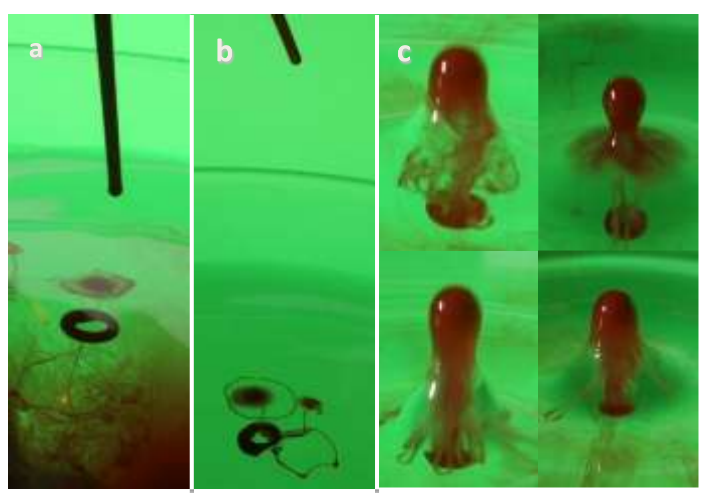

Figure 2: a) Drop height of about 2 cm. b) Drop height of about 10 cm c)Drop height of about 30 cm.

Worthington jets are driven by surface tension effects. When the impact of the droplet depresses the surface of the water, the surface tension of the water acts upward pulling water surface up into a jet. Vorticity describes how much each fluid particle is rotating about its own axis. Vortex rings are driven by viscous effects. They are formed as a free jet of fluid moves through a static fluid. Shear stress at the interface between the different fluid velocities creates Kelvin-Helmholtz instability. This causes the fluid at the boundary to roll up on itself, forming a vortex ring around the perimeter of the jet of fast moving fluid. Figure 3 (Hsiao and Quintero, 1988) at right shows the formation of a vortex ring and a Worthington jet from a water droplet impact.

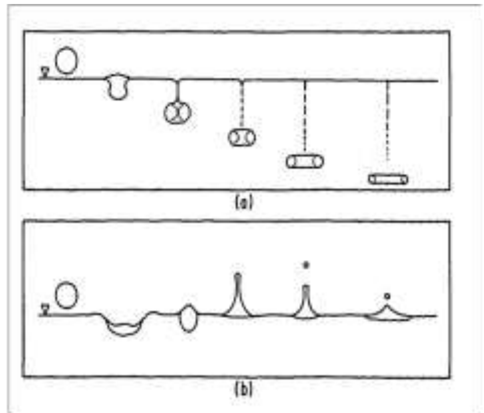

Figure 3: Diagram of a vortex ring (a) and a Worthington jet (b) forming after a droplet impact.

The dimensionless Weber number (We) describes the relation between the inertia and the surface tension of a falling droplet (Weber Number). Hsiao and Quintero (1988) studied the physics of a droplet of a given fluid, mercury, impacting a pool of the same type of fluid. For values of We above a critical Weber number (We_c) of 8, they observed a jet, but below We_c number they observed a vortex ring. Weber number was calculated for the experiment of blood falling into water for Photo a in Figure 1 (drop height 2cm), Photo b in Figure 1 (drop height 10cm), Photo c in Figure 1 (drop height about 30cm), and the main flow visualization photo on the cover page (drop height about 40cm). Weber number (We) was calculated from Equation 1 (Weber Number):

$$We = \frac{\rho\, v^2\, L}{\sigma} \tag{1}$$

In Equation 1, the variable ρ is the density of blood, which was taken to be approximately 1055 kg/m^3; this value was obtained by averaging a range of values (Elert, G., 2004). The diameter of the falling droplet, which was about 0.002m, was used as the characteristic length, L. The variable σ is the surface tension of blood, which was calculated by Equation 2 (Rosina, J. et al., 2007):

$$\sigma(T) = (-0.473\, T + 70.105) * 10^{-3}\, \frac{N}{m} \tag{2}$$

In Equation 2 the value T, the ambient air temperature, was 20°C. The value of σ, surface tension of blood, was calculated to be 0.0606 Nm^{-1}.

The velocity, v, was taken to be the velocity of the droplet at impact with the water. Velocity was estimated using kinematics in Equation 3:

$$v_f^2 = v_i^2 + 2\,a\,d \tag{3}$$

The initial velocity, v_i , was 0 m/s for each scenario. The acceleration due to gravity, a, is 9.81 m s^{-2}. The droplet velocity at impact, v_f was calculated to be 0.63 m s^{-1} for Photo a, 1.40 m s^{-1} for Photo b, 2.43 m s^{-1} for Photo c, and 2.8 m s^{-1} for the main photo.

Using these values, We was calculated for the different drop heights. The results are presented in Table 1:

Table 1: Weber number and phenomena observed

	Drop Height (m)	We (dimensionless)	Phenomena Observed
Photo a	0.02	14	Vortex ring
Photo b	0.10	68	Vortex ring
Photo c	0.30	205	Vortex ring and Worthington jet
Main Photo	**0.40**	**273**	**Vortex ring and Worthington jet**

Unlike the experiment performed by Hsiao and Quintero (1988), vortex rings were observed without jets for We as high as 68. There were not enough individual experiments to determine a critical Weber number for the transition between vortex rings and jets, but it is clear that the value of W_c for this experiment was much higher than that performed by Hsiao and Quintero (1988). This difference could be explained by the fact that Hsiao and Quintero only focused on the interaction of a drop of fluid with the *same type of fluid*. In this experiment, the drop and the pool had different surface tension and slightly different densities. Blood's non-Newtonian nature may also be affecting the flow phenomena observed. Furthermore, their results indicated that a drop of mercury falling into mercury would produce *either* a Worthington jet *or* a vortex ring. Blood falling into water showed *both* jets *and* vortex rings forming for a wide range of Weber numbers. This suggests a critical *range* for We of blood in water, rather than a critical *number*. The unexpected presence of jets and rings together is likely related the fact that blood and water have different fluid properties, which are interacting.

Compared to water and mercury, blood is difficult to describe chemically. Blood is a suspension of complicated organic molecules and cells. It is a shear-thinning non-Newtonian fluid. There are many biological factors that influence its properties. This makes describing why a fluid flow involving blood does what it does very difficult, but all the more fascinating.

Imaging Techniques

The photo uses basic boundary seeding techniques (the fact that blood is red and more opaque than water) to see the interface between the two fluids. The image was shot on 1/29/2011 with an Olympus FE-340 8.0 megapixel digital camera. The main photo was shot with a shutter speed of 1/640 sec and an ISO of 64. The focal length is 7.7 mm. The field of view is approximately 2.5 cm wide and the camera was about 10 cm away from the jet formed. The image is 842x918 pixels. The photo was taken using the "super-macro" setting on the camera. The only lighting used was natural sunlight on a sunny afternoon, and is coming from the left side of the photo. Light also reflected off the green backdrop, lighting the jet from behind. The sunlight reflected off of the surface of the ripples propagating from the droplet impact provides an interesting balance with the Worthington jet in the photo. The contrast was heightened in Photoshop and the original image, Figure 4 at right, was cropped to focus in on the flow. The high contrast between the green and the red is artistically interesting; however, different colored lighting from different sides could help highlight the shape of the jet and the ripples better.

Figure 4: Original image (pre-Photoshop)

Future Improvements

The image of the Worthington jet could be better if motion blur were reduced. This could possibly be achieved by setting a longer shutter speed, while lighting the apparatus with a strobe for only a small time. After discovering the interesting relationship between vortex ring formation and Worthington jet formation, I would like to retry the setup with increased drop heights to try to find a We at which vortex rings no longer form. I would love to explain some of the other phenomena that were observed during the photo shoot. I observed drops of blood scooting around on the water surface, some photos of which can be seen in the Appendix.

Implications

The surface tension of blood, 0.0606 Nm^{-1}, is less than that of water, 0.0728 Nm^{-1} (Surface tension of water). I find this ironic in light of the saying "blood is thicker than water," because if I were choosing a fluid property to reflect relative strength of interpersonal relationships, I would choose surface tension. Even so, I feel that this image reflects on the statement. The fluid interactions between blood and water are more complex than those of just water, as evidenced by the two experiments' differing critical Weber numbers and the unexpected formation of both vortex rings and Worthington jets simultaneously in the blood-water combination. A drop of blood falling into water was certainly more interesting to watch. The greater density of blood carries it though the water. The greater weight of family relationships carries us through life together. As the drop of blood falls through the water, though there is some mixing, the blood mostly stays together in a vortex ring. As my family moves though life, though we find other friends along the way, we stay together in a support circle like a vortex ring. Blood is indeed thicker than water.

Works Cited

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Appendix

Other interesting surface tension effects captured: