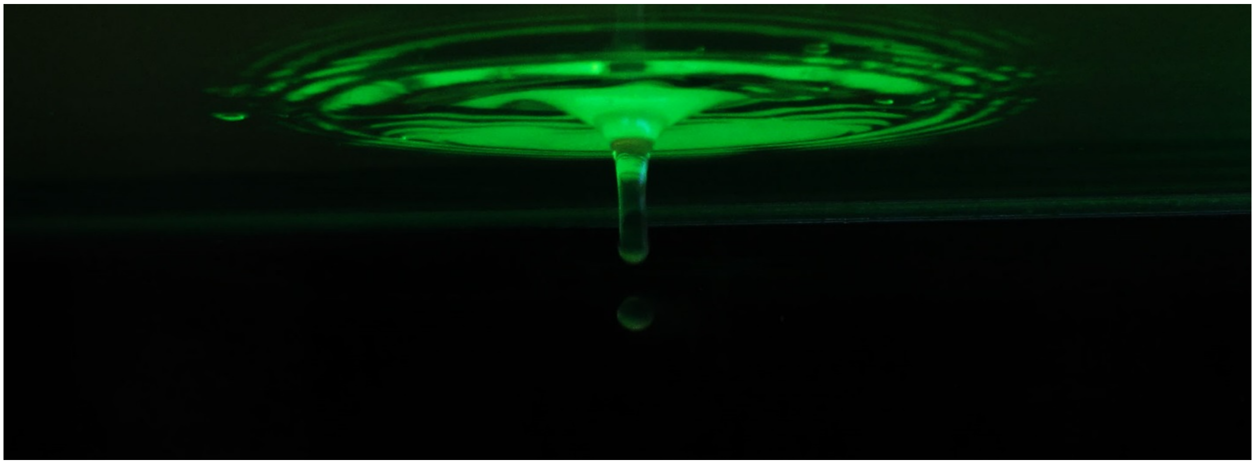
THE RISING INVERTED

The Art and Physics of a SPLASH

Project 4: Group 2



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MCEN 4151: Flow Visualization

04 April, 2013

Origins and Motivation

Van Gogh's Vortex is the result of the fourth project, Group Project number 2, for the Flow Visualization class at the University of Colorado at Boulder. My group had the idea to use water to demonstrate the double slit wave phenomenon. The potential for different images was low and so we asked what else we could do with the setup, a fish tank with shallow water. The water was replaced with highlighter water and the lighting with black lights. Then streams were launched at the surface; however this produced more commonly messy images due to a buildup of splash back on the front panel. In an attempt at getting cleaner images, single drops were dropped onto the surface by Trevor. This produced clearer phenomena and cleaner images (one focusing was sorted out using the wood block from the double slit experiment).

Special thanks to Trevor Beatty, Gabe Bershenyi, and Jennifer Milliken for assistance in set up, concept generation, and execution of the experiment.

Experimental Setup

The experiment was setup in the Media Shack in the Integrated Teaching and Learning Lab, ITLL, at the University of Colorado due to good lighting control and available equipment. A fish tank was filled to a depth of approximately 2.5 cm with highlighter water (water with highlighter ink dissolved in it). A block of wood off to the side was used to focus with and black velvet was draped on the back panel to absorb light. Black lights were positioned above and to the side of the tank. Two different apparatuses were used to produce different sized drops, a syringe and a condiment bottle. For this image the condiment bottle was used approximately 30 cm above the fluid surface. Several drops were dropped in succession for each photographing session in attempt of capturing the drop at different points in its fall and impact.

Physics of a Drop Impacting a Common Fluid Surface

Possible Outcomes

Several things can occur when a drop of fluid impacts a fluid surface. Assuming that the two fluids are in fact the same, or at least miscible, then four primary outcomes are possible, some of which can lead to even more variety. If a drop is large enough and moving slow enough then it can land on the surface and float for a period of time as if it is immiscible. If a drop is small enough and moving slowly, but with enough relative speed to its size, then it is likely to bounce off the surface at impact much like a rubber ball on a solid floor. If a drop is falling fast enough but not too fast, relative to its size and other physical/fluid parameters, then it will tend to coalesce with the fluid surface and send a vortex ring down into the fluid with entrained air. The fourth possibility requires the drop to be falling the fastest of the four and results in a splash that can vary depending on how fast the drop is moving at impact [Rein]. Figure 1 shows the four possible outcomes, floating, bouncing, coalescence, and splashing.

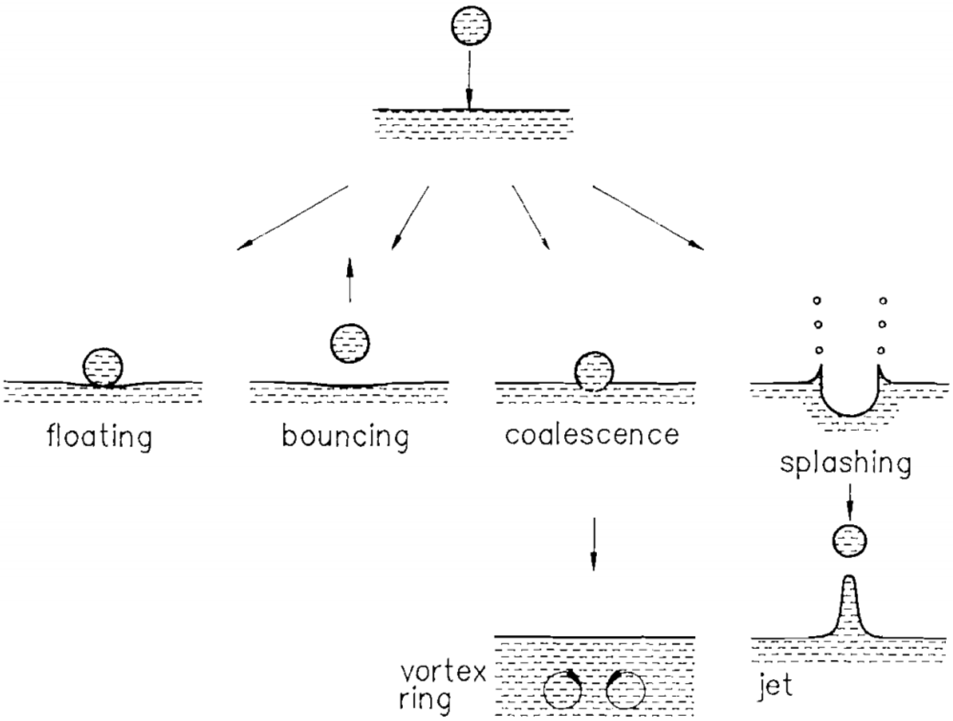

Figure 1: Impact of a drop on a liquid surface: floating, bouncing, coalescence, and splashing [Rein]

Dimensionless Quantity Correlations

There are many quantities that can affect the outcome of drop impact with a fluid surface. The most influential of these are the velocity at impact, the drop size at impact, surface tension, and viscosity. Impact velocity and drop size together act to determine the impact energy (along with relatively negligible other sources such as internal rotation and/or oscillation). There are essentially three non-dimensional numbers that consider these parameters: Weber (We), Reynolds (Re), and Froude (Fr) numbers [Rein]. These dimensionless quantities are defined and calculated for The Rising Inverted image in Table 1

Table 1: Related dimensionless quantities and their calculations

Quantity	***Formula***	***Plugged in Parameters***	***Calculated Values***
Re	$\frac{vD}{\nu}$	$\frac{(2.4\ {}^{m}/_{s})(0.003\ m)}{1.004\times 10^{-6}\ {}^{m^2}/_{s}}$	7,171
We	$\frac{\rho v^2 D}{\sigma}$	$\frac{\left(1000\ {}^{kg}/_{m^3}\right)(2.4\ {}^{m}/_{s})^2(0.003\ m)}{0.07197\ {}^{N}/_{m}}$	240.1
Fr	$\frac{v}{\sqrt{gD}}$	$\frac{2.4\ {}^{m}/_{s}}{\sqrt{\left(9.81\ {}^{m}/_{s^2}\right)(0.003\ m)}}$	13.99

In literature, the We is considered by some to be the only necessary quantity to describe the behavior of the impact and by others as only one of several necessary quantities. All however recognize the great influence that the We has on the outcome of drop impact. Schlotland (1960) performed several experiments investigating the effect of gas density above the liquid surface on drop impact phenomena. One of the results of his research was that a critical We exists for the transition from bouncing to coalescing that was close to $We_{co} \approx 3$ (however the density ratio was not explicitly mentioned) [Rein]. Hsiao et al. (1988) collected data from several drop impact experiments from several sources and performed a series of mercury experiments in an attempt to demonstrate that a critical We exists for the coalescence to splash transition. Though their plots against the Fr demonstrate a shallow linear trend [Hsiao], it is generally accepted that for low viscosity fluids and $1 < Fr < 21$ the critical We for coalescence to splash transition is $We_{sp} \approx 60$ [Rein]. Although the We has a very apparent effect on the behavior of a drop impacting a fluid surface, most associated research was only done with low viscosity fluids (such as water) and within the range of Fr values mentioned earlier.

The Fr, though potentially less influential than the Re, has been used in more papers considering the outcomes of a drop impacting a fluid surface. Rodriguez and Mesler explored the relationship of the Fr and Re on the outcomes of the impact, and demonstrate an interesting occurrence in the low Fr regimes, both in the raw and processed data plots. At the lower Fr numbers (less than 1/12) the drops began to float on the surface, and splashing tended to cease regardless of Re [Rodriguez]. Since Hsiao et al. (1988) did not consider extremely low Fr values in their relations with We, it is quite possible that even the We loses its influence as the Fr approaches near zero values.

Thompson and Newall (1885) explored the relationship between kinematic viscosity and the coalescence to splash transition. They found that lower kinematic viscosities resulted in splashing while higher kinematic viscosities resulted in coalescing. It follows that the Re should also have a significant impact on the drop impact phenomena in question [Rein].

The Splash Phenomena

Should the We be large enough to produce a splash such as in The Rising Inverted, then several distinct stages will occur and depending upon the exact conditions one of three variations can be the end result. In most cases there are 6 distinct stages. Immediately upon impact there will be an ejection of a liquid film (stage 1). As the drop forces its way down into the surface a crater is formed and the film grows into a crown (stage 2). The crown and crater grow to their maximum sizes (stage 3). The crown and crater eventually begin to collapse (stage 4). As they collapse a central jet, the Worthington jet, is formed (stage 5). The sixth stage is dependent upon the impact energy of the drop [Rein]. Figure 2 shows an example six stages of a mid-range impact energy splash.

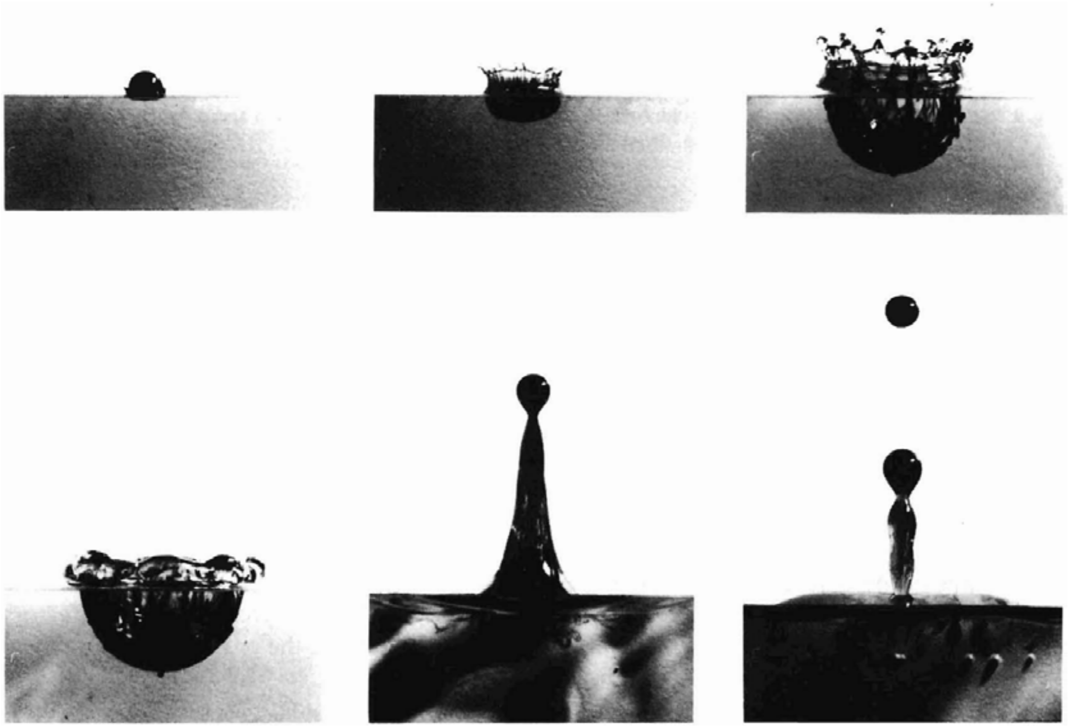

Figure 2: Mid-range impact energy splash showing the six stages [Rein].

Low impact energy splashes result in a stable Worthington jet which does not separate at the tip, but instead sinks back down into the surface and rises again in an oscillatory fashion. The jet rises, falls, rises, falls, repeatedly getting shorter each time following a dampened oscillating motion like a mass-spring-damper system. Mid-Range impact splashes produce an unstable Worthington jet which pinches off at the end forming one or more drops that continue to rise. These newly formed drops have a much lower We and tend to coalesce upon impact producing vortex rings that travel downward. High energy impact splashes differ starting at stage 4, where the crown continues to grow and fall in on itself. The crown walls meet eventually forming a bubble and sending two jets out from the merging point. One jet rises from the bubble and the other projects down toward the rising Worthington jet (stage 5). The downward bubble jet eventually connects with the rising Worthington jet, preventing the Worthington jet from actually penetrating the bubble (stage 6) [Rein].

There are two methods that can be used to describe the formation of the Worthington jet in stage 5: force diagrams and energy states (low to mid-range impact energies are assumed for the following examples). For both methods assume that the collapsing crown forms a crest around a hemispherical crater that is deeper than the crest is high (see Figure 3). There are essentially three forces acting on the crest rim and the crater: surface tension, gravity, and buoyant forces. For the crest rim, gravity is greater than buoyant forces and sum to a net downward force. The surface tension acting on the crest rim acts tangent to the surface and down from the concavity. Since the point of inflection is farther from the peak of the crest on the crater side, the net surface tension points inward and down. The net force on the crest is therefor down and toward the crater. For the crater, the buoyant forces are greater than gravity producing a net upward force from the crater's center. The surface tension acts tangent to the surface and up from the concavity. Since the crater is symmetric the net surface tension force points directly upward, resulting in a net upward force on the crater. Figure 3 illustrates these net forces with black arrows. These forces result in the motion also illustrated in Figure 3, by the blue arrows, which would tend to force a column of fluid vertically from the surface as is the case.

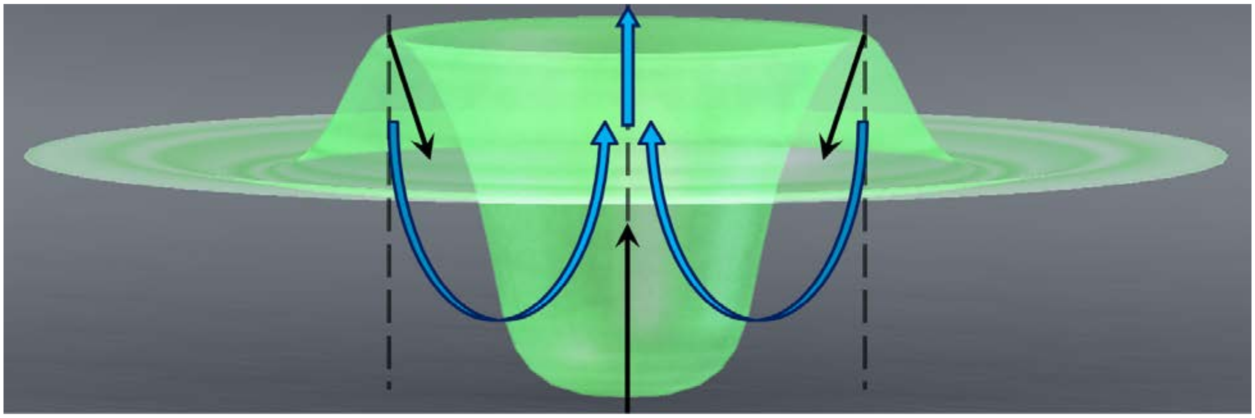

Figure 3: Stage 4, collapsing crown and crater. Associated forces are shown with black arrows and resulting motion is shown using blue arrows.

When considering energy states it is necessary to start before the initial impact occurs, when the energy of the system is mostly kinetic energy. Once impact occurs, the energy slowly transitions from kinetic to potential energy. At stage 3, the maximum crown and crater size, all kinetic energy has become potential energy (with minimal losses to viscous and friction effects). As the crater and crown begin to collapse, the energy state transitions from potential back to kinetic energy, however the zero potential is never reached. As the crater and crown lose energy, it transitions to the rising jet, going from gravitational and surface tension potential energies to mostly gravitational with some kinetic energy in the transition between stages. As the jet begins to fall, the energy state again transitions from potential to kinetic and, excepting frictional and viscous losses, continues to transition in different ways depending on the behavior following jet formation.

Flow Visualization Techniques

The experiment was run with black velvet draped behind the rear panel minimize light reflection and create a solid background. The room was kept dark except for a black light above to cause the fluid to fluoresce and a black light from the side to do the same while accentuating the shadows. The fluid itself was water nearly saturated with highlighter ink causing it to fluoresce under black lighting. The only other necessity was constant cleaning of the front panel of the fish tank to remove water droplets.

Photographic Techniques

The camera used was a Canon Power Shot SX 500 IS. A high shutter speed was necessary to avoid motion blur. For this reason a shutter speed of $^1/_{200}$ sec was used. Since more light was required due to this fast exposure, an f-stop of 3.4 was used. This is the smallest f-stop, since a great depth of field was not necessary. To reduce the noise the lowest possible ISO of 100 was used. The camera was used within 20 cm of the impact site in order to fill as much of the photo with the splash as possible. A list of all pertinent photo information is found in the appendix. In Photoshop, the image was cropped down to remove surroundings and reflections. An overall S-curve was used to increase the contrast and remove background reflections. Figure 4 shows these curve adjustments for the image.

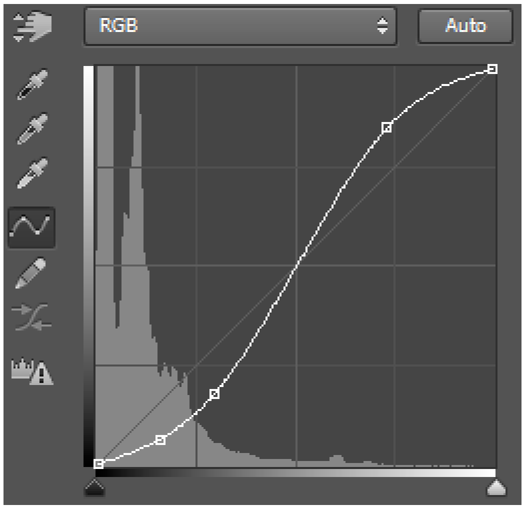

Figure 4: Curves adjusted to produce final image from original.

Discussion

To me this image captures the mystery, complexity, and truly amazing nature of a simple splash. The image was inverted to add to this sense of wonder and other-worldly feel, making it overall more interesting and captivating. The use of highlighter fluid and black lights provided the ability to develop great color, contrast, and clarity. My only issues with the image are the reflections on the back of the tank, on the bottom of the tank, and on the surface of the liquid. These forced me to increase the contrast beyond what I would have really liked in order to remove those reflection elements that were distracting. The physics of the Worthington jet is depicted fairly well, and I wish that I had had more time, and paper length, to research and discuss more of this physics such as what factors contribute to jet height. A better image could have been captured with a more elaborated set up and the ability to take several photos within hundredths of a second of each other. This would have captured the physics even better and could have demonstrated the entire splash sequence. Future developments of this experiment could include varying the drop height and drop size to capture the different phenomena associated with different We values. It could also be very interesting to explore the effects of varied Re values by using fluids with different viscosities and recording the transitions zones into the different phenomena. There is also the possibility of attempting such experiments using non-Newtonian fluids such as shear thickening or shear thinning fluids and capturing their drop impact and splash phenomena.

References

Hsiao, Mingying, Seth Lichter, and Luis G. Quintero. "The Critical Weber Number for Vortex and Jet Formation for Drops Impinging on a Liquid Pool." *Physics of Fluids* 31 (1988): 3560-562. *AIP Physics of Fluids*. American Institute of Physics. Web. 30 Mar. 2013.

Rein, Martin. *Drop-Surface Interactions*. Italy: CISM, Udine, 2002. *Books.Google*. Google. Web. 30 Mar. 2013.

Rein, Martin. "Phenomena of Liquid Drop Impact on Solid and Liquid Surfaces." *Fluid Dynamics Research* 12 (1993): 61-93. *IOP Science*. IOP Publishing. Web. 30 Mar. 2013.

Rodriguez, Francisco, and Russell Mesler. "Some Drops Don't Splash." *Journal of Colloid and Interface Science* 106.2 (1985): 347-52. *Science Direct*. Academic Press, Inc. Web. 30 Mar. 2013.

"Surface Tension." *Wikipedia*. Wikimedia Foundation, n.d. Web. 30 Mar. 2013.

Worthington, A. M. *A Study of Splashes*. New York: Longmans, Green, and, 1908.*Openlibrary*. State of Colorado. Web. 30 Mar. 2013.

Appendix

Photographic Information

Photograph Date and Time	**18 March, 2013 at 21:02**
Camera Type	**Canon PowerShot SX500 IS**
Shutter Speed	**1/200sec**
Aperture	**f/3.4**
ISO Setting	**100**
Lens Focal Length	**4.3 mm**
Distance from Lens to Impact	**20 cm**
Field of View	**Approximately: 25 x 45 cm**
Original Image Size	**4608 x 2592 pixels**
Final Image Size	**2028 x 741 pixels**

Original Image