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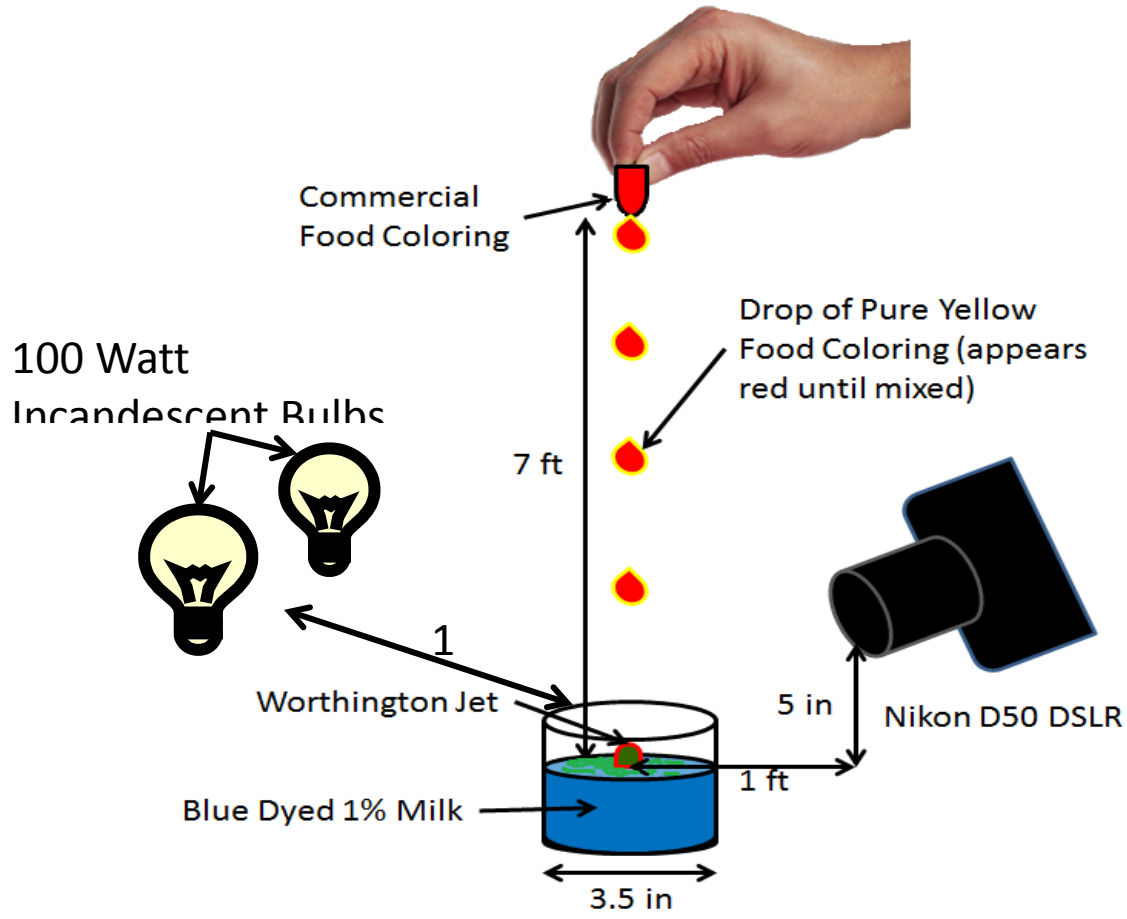
MCEN 4151: Flow Visualization

Professor Hertzberg

May 2, 2012

Team Project #3: The Worthington Jet

This image was created to fulfill the requirements of the third team project in an undergraduate flow visualization class at the University of Colorado. The raw image was created in the bathroom of my apartment with assistance from Jacob Anderegg using the materials and arrangement seen in the following figure. The intent of the image was to capture and effectively present the fluid phenomena that occur immediately after a drop of food coloring strikes the surface of a glass of milk.




As can be deduced from the picture, Jacob Anderegg lay down on the floor with a Nikon D50 DSLR in the orientation shown to capture the flow phenomenon at the surface of the milk. Commercial McCormick brand food coloring was then dropped from a height of approximately seven feet from the

surface of the blue dyed milk, which was in a 3.5 inch diameter glass cup, at a steady rate of about 1 drop per second onto the surface of the milk. Jacob took photographs at two frames per second for about 20 seconds, allowing for the raw image of the flow to be captured.

The depth of the milk (L) in the glass was approximately 2.5 inches, while the diameter of the droplet of food coloring (d) was no less than 0.125 inches. This makes the ratio of cavity depth to drop diameter (L/d) approximately 20, which is between the classification numbers of 50 and 0.4 which classify deep and shallow liquid depth impacts, as noted by Ogawa et al. (2006). The droplets shed from the crown of the flow are typically characteristic of a shallow impact and a result of interaction between the bottom of the glass and the liquid, therefore the flow will be treated as a result of a shallow impact, and thus the Weber number (Web) is the appropriate non-dimensional scale. However, the falling velocity ($U_d$) must first be calculated using Equation 1, which relates kinematic and potential energy of the droplet.

$$U_d = \sqrt{2gL} = \sqrt{2 * 32.2 \frac{ft}{s^2} * 7ft} = 21 \ \frac{ft}{s}$$

Equation 1

In Equation 2 $\rho$ is the density, $U_d$ is the falling velocity of the droplet prior to striking the surface of the liquid, and $\sigma$ is the surface tension of the liquid[4]. The density of 1% milk is 64 pounds per cubic foot[2], and the surface tension is 5.16x10$^{-2}$ Newtons per meter[1]. With conversion factors accounted for, the Weber number for the flow can be calculated as:

$$Web = \frac{\rho * {U_d}^2 * d}{\sigma} = \frac{64 \frac{lbf}{ft^3} * \left(21 \frac{ft}{s}\right)^2 * 0.125 \ in * \left(\frac{ft}{12 \ in}\right)}{0.0516 \frac{N}{m} * \left(\frac{.158 \ {}^{lbf}/_{ft}}{{}^{N}/_{m}}\right)} = 3.6x10^4$$

Equation 2

According to Hsiao et al. (1988), the critical weber number is 8. Above this Weber number a splash is expected. When the drop impacted the surface its energy was sufficient to create a cavity (looking much like a crater), which then collapses inward and creates a jet of fluid which is referred to as the Worthington jet[3]. The Weber number in this experiment was rather high, and therefore this phenomenon occurred as expected.

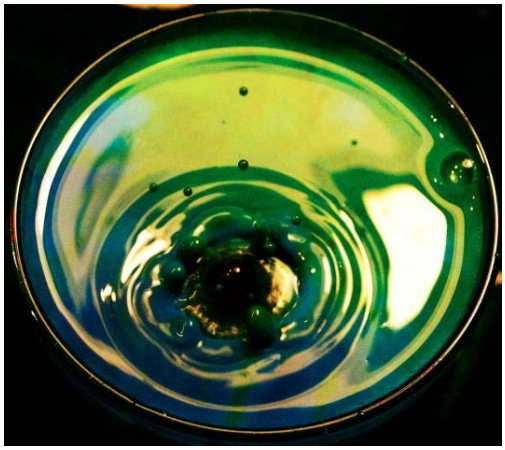
The flow was made visual by illuminating two 100 watt incandescent light-bulbs approximately one foot away from the surface of the milk. Prior to photographing this image the milk had been saturated with commercial blue food coloring, which is available at most grocery stores. Drops of yellow food coloring appeared red prior to mixing with the blue colored 1% fat milk, at which point the mixture turned green. This contrast between differing food coloring concentrations also made the flow

decipherable in the image. The steady stream of drops striking the surface of the milk made it easier to capture a Worthington Jet without the use of a high speed camera.

The raw image was taken with a Nikon D50 DSLR camera. The focal length of the lens during the capture was recorded as 55.0 millimeters. An exposure time of 1/640 second with f/5.6 and an ISO of 1600 were used to capture the image. The image was originally 3008 by 2000 pixels and covered a 8 inch by 5 inch field of view. The lens was approximately 13 inches from the surface of the milk at the time of the exposure.

Edits were made to the raw image in Photoshop CS5.1 to produce the final image. The image was first cropped to 1634 by 1634 pixels, leaving a 3 inch by 3 inch field of view to draw focus to the flow and remove the unnecessary background that could distract the viewer. The brightness and contrast were first enhanced to intensify the reflection from the light sources. The curves were adjusted to draw focus to the blues and greens of the image, which made the drops suspended in the air more visible. Finally the vibrance of the image was enhanced to Photoshop's full capability and the color balance was adjusted to further deepen the blues and intensify the green in the image.

Raw "Before" Image



Post-Photoshop "Final" Image

This image depicts the formation of a Worthington jet as a result of a drop of food coloring impacting the surface of milk. The capture is very crisp and clearly reveals the physics of the flow during the emergence of the jet from the milk. After manipulations in Photoshop the final image was made to fulfill the intent of the project. The spectrum of blue and green in the milk as well as the red jet make for a very artistic effect of the photo.

References:

[1]Antonio J. Bertsch (1983). Surface tension of whole and skim-milk between 18 and 135 °C. *Journal of Dairy Research,* 50, 259-267. doi:10.1017/S0022029900023098

[2]http://www.aqua-calc.com/page/density-table/substance/Milk-coma-and-blank-lowfat-coma-and-blank-fluid-coma-and-blank-1-percent-sign--blank-milkfat-coma-and-blank-with-blank-added-

blank-nonfat-blank-milk-blank-solids-coma-and-blank-vitamin-blank-A-blank-and-blank-vitamin-blank-D

[3]Hsiao, M., Lichter, S., & Quintero, L. G. (1988). The critical Weber number for vortex and jet formation for drops impinging on a liquid pool. *Physics of Fluids*, *31*(12), 3560-3562. doi: 10.1063/1.866872

[4]Ogawa, A., Utsono, K., Mutou, M., Kouzen, S., Shimotake, Y. & Satou, Y. (2006). Morphological study of cavity and Worthington jet formations for Newtonian and non-Newtonian liquids. *Particulate Science and Technology*, 24, 181-225. Doi:10.1080/02726350500544224