Get Wet Report

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I. INTRODUCTION

This report documents the visualization techniques and physics of a specific flow phenomena for the Get Wet assignment of the Flow Visualization course at the University of Colorado at Boulder. The goal of this document is to create and describe the image of food dye falling in water presented on the cover page (p. 1). Food dye falling through cold water demonstrates complex Rayleigh-Taylor instability of a fluid, also known as umbrella instability. The following text describes this phenomena and identifies unique aspects of the flow that relate to aesthetically interesting visualization techniques.

II. EXPERIMENTAL PROCESS

Creating Rayleigh-Taylor 'umbrellas' using food dye was discovered by the author accidently while trying to visualize bubble trajectory in a glass of beer. A series of experiments to trace the bubbles were run by mixing various liquids into a glass of Coors Light beer and documenting the interactions using photos and video. The fluids mixed with the beer in the experiments included shampoo, blowing bubble solution, fabric softener, vegetable oil, mouthwash, half and half, dish soap, food dye, shaving cream, vinegar and effervescent denture cleanser tablets (for effect). A sampling of video screenshots from the experiment are shown below.

Figure 1. Experiment photos of beer mixing with half and half (left), dyed vinegar (middle) and bubble solution (right).

While none of the liquids used in the experiment successfully traced the beer bubble trajectory as desired, an interesting phenomena was discovered when food dye was mixed with vegetable oil and then poured into the beer - the oil rose to the top of the beer and strings of dye descended from the oil. A video screenshot of the dye/oil mixture in the beer is shown below.

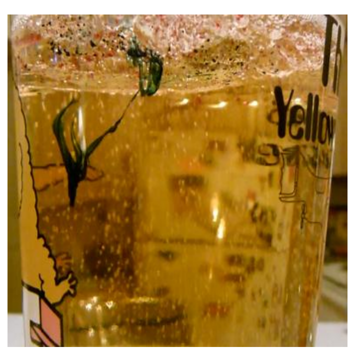

Figure 2. Food dye descending from vegetable oil in beer.

The dye/oil experiment was attempted again in cold water in order to determine if the stringing effect of the dye was independent of the base fluid. Interestingly, the food dye created an unexpected umbrella effect as it descended in the water, forming the basis for the investigation and visualization image.

III. FLOW APPARATUS

Figure 3 depicts the experimental setup used to capture the image of the food dye umbrellas. First, a pint glass of cold water filled one half inch from the top was placed six inches in front of a white background, in this case a label-free shoe box. A reading lamp with a 75 W white bulb was placed 14 inches over the glass while a 66 W kitchen overhead light stood 51 inches above the pint, creating the lighting for the photo. A layer of vegetable oil was then poured into the remaining volume of the glass. Two drops of food dye (propylene glycol - one red and one blue) were dropped into the oil approximately one inch apart and were temporarily suspended in the oil as spherical droplets of approximately 4 cm diameter (radius of 0.002 m). The dye droplets were then pierced with a toothpick to begin the dye's descent through the water. Immediately after, the camera was held six inches from the glass and the falling dye was photographed.

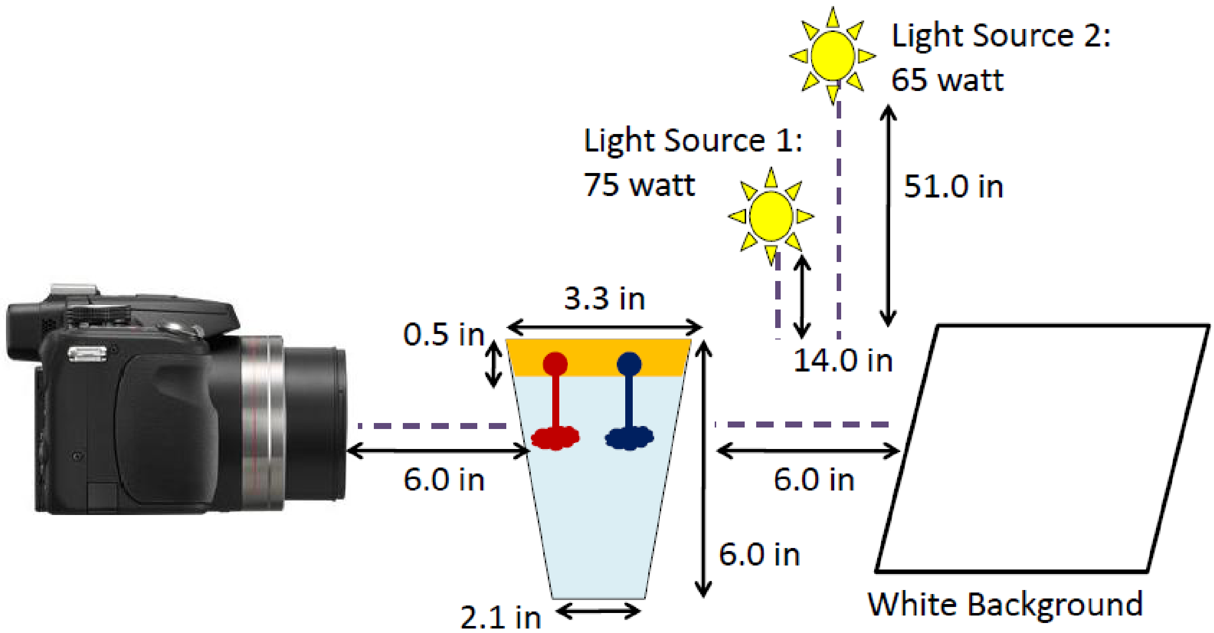

Figure 3. Flow apparatus including camera location, fluid container and light sources (FZ100 camera image courtesy of Panasonic[1])

IV. DESCRIPTION OF FLOW

As the dye begins to fall from the oil, the umbrella instability phenomena begins almost immediately. Several forces create the umbrella effect including viscous forces, inertia, gravity and microscopic bombardment of the food dye particles. Because the propylene glycol dye has a slightly higher density than the water[2] (1038 kg/m³ for the dye, 1000 kg/m³ for water [a specific gravity of 1.038]), the dye slowly sinks to the bottom of the glass due to the acceleration of gravity and carries some amount of inertia. The dimensionless Froud number *Fr* is the ratio of inertial forces to gravity and is defined as

$$Fr = \frac{U_d}{\sqrt{gR}} \qquad (1)$$

where U_d is the velocity of the dye particles, *R* is the radius of the initial spherical dye droplet and *g* is the acceleration of the dye due to gravity (9.8 m/s²). Bosse et al.[2] recommend defining the dye velocity as the difference in densities of the dye ρ_d and the still fluid density (the water) ρ_f and the effects of gravity and kinematic viscosity ν:

$$U_d = \frac{(\rho_d - \rho_f)R^2 g}{\rho_d \nu} \quad (2).$$

Assuming a static viscosity for the dye of 48.6 centipoise which converts into a kinematic viscosity of 4.7E-5 m²/s when divided by the density of the dye, the velocity is found to be

$$U_d = \frac{\left(1038\,\frac{kg}{m^3} - 1000\,\frac{kg}{m^3}\right)(0.002\ m)^2 (9.8\,\frac{m}{s^2})}{(1038\,\frac{kg}{m^3})(4.7E-5\,\frac{m^2}{s})} = 0.03\ m/s.$$

It should be noted that the rate of the dye falling was also measured using a ruler and stopwatch at a rate of 1.5 cm/s which agrees well with the value above. Using the calculated velocity the Froud number becomes

$$Fr = \frac{0.03\,\frac{m}{s}}{\sqrt{(9.81\ {}^{m}/_{s^2})(0.002\ m)}} = 0.2$$

meaning that effects from gravity dominate any inertial effects which is what is expected for continuously falling dye accelerating by earth's gravity only. The blobs of dye that make up the umbrella shape are formed due to an increasing Reynolds number as the dye flows through the water[3]. The Reynolds number is the dimensionless ratio of inertial forces to viscous forces and is defined for the dye as

$$Re = \frac{U_d R}{\nu} = \frac{(0.03\,\frac{m}{s})(0.002\ m)}{(4.7E-5\,\frac{m^2}{s})} = 1.3 \quad (3).$$

The low Reynolds number close to unity signifies that the inertial and viscous forces (forces acting against the still water) are nearly in balance, meaning that instability in the form of the umbrella blobs is to be expected. The calculated Reynolds number fits within the range of blob formation (1 ≤ Re ≤ 100) as suggested by Bosse et al.[4] The relatively large food dye particles are randomly distributed within the initial dye droplet and when colliding aid in the formation of the blobs.

V. VISUALIZATION TECHNIQUES

The apparatus and lighting described in Section III were used to visualize the umbrella instability effect caused when the food dye descends through the water. The experiment was conducted in room temperature air (70 °F) and cold water was used (56 °F). Fluid properties used in the calculation of dimensionless numbers were adjusted for the fluid temperatures. The food dye and vegetable oil used were standard products available at any supermarket. Tap water was used for the still fluid medium. The flash on the camera was not used for lighting.

VI. PHOTOGRAPHIC TECHNIQUES

a). Camera Settings

A 14.1 megapixel Panasonic Lumix DMC-FZ100 digital camera was used for the image. The photograph of the fluid flow was taken with the camera lens six inches from the glass container as depicted in Figure 3. A small focal length *f* of 4.5 mm was used in order to maximize the field of view while holding the camera close to the glass. For the exposure, a shutter speed of 1/60 s and an f-stop (relating to aperture size) of *f*/28 was used. The shutter speed and aperture diameters were chosen to balance the incoming light into the camera lens with a relatively quick exposure time in order to capture the rapidly changing dynamics of the fluid flow. An ISO setting of 250 was used since ample light was available in the apparatus.

b). Image Post Processing

Adobe Photoshop CS5 was used for post processing of the Get Wet image. The original 3240 x 4320 pixel JPEG image was imported into Photoshop to begin post processing. The image was then cropped to 2804 x 3161 pixels in order to remove as much of the glass container and background as possible. The 'With Perspective' option was used when cropping in order to straighten the tapered edges of the glass that were present in the original image. The contrast was then adjusted from zero to 100 in order to highlight the streamlines of the food dye. The white background was creating using the paint bucket tool. The erase and smudge tools were then used to smooth out rough pixels at the dye/background interface. Finally, the zoom feature was used to enlarge the droplets of dye in the final processed image. The original image and post processed image are shown side-by-side in the figure below.

Figure 4. Original image (left) and image following post processing (right).

VII. IMAGE ANALYSIS AND CONCLUSIONS

The image accurately captures the beginning stages of an example of Rayleigh-Taylor instability. The trajectory physics of the dye forming strands from blobs is shown well; more abstract interactions such as viscosity and gravity are not as easily distinguished in the image. Overall, the goals of describing the physics of the instability with a aesthetically pleasing image were achieved; the umbrella blobs are clearly visible and account for most of the interaction with the dye as the Reynolds number increases. Additional research on if and how the vegetable oil affects the physics of the flow was not conducted but would be an interesting next step. The image could be improved by using a better backdrop than the shoebox; the grainy nature of the wooden box resulted in a muddled interface of pixels between the water and the food dye. Using a brighter light or higher ISO setting would also be effective in highlighting the dark coloring of the food dye.

VIII. REFERENCES

[1]Panasonic. "DMC-FZ100K - Lumix Digital Cameras." Panasonic Digital Cameras. 2009. Accessed 9 February, 2011. <http://www2.panasonic.com/consumer-electronics/shop/Cameras-Camcorders/Digital-Cameras/Lumix- Digital-Cameras/model.DMC-FZ100K.S_11002_700000000000000005702#tabsection>.

[2]Dow Chemical Company. "Dow Propylene Glycol USP/EP." Technical Data Sheet - Propylene Glycol. 2010. Accessed 2 February, 2011. <http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0048/0901b80380048696.pdf?filepath=propyleneglycol/pdfs/noreg/117-01619.pdf&fromPage=GetDoc>.

[3]T. Bosse et al., “Numerical Simulation of Finite Reynolds Number Suspension Drops Settling Under Gravity,” Physics of Fluids 17, no. 3, Phys. Fluids (USA) (March 2005): 37101-1.

[4]T. Bosse et al., “Settling and Breakup of Suspension Drops,” Physics of Fluids 17, no. 9, Phys. Fluids (USA) (2005): 1.