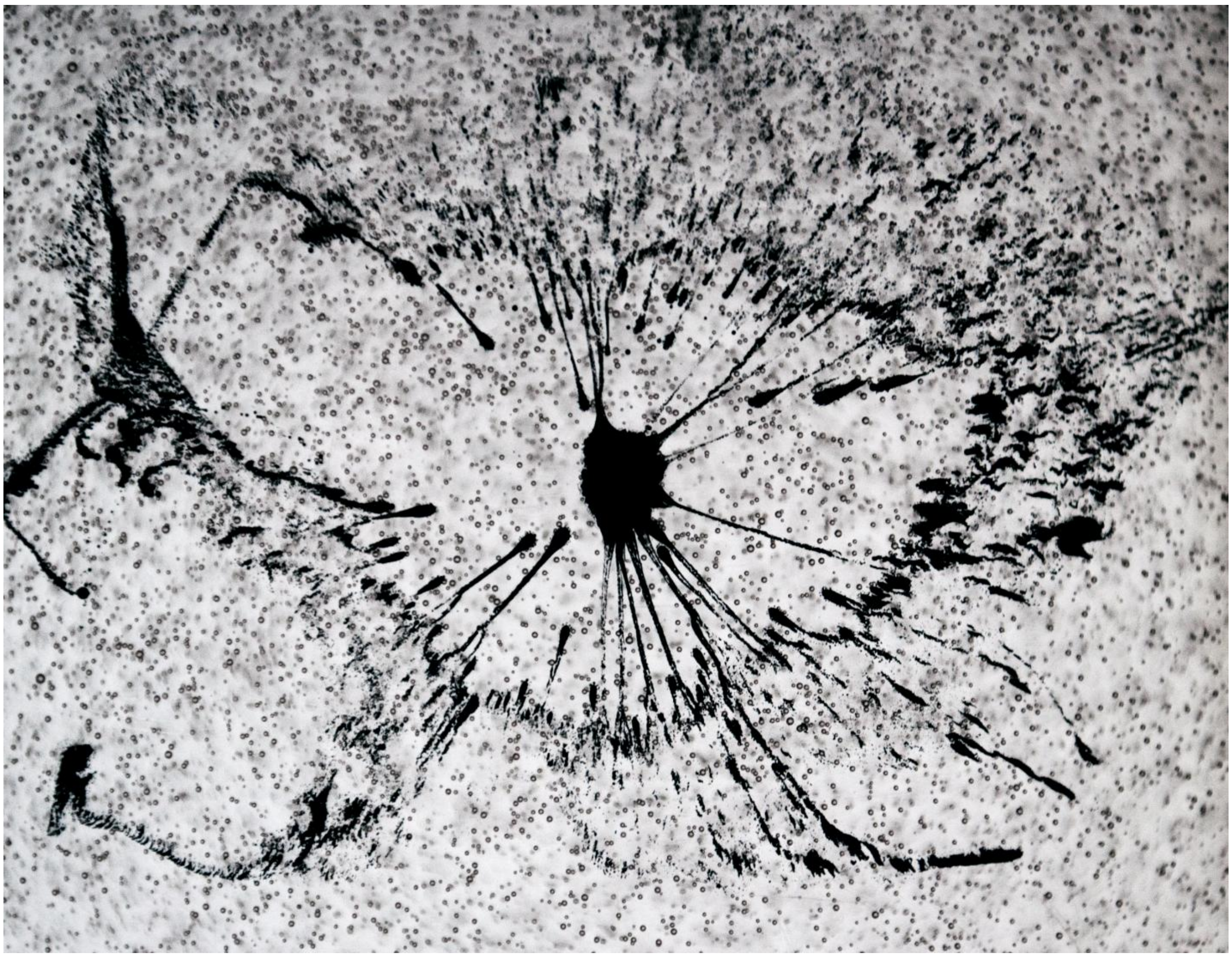
Magnetically Excited Ferrofluid and Air Suspended in Liquid Hand Soap



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February 12th, 2013

MCEN 5151-001
Flow Visualization
Spring 2013
Professor Jean Hertzberg

Introduction and Purpose

This photograph and paper was for the initial "Get Wet" assignment in the Flow Visualization course taught at the University of Colorado at Boulder. The assignment pushed mechanical engineering, art, and film students to explore, capture, and explain any and all types of fluid phenomenon. A commonly visualized fluid is ferrofluid; an oil based liquid that contains nanoscale iron particles. When introduced to a magnetic field, ferrofluid "spikes" in the direction of the magnetic field lines. The force from the magnetic field and the surface tension effects within the fluid determine the length and size of the spikes [1]. Ferrofluid is typically visualized in air, so the intent of this particular visualization was to witness ferrofluid inside of a highly viscous liquid. The underlying physics discussed will not show how the flow was created with a magnetic field, but rather why the flow stays stationary as this photograph was taken in the absence of a magnetic field. This will reveal a very complex relationship between buoyancy, weight, and viscous force.

Flow Generation

Ferrofluid is a pitch black liquid. In order to more easily visualize the black color of the ferrofluid, it was placed within a clear liquid. Clear hand soap has a dynamic viscosity roughly 400,000 times that of air and was an economic choice for a high viscosity liquid medium [2]. The soap bottle itself acted as the container for the phenomenon and was highlighted by a white liquid crystal display (LCD) backdrop from a laptop screen. The container was placed on a small white stand (a book) to center it more with the white LCD backdrop. There were also two 60[W] fluorescent light bulbs above that lit the front of the container to increase brightness without introducing glare.

The soap bottle contained many air bubbles due to being agitated. These bubbles acted as a focal point for the picture and so were not allowed time to settle and dissipate. Three drops of ferrofluid (roughly 0.15[mL]) were inserted into the container via an eye dropper. The container was then sealed with a top to prevent fluid from spilling onto the laptop. A spherical neodymium magnet (12[mm] in diameter) was used to manipulate and control the ferrofluid from outside the container. For the particular image created here, the magnet was used to create a circle with the ferrofluid and then was placed in the center of the circle to draw the ferrofluid toward the middle. The magnet was then set aside and the fluid remained stationary due to the large viscous effects. Using a handheld DSLR (digital single-lens reflex) camera, multiple images of the phenomenon were captured from different angles and focal lengths. The magnet can be reintroduced to create different flow shapes. After some time however, the ferrofluid begins to "cloud" up the container from prior ferrofluid trails. Due to this, the experiment was preformed two times in different soap bottles. The experimental setup is shown in Figure 1 below.

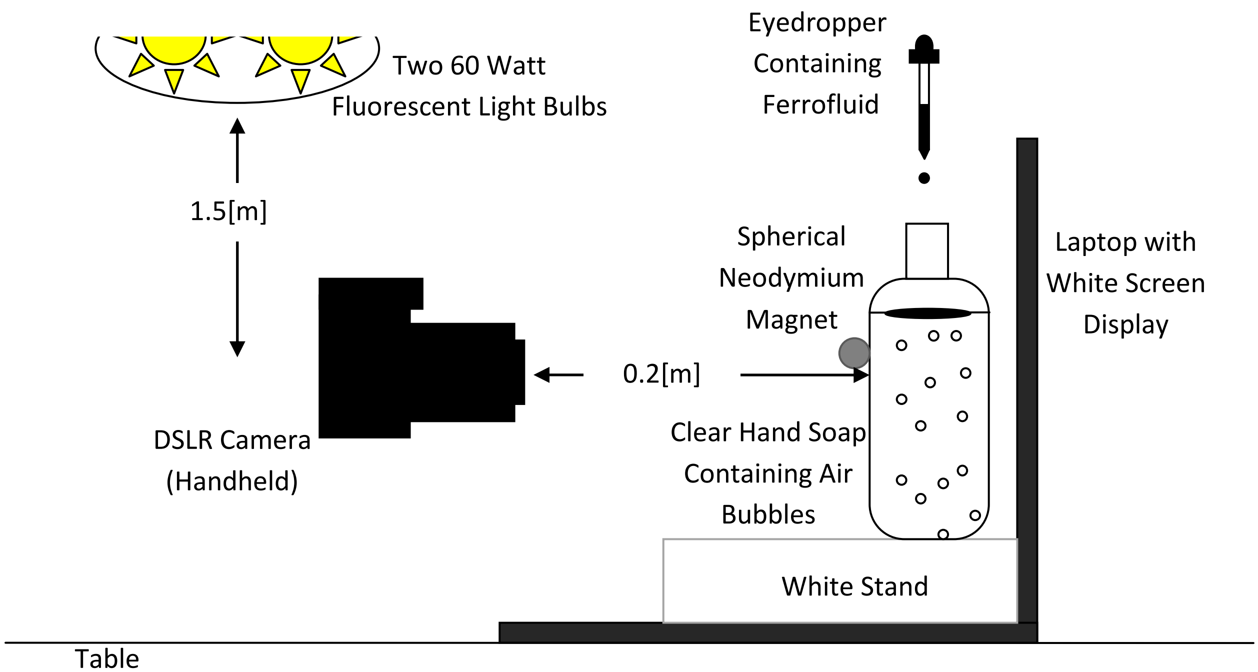

Figure 1: Experimental Setup

Fluid Physics

To reiterate again, the physics discussed here are the physics that occurred at the time of the photograph, hence there will be no mention of flow due to a magnetic field (for more information on ferrofluid physics, see Reference [1]). The physical phenomenon observed in the photograph involves three forces; weight, buoyancy, and viscous drag. To begin, a table with relevant properties of all three fluids (ferrofluid, air, and liquid soap) is given below in Table 1.

Table 1: Fluid Properties

Property at 25°C	Ferrofluid [3]	Air [4]	Liquid Soap [2]
Density ρ [kg/m^3]	1210	1.184	1022
Kinematic Viscosity μ [kg/m-s]	$6*10^{-3}$	$1.849*10^{-5}$	8
Dynamic Viscosity ν [m^2/s]	$4.96*10^{-6}$	$1.562*10^{-5}$	$7.83*10^{-3}$

In order to determine the required calculation lengths, the most slender part of the soap container was measured with calipers. Then, using the ruler tool in Photoshop (a tool that gives relative unitless length values) and proportions between the measured length and the Photoshop "lengths," actual lengths were determined (see Figure 2 below). The characteristic length of the ferrofluid will be taken as the streak width (0.5[mm]) as this represents the fluid within the spherical droplet shape, and the characteristic length of the air will be taken as the bubble diameter (0.3[mm]).

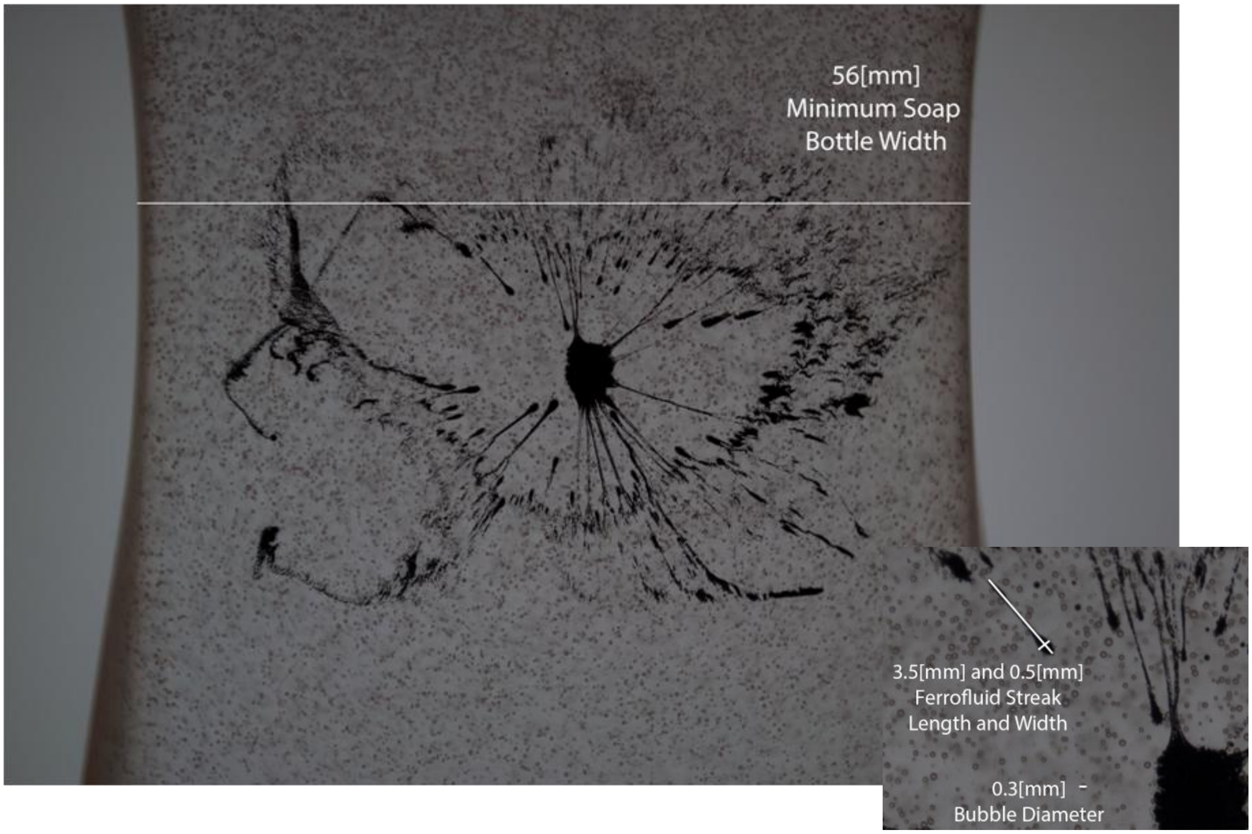

Figure 2: Top Left -Original image with measured reference scale
Bottom Right- Magnified view with key extrapolated lengths

When fluid (or solid) particles are suspended in a liquid carrier, their motion can be described by a nondimensional quantity known as the Archimedes number. The Archimedes number represents a ratio of buoyancy/gravitational forces to viscous forces when the particles and the liquid carrier have different densities [5]. If the particles and the liquid carrier have the same density, then the Archimedes number is 0 and it is meaningless. The concept is similar to the Grashof number, except with the Grashof number, the density difference is caused by a temperature gradient as opposed to a substance difference [4]. When the Archimedes number is positive, the particles will sink and when the Archimedes number is negative, the particles will float. When the magnitude of the Archimedes number is greater than 1, then buoyancy/gravitational forces dominate the fluid motion, and when the magnitude is less than 1, then the viscous forces dominate the motion. The Archimedes number for both ferrofluid and air are [5]:

$$\mathrm{Ar_{ff}} = \frac{\mathrm{g}L_{\mathrm{ff}}^3(\rho_{\mathrm{ff}} - \rho_{\mathrm{soap}})}{\nu_{\mathrm{soap}}^2 \rho_{\mathrm{soap}}} = \frac{\left(9.81\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]\right)(0.0005[\mathrm{m}])^3\left(1210\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] - 1022\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]\right)}{\left(7.83 * 10^{-3}\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]\right)^2\left(1022\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]\right)} = 3.7 * 10^{-6}$$

$$\mathrm{Ar_{air}} = \frac{\mathrm{g}L_{\mathrm{air}}^3(\rho_{\mathrm{air}} - \rho_{\mathrm{soap}})}{\nu_{\mathrm{soap}}^2 \rho_{\mathrm{soap}}} = \frac{\left(9.81\left[\frac{\mathrm{m}}{\mathrm{s}^2}\right]\right)(0.0003[\mathrm{m}])^3\left(1.184\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] - 1022\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]\right)}{\left(7.83 * 10^{-3}\left[\frac{\mathrm{m}^2}{\mathrm{s}}\right]\right)^2\left(1022\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right]\right)} = -4.3 * 10^{-6}$$

Here the Archimedes numbers for both particles are much less than 1 meaning that viscous forces dominate the fluid motion (or lack thereof). The numbers also indicate that the ferrofluid will sink and the air will rise. Because the viscous forces dominate both particles, it can be assumed that the Reynolds number is very low in each case. At very low Reynolds numbers, Stokes equation can be used to determine the terminal velocity of the particles [6]. The particles reach a terminal velocity when the buoyancy, weight, and viscous forces come into equilibrium. This happens because the viscous force increases proportionally with particle velocity; the particle has a non zero acceleration when not in equilibrium but this increase in velocity decelerates the particle via an increase in viscous force. The viscous force always acts opposite to particle motion, so it points up for sinking particles and down for rising particles. The terminal velocities for both ferrofluid and air via Stokes equation (with very small particle viscosities to liquid carrier viscosity) are [6]:

$$V_{ff} = \frac{gL_{ff}^2(\rho_{ff} - \rho_{soap})}{12\mu_{soap}} = \frac{\left(9.81\left[\frac{m}{s^2}\right]\right)(0.0005[m])^2\left(1210\left[\frac{kg}{m^3}\right] - 1022\left[\frac{kg}{m^3}\right]\right)}{12 * 8\left[\frac{kg}{m * s}\right]} = 4.8 * 10^{-6}\left[\frac{m}{s}\right]$$

$$V_{air} = \frac{gL_{air}^2(\rho_{air} - \rho_{soap})}{12\mu_{soap}} = \frac{\left(9.81\left[\frac{m}{s^2}\right]\right)(0.0003[m])^2\left(1.184\left[\frac{kg}{m^3}\right] - 1022\left[\frac{kg}{m^3}\right]\right)}{12 * 8\left[\frac{kg}{m * s}\right]} = -9.4 * 10^{-6}\left[\frac{m}{s}\right]$$

The positive velocity indicates that the ferrofluid is moving downward while the negative velocity indicates that the air is rising. From these terminal velocities, corresponding Reynolds numbers can be computed. The Reynolds number compares inertial effects to viscous effects [7]. As described earlier, the Reynolds numbers were assumed to be low because of the stationary behavior of the fluids. The corresponding Reynolds numbers are [7]:

$$Re_{ff} = \frac{V_{ff}L_{ff}}{\nu_{ff}} = \frac{\left(4.8 * 10^{-6}\left[\frac{m}{s}\right]\right)(0.0005[m])}{4.96 * 10^{-6}\left[\frac{m^2}{s}\right]} = 4.8 * 10^{-4}$$

$$Re_{air} = \frac{V_{air}L_{air}}{\nu_{air}} = \frac{\left(9.4 * 10^{-6}\left[\frac{m}{s}\right]\right)(0.0003[m])}{1.562 * 10^{-5}\left[\frac{m^2}{s}\right]} = 1.8 * 10^{-4}$$

These low Reynolds numbers are expected and indicate that the flow is very laminar and also can be quantified as Stokes/creeping flow (Re<<1) [6]. This verifies the use of using Stokes equation to calculate the terminal velocities. From the calculations of Archimedes number, terminal velocity, and Reynolds number, it is apparent why both the ferrofluid and air appear to be stationary even though the ferrofluid is denser than the soap and the air is less dense than the soap.

Visualization Method

There were two main visualization techniques used; ferrofluid and air. The EFH1 ferrofluid was purchased from a Ferrotec distributer called Applied Magnets and relative material concentrations as well as the material safety data sheet (MSDS) can be found in Reference [3]. The air was already contained within the liquid hand soap. The soap was Dial White Tea and Vitamin E Hand Soap (off the shelf) and relative material concentrations as well as the MSDS can be found in Reference [2]. This flow was created inside with two major sources of light. Two 60[W] fluorescent light bulbs on the ceiling (1.5[m] above the camera) provided light for the front of the image. There was also the light coming off of the white laptop screen that provided a backlight. All the surfaces near the container were white such that no color reflected into the picture and so the image would have high contrast and brightness. This picture was taken at night and the flash on the camera was turned off.

Photographic Technique and Image Post Processing

A Nikon D5000 12.3 effective megapixel DX format DSLR F-mount camera was used to take raw images formatted in .nef (Nikon electronic format). The field of view is roughly 80[mm] wide by 50[mm] tall such that the flow visualized takes up most of the space. When decreasing the field of view, it became impossible to put the image in focus and so the smallest field of view while still maintaining focus was used. This put the camera lens about 200[mm] away from the container. The focus was set to manual such that the clearest image could be achieved. The focal length was set to 46[mm] to both maintain focus with minimizing the field of view and to match closely with the perspective of the human eye (50[mm]).Because the camera was handheld to achieve shots at multiple angles and focal lengths, the shutter speed was set to 1/60th of a second even though the image was stationary. The aperture was set automatically within the camera and was 8.7[mm] (from an f-stop of 5.3). The ISO (sensor sensitivity gain) was set to 320 to increase brightness at the fast shutter speed but still maintain on non grainy image. The original image (seen in Figure 2 above) was 4288 by 2848 pixels.

Image post processing was completed entirely in Adobe Photoshop CS6 Extended. The image was cropped to remove the container edges and a standardized width-height ratio was used (8.5” x 11”) leaving the final image to be 2618 by 2023 pixels. The contrast was increased such that the lighter grey color that dominated the image became closer to white. Finally, the slight amount of red/brown color was reduced through changing the red contrast and through decreasing the saturation of the image as a whole. Because this image doesn’t have very vibrant colors, it looks more striking in black and white.

Conclusion

One of the interesting things about this phenomenon is that the fluid is essentially not moving, and this is perfectly captured in a still picture. Still though, the image readily reveals where the magnet was placed and where the magnetic field lines were. The image has very simple colors, and almost looks like it was taken with a microscope. The bubbles contrast the ferrofluid well and without the bubbles, this image would look just like an ink stain. However, the bubbles can be distracting at times and some are a little out of focus. One observation is that through the experiment a slow chemical reaction between the ferrofluid and soap was taking place, and now the soap viscosity has changed to something similar to water. This was my first time learning how to manually use a camera and edit images in Photoshop, so I am excited to see what else I can learn and create with fluid flows.

References

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