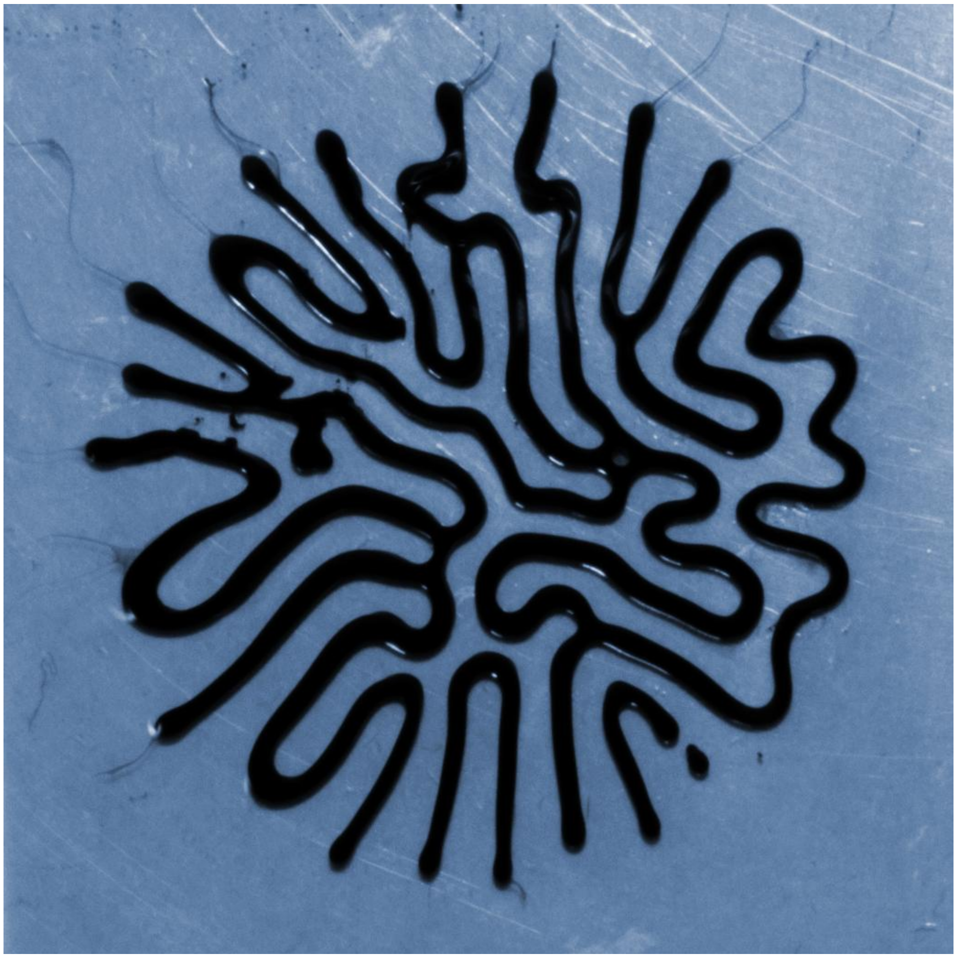
Magnetically Excited Ferrofluid on a Thin Film of Windex



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May 2nd, 2013

MCEN 5151-001
Flow Visualization
Spring 2013
Professor Jean Hertzberg

Introduction and Purpose

This photograph and paper are for the third and final team assignment in the Flow Visualization course taught at the University of Colorado at Boulder. This assignment allowed graduate and undergraduate engineering and art students to work together to generate and capture complex and beautiful flow phenomenon. Regrettably, due to schedule conflicts and time constraints, our team was not able to work together. The specific intent of this project was to visualize thin film effects of ferrofluid. Typically a thin film refers to a layer in the nano to micro scale; however in this paper a thin film dictates a layer with a height considerably smaller than the planar dimensions. Ferrofluid contains suspended nanoscale iron filings that point the fluid in the direction of magnetic field lines [1]. Therefore, ferrofluid is typically visualized as spiked formations while under the presence of a magnetic field. Ferrofluid reaches an equilibrium state when the surface tension and weight force counteract the force from the magnetic field [2]. Usually, the force from the magnetic field is large enough to “lift” the ferrofluid up against gravity. In order to stop this from happening and visualize a thin film effect, either the weight force must be increased (via density), or the surface tension must be increased. Since density is a fluid property, visualizing the thin film effect can be accomplished by increasing surface tension forces. This is achieved by placing the ferrofluid on a layer of Windex. The very first image that I captured for this class also involved ferrofluid. Coming full circle and ending on ferrofluid brings some amount of closure for me.

Flow Generation

The general procedure of this experiment is as follows. First a thin layer of Windex is put down. Next, several droplets of ferrofluid are added on top of the Windex. Finally, a magnetic field is introduced underneath the fluids and the image is captured. The fluids were contained in a shallow, clear, ceramic Petri dish 3.5[in] in diameter. The Petri dish was set on top of a white piece of printer paper. This was done such that the black ferrofluid would contrast well with the white background. The Petri dish and paper were set on top of a cardboard box that was roughly 18[in] tall. A hole was cut into the side of the box that allowed for a magnet to be handheld inside the box under the Petri dish. The magnet chosen was a spherical neodymium magnet (0.5[in] in diameter). Using a syringe, approximately 1 tablespoon of Windex was added to the Petri dish. With a different syringe, 5 drops of ferrofluid were laid gently on top of the Windex. Inside the Petri dish, the fluid height was about 0.125[in]. The magnet was held underneath the Petri dish roughly 6[in] away and was used to manipulate and control the ferrofluid flow.

A DSLR (digital single-lens reflex) camera that was mounted on a tripod was used to capture the image. The tripod was set up such that two legs were vertical and resting on the cardboard box and the third leg was extended longer and prevented the camera from tipping backwards. The Petri dish was placed under three 60 [Watt] florescent light bulbs. A black cover was held over the camera and the Petri dish to help eliminate some light glare in the Petri dish. The experiment was performed a total of three times after the correct procedure was determined. The experimental setup is shown in Figure 1 below.

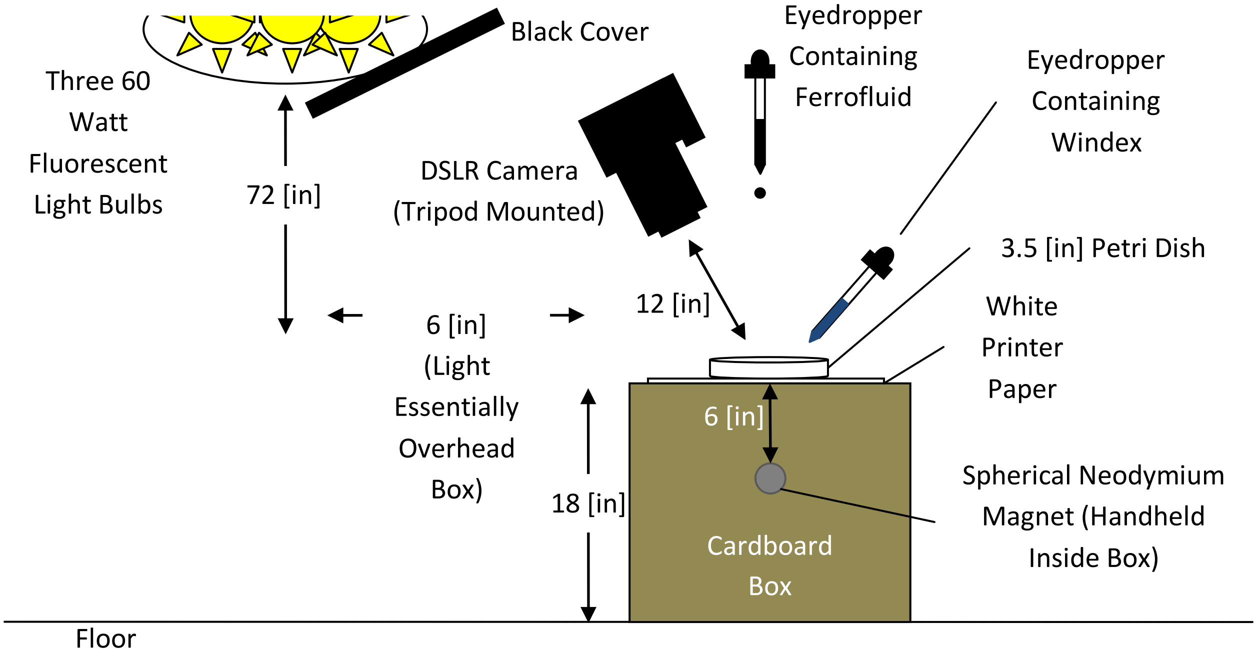

Figure 1: Experimental Setup

Fluid Physics

After the magnet is introduced underneath the ferrofluid, the fluid flows laminarly until an equilibrium position is met. The thin film effect of ferrofluid can be characterized as Stokes (creeping) flow [2] and exists at Reynolds numbers less than one. In order to verify this, an estimate of the Reynolds number must be made. The characteristic length for this flow is the width of one of the fluid fingers. This is determined using the known diameter of the Petri dish and is estimated at 0.05[in]. The time it took the ferrofluid to move to equilibrium after the magnetic field was introduced is approximately 5 seconds. This measurement was taken from a video recording of the phenomenon. The ferrofluid essentially starts at a center point and travels the radius of the circular shape in the image. This is approximately 0.5[in]. Combining the length and time traveled gives an approximate velocity of 0.1[in/s]. The kinematic viscosity of ferrofluid is taken as 0.00769[in^2/s] [3]. The Reynolds number of the flow is then:

$$\mathrm{Re} = \frac{\mathrm{VL}}{\nu} = \frac{\left(0.1\left[\frac{\mathrm{in}}{\mathrm{s}}\right]\right)(0.05[\mathrm{in}])}{0.00769\left[\frac{\mathrm{in}^2}{\mathrm{s}}\right]} = 0.65$$

Because the above Reynolds number is less than 1, the flow is considered creeping. In creeping flow, the Navier-Stokes equations (equations that describe the velocity of a fluid flow field for all space and time) reduce to the Stokes equations [4]. The Stokes equations (in condensed vector form) are written as:

$$\nabla \cdot \mathbf{T} + \mathbf{f} = 0$$

In this equation, **T** is the Cauchy stress tensor and **f** is the sum of all the applied body forces. The Cauchy stress tensor is an application of the Cauchy Stress Principle which states that all local stresses must be in equilibrium [2]. The stress tensor accounts for all types of normal and shear stress and can be written in matrix form as:

$$\mathbf{T} = \begin{bmatrix} \mathrm{T_{xx}} & \mathrm{T_{xy}} & \mathrm{T_{xz}} \\ \mathrm{T_{yx}} & \mathrm{T_{yy}} & \mathrm{T_{yz}} \\ \mathrm{T_{zx}} & \mathrm{T_{zy}} & \mathrm{T_{zz}} \end{bmatrix}$$

In the matrix above, the three diagonal entries represent normal stresses (pressure) while the off diagonals represent shear stresses.

The body force **f** takes into account both the weight force and the magnetic force. The weight force is given by the volume and density of the ferrofluid as well as the gravitational acceleration and is given by:

$$\mathbf{f_{weight}} = \mathrm{\rho_{ferrofluid} V_{ferrofluid}} \mathbf{g}$$

The magnetic force is a function of the strength of the magnetic field ($\mathbf{H_0}$) and also the mass of the ferrofluid ($\mathrm{\rho_{ferrofluid} V_{ferrofluid}}$) [2]. This is given as:

$$\mathbf{f_{magnetic}} = \nabla(\mathrm{\rho_{ferrofluid} V_{ferrofluid}} \cdot \mathbf{H_0})$$

A final equation that must also be satisfied is the condition of continuity (mass conservation) [4]. This is generally written in terms of velocity components as:

$$\nabla \cdot \mathbf{u} = 0$$

If the unknown stresses and the strength of the magnetic field is known, then the above equations should be solvable in order to determine a flow field.

If assuming the flow to be 2D, then there is a single normal stress coming in/out of the page and two shear stresses along the page dimensions. From observing the flow, it appears as though the shear stresses are low since the fluid easily flows along the planar direction. The low shear stress is likely caused by the non solubility of the ferrofluid and the Windex. Since there is little to no bonding, the ferrofluid/Windex interface acts as a lubricating surface where friction is minimized. This means that when a small shear force is applied (via the magnetic field) a large deformation is seen in the planar direction. The normal stress is high and this causes the flow to remain in two dimensions. The high normal stress comes from strong surface tension interactions. This is likely also due to the non solubility of the ferrofluid and the Windex as surface tension helps to prevent mixing

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Visualization Method

The two main visualization techniques used were ferrofluid and Windex. 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]. Ferrofluid is an opaque black liquid that is very good at absorbing light. It is also slightly reflective due to an oil content. The SC Johnson Original Windex was purchased off the shelf and relative material concentrations as well as the MSDS can be found in Reference [5]. Windex is a semi transparent blue liquid that is good at transmitting light. It is not very reflective.

This flow was created inside with two major sources of light. There were three 60[W] fluorescent light bulbs on the ceiling (72[in] above the camera). These lights were directly blocked by a black cover such that the light scattered around and provided lighting for the sides of the image. The other source of light came from the flash on the camera. The flash was used because it directly and evenly lit the image. There was some glare from the flash, but this did not intersect the flow and was cropped out.

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 calculated from the known dimensions of the Petri dish and is roughly 5.25[in] wide by 3.5[in] tall. Without a macro lens, this was the smallest field of view achievable while still retaining focus. The lens was zoomed in all the way which put the focal length at 55[mm] and the camera lens about 12[in] away from the Petri dish. The focus was set to manual such that the clearest image could be achieved. The aperture was set automatically within the camera and was 1.9[mm] (from an f-stop of 29). Because the camera was tripod mounted, a slow shutter speed (6/10th of a second) was adequate. With the longer exposure time, a low ISO (sensor sensitivity gain) of 100 ensured that the image was non-grainy. Since the flow is stationary, time resolution is not an issue. The image is spatially resolved as best as possible without a macro lens. The original image was 4288 by 2848 pixels and is seen in Figure 2 below.

Figure 2: Original Image

Image post processing was completed entirely in Adobe Photoshop CS6 Extended. The image was cropped to frame the ferrofluid with a standard square width-height ratio. With the crop, the final image is 1038 by 1038 pixels. The contrast was enhanced to increase the distinction between the ferrofluid and the background. Finally, both the saturation and the vibrance were increased to bring out the blue tint of the Windex.

Conclusion

The intent of this project was to capture thin film behavior of ferrofluid and this was accomplished. The thin film effect of ferrofluid is a phenomenal sight. When ferrofluid exhibits high surface tension effects but shears easily, the fluid behaves unexpectedly. The normally ordered structure of ferrofluid within a magnetic field becomes unpredictable. Still though, the general shape of the magnetic field is visible. For this particular project, I think that a movie would have captured the physics and phenomena better; however I chose not to make another movie after the last team project. The picture is very striking and unlike anything I have seen before. The Petri dish I used had some visible scratches that are illuminated in the picture and a cleaner dish should be used in future experiments. This picture was a great way to finish off the Flow Visualization course and the semester.

References

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