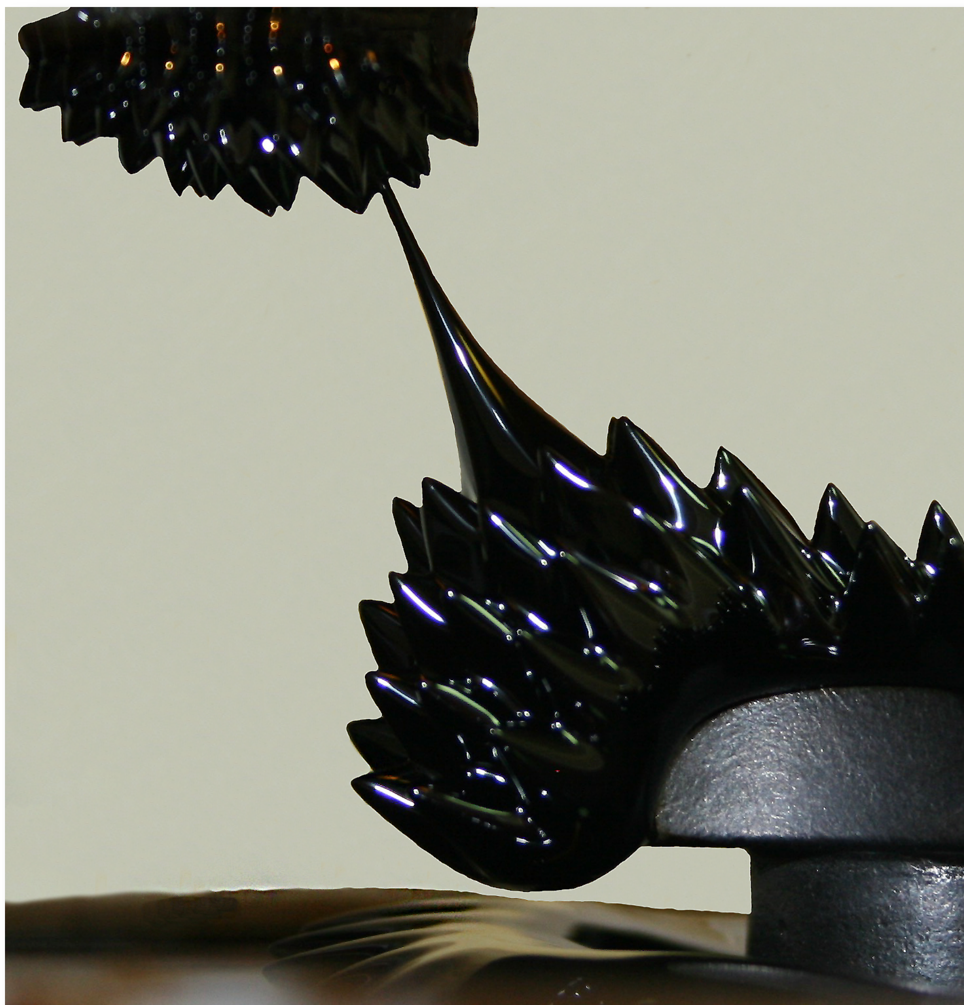
TEAM EXPERIMENT 1: FERROFLUID



Jeremy Tyler Parsons

University of Colorado: MCEN 5151-Flow Visualization *11/3/2016*

Introduction

The image shown was created for MCEN 5151-Flow Visualization for the Team I assignment. The intent of the assignment was to plan and conduct an experiment that demonstrates a fluid phenomenon of interest to the team and image the results. For this experiment, our team chose to investigate the intriguing physics of ferrofluid and the effects of introducing multiple, magnetic fields. The following report will detail the experimental setup and photographic techniques used to capture the ferrofluid image shown, as well as the fluid mechanics driving the dynamics of the ferrofluid illustrated in the image.

Fluid Physics

Ferrofluid was originally discovered by NASA in the 1960’s, when scientists were investigating potential methods of controlling fluids in space (1). The benefits of the unique physical properties of ferrofluids were immediately obvious, as the flow could be directly influenced with the presence of a magnetic field.

Ferrofluid is a very unique fluid, as it is actually a stable colloidal dispersion of nano-scale ferromagnetic particles in a carrier liquid (2). In the case of the ferrofluid we utilized, the carrier liquid was a simple mineral oil and the particles were most like a ferrite such as magnetite, about 10nm in diameter. When exposed to a magnetic field, the particles react to the resulting magnetic forces and the carrier fluid acts as a proxy to visualize the direction and amplitude of the magnetic fields the ferrofluid is exposed to. The shape is due to an effect called normal field instability (3). The normal field instability results when the nano-scale particles in the ferrofluid are in the most favorable energy state. This is formulated via Maxwell’s equations, where the divergence of the B field is zero and the curl of H is zero.

The presence of a magnetic field leads to induces a pressure differential at the interface between the internal of the fluid and the surface. This differential in pressure causes the ferrofluid to elongate in the direction of the magnetic field that is being applied. The peak-to-peak spacing is proportional to the Taylor Wavelength for hydrodynamic instabilities, while the amplitude of each spike is a function of the intensity of the magnetic field applied.

$$1.\quad \oint \mathbf{E} \cdot d\mathbf{A} = \frac{q_{enc}}{\varepsilon_0}$$

$$2.\quad \oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$3.\quad \oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$4.\quad \oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 \varepsilon_0 \frac{d\Phi_E}{dt} + \mu_0 i_{enc}$$

Figure 1: Maxwell’s Equations of Electromagnetism (4)

Experimental Setup

The image was created by exposing the ferrofluid to two separate magnetic fields, one steady and one dynamic. To do this we created an experimental setup to manipulate the ferrofluid using stacks of neodymium magnets in different locations to create the dynamic response of the ferrofluid to each magnetic field.

A word of caution: ferrofluid is nontoxic but is extremely prone to staining and can permanently stain about any surface it comes in contact with. It is important to wear old clothing, cover any surfaces that may be stained by the ferrofluid and consider the effects of each step in the experiment on the ferrofluid prior to executing them. In order to minimize this risk, we covered the table we were shooting on with plastic and surrounded the apparatus with a sheet of foam to contain any accidental splash droplets. It is also very important to avoid any direct contact between the ferrofluid and a magnet. Since the ferromagnetic particles suspended in the carrier fluid are so small they will become permanently attached the magnet. Thus any magnets introduced had a boundary in between them. In our case we used sheets of acrylic to isolate the magnets from the ferrofluid while introducing each magnetic field. The ferrofluid was placed in a small container and the sheets of acrylic were then placed above and below the container. The first stack of magnets was placed against the lower acrylic sheet, directly beneath the subject to create a steady magnetic field first. Once the ferrofluid had formed a steady-state pattern on the subject, the second stack of magnets was introduced on against the upper, acrylic sheet.

Initially, the second magnetic field added was added by hand it was very difficult to control. The subtle differences in distance had a dramatic impact on the dynamic response of the ferrofluid. The “leap” from the subject to the upper acrylic sheet was too fast to image properly. Thus we introduced two blocks of soft foam to control the initial height of the upper magnets and pressure could be slowly applied to bring the magnets closer to the ferrofluid. This allowed for a much more controlled response that could be more easily documented and offered much more resolved images.

To create a diverse range of responses from the fluid, we brought a variety of iron and steel objects and introduced them into the fluid progressively throughout the experiment. Each object created a different response in the steady-state and dynamic visuals of the ferrofluid. For reference the experimental setup is shown below.

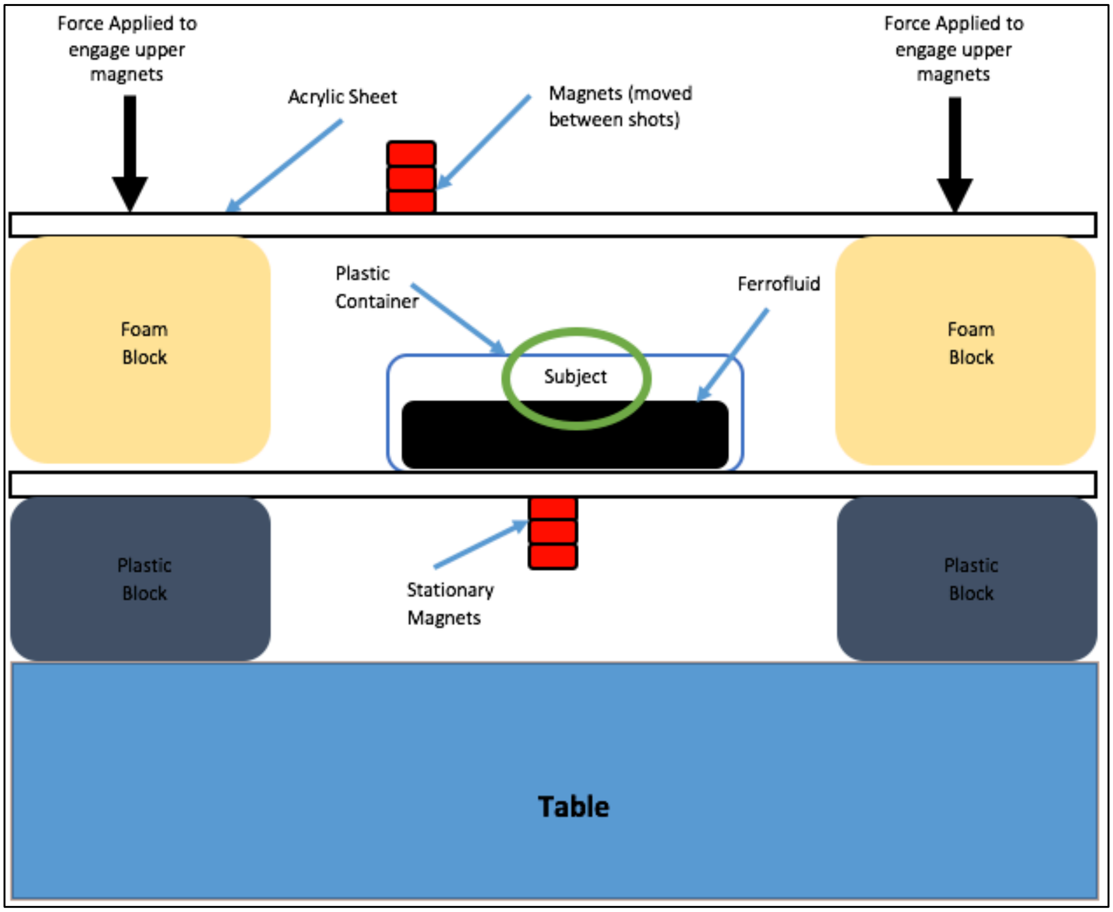


Figure 2: Experimental Setup

Photographic Technique

The image was shot on October 14th, 2016 in a design studio in Fleming building at the University of Colorado, using a Canon Rebel XTI digital DSLR camera. The following equipment and parameters were used to capture the image:

- Lens: 18-55mm Macroscopic Lens
- Shutter Speed: 1/60 Second
- Exposure Settings: ISO 200, F/5.6
- Image Resolution: Original- 3888 × 2592 pixels, Edited- 1475 × 1536 pixels
- Editing: Photoshop CS6 was utilized for post processing the image

A shutter speed of 1/60s was utilized to capture the ferrofluid dynamics as it leapt from one magnetic field to the next, as shown in the image. Originally I leaned toward a faster shutter speed since the fluid was moving rather quickly across the frame. However, in the process of experimenting with balancing aperture and shutter speed, this image came stood out among the rest during import. The field of view in the original image is about six inches across in total while the bottom “crown” of the ferrofluid is about 2 inches wide.

Photoshop CS6 was used to post process the original image and focus the viewer's attention toward the fluid being visualized. The resolution of the initial image was 3888 × 2592 pixels and was cropped down to 1475 × 1536 pixels to remove any distracting elements from the photo and focus on the physics of the ferrofluid being illustrated. The background was removed to draw isolate the flow in question and the vibrancy was adjusted down just slightly to reduce some of the intensity of the glare off of the ferrofluid spikes. The original and post-processed images are shown below.

Original Image

Figure 4: Original Image, Unedited

Edited Image

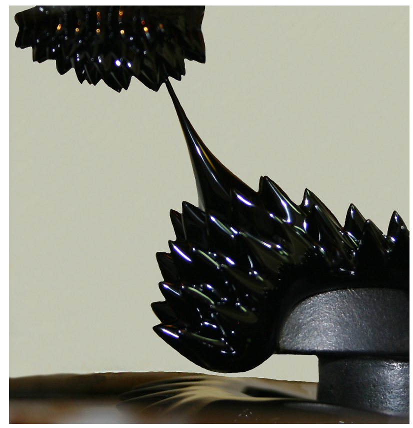


Figure 3: Final Image, After Post Processing

Commentary

I have always found ferrofluid to be very fascinating and the aesthetic visuals created by its unique physical properties made the experiment very enjoyable to conduct. The team and I concur that we would alter the setup if we were to conduct this experiment again. By incorporating a more controlled background the image would have taken less post processing to illustrate the flow clearly and I think this would have lent to increasing the overall image quality. Besides that, I still enjoy this visual of the ferrofluid in the final image. It has an interesting, almost alien, character when exposed to the magnetic fields that seems to jump off the page toward the viewer.

Acknowledgements

I wish to acknowledge Joseph Straccia, Max Scrimgeour and Peter Brunsgaard for their collaboration on this team assignment. They were instrumental in conducting the experiment and creating the images illustrating the physics of the ferrofluid. Please refer to their work for more imagery and information regarding this experiment.

Citations

1. "Ferrofluid Resources." Exploring the Nano World. 2008. Accessed November 3, 2016. http://education.mrsec.wisc.edu/background/ferrofluid/.
2. Odenbach, Stefan. Ferrofluids: Magnetically Controllable Fluids and Their Applications. Berlin: Springer, 2002.
3. Lin, Joshua. "Spikes on Ferrofluid?" Physics Stack Exchange. November 29, 2014. Accessed November 04, 2016. http://physics.stackexchange.com/questions/149414/spikes-on-ferrofluid.
4. Watson, George. "Maxwell's Equations." December 11, 1997. Accessed November 04, 2016. http://www.physics.udel.edu/~watson/phys208/maxwell-review.html.