Team Project #2: Fun With Ferrofluids

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Project Objective

The objective of this project was a little more vague than the others we've attempted. Two years ago, my Senior Design Capstone project was to design and create a series of ferrofluid exhibits for an interactive laboratory here on campus. I mentioned the project to my team, and after showing some pictures to Amanda Kennedy, Vick Selvaraja, and Athena Ross, we decided that we could use the exhibits to produce some unique and interesting photos. The exhibits consist of "The Stained Glass Window," a spice rack of rainbow colored jars with ferrofluid suspended inside, "The Electromagnet Tree," a metallic sculpture powered by an electromagnet to attract ferrofluid, and "The Jungle Gym," a series of crank and gear powered magnets that dance around a pool of ferrofluid, generating interesting magnetic fields. Athena took advantage of the Stained Glass Window, Vick did his own rendition of the Hele-Shaw phenomenon, and Amanda and I utilized the Electromagnet Tree to create some artistic images with this unique and interesting fluid.

Experimental Apparatus and Flow Phenomenon

A ferrofluid is a type of liquid (usually oil or water) that contains nanoparticles composed of iron. A surfactant is then used to prevent the iron particles and liquid separating from one another. When a magnetic field is introduced to the ferrofluid, the ferrofluid will form peaks and valleys (Figure 1) that give a graphical representation of the magnetic field lines passing through the liquid.[i] The fluid will be most attracted to areas with a high magnetic flux, and the peaks will point in the direction of the field lines. These peaks and valleys are formed due to an effect known as normal-field instability, which states that the peaks and valleys are the lowest energy formation for the fluid. The spikes in the ferrofluid drive the magnetic field further, whilst surface tension and gravitational forces tend to stabilize the flow.[ii] The balance of these forces results in the static spike structures distinctive of ferrofluid. It is also important to note that the peaks are where the magnetic field lines are concentrated by the ferrofluid. When the magnetic field is removed, the ferrofluid returns to its liquid state.

Figure 1: Ferrofluid displaying peaks and valleys due to the normal-field instability.[i]

A ferrofluid is permeable due to the iron flakes suspended within it. It is used as a flow visualization technique for envisioning magnetic fields. The higher the magnetic permeability the more magnetized a material will be when exposed to a magnetic field. The permeability of free space (a vacuum) is $\mu_0=4\pi*10^{-7}$ N/A^2. The permeability of other materials will typically be expressed as relative permeability, $\mu_r=\mu/\mu_0$, which shows how it compares to the permeability of free space. If the relative permeability is greater than 1, then the material will be attracted to a magnet. For reference, steel has a relative permeability of about 100, and iron has a relative permeability of about 5,000, hence ferrofluid's ability to maintain the magnetic field within itself once it is applied.

Magnetic field lines have a tendency to want to stay inside of magnetically permeable materials as long as possible. For example, if one were to put an iron cylinder above an electromagnet most of the lines would go straight through the shape, and only a few would leak out the sides. This results in a smaller magnetic flux on the sides than through the end of the cylinder. This same principle also applies to how the field lines pass through the tree. The field lines will stay inside the sculpture as long as possible, and will want to exit through the ridges more than through the smooth sides. The magnetic flux will be concentrated at the points of the sculpture (Figure 2). This is why the ferrofluid sticks to the ridge of the coils and not the sides. In general the magnetic flux will be greatest close to the electromagnet and along peaks and ridges of the sculptures.

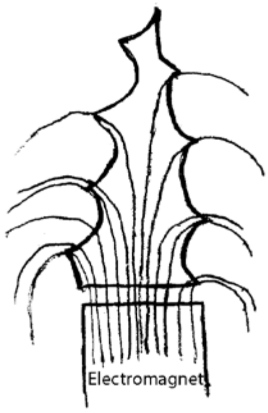

Figure 2: Magnetic field lines through the "tree"[i]

Optimization of the electromagnetic design was part of the project two years ago. As electromagnetics are not necessary to understand how the fluid works, I will leave this explanation out. For reference and interest, Figure 3 is a picture of the setup with the electromagnet, to understand the size and scale of the magnet powering the tree. Despite the optimized design, overheating can still pose a problem to the exhibit's functionality, leaving a limited amount of time within which the photos could be taken.

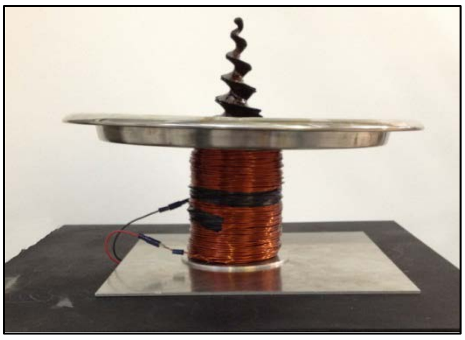

Figure 3: Ferrofluid "Tree" and hidden electromagnet

Flow Visualization Technique

The flow visualization technique used in this project was the fluid composition itself. The iron flakes suspended in the surfactant give the fluid its color and allow it to reflect light better. But most importantly, it makes the fluid magnetically permeable, giving the fluid the unique ability to give shape to magnetic fields in the peak and valley formation. When the fluid is in the presence of a magnetic field, its characteristic formation is representative of the normal-field instability. In other words, the fluid takes on the least-energy intensive form and is a perfect force balance between gravitational, magnetic, and surface tension forces.

The tree is used to shape the applied magnetic field in unique and interesting ways. It concentrates the magnetic field along ridges and spirals, allowing the ferrous fluid to "climb" the statue. A pool of ferrofluid, about ¼" deep, ensures that there will be enough ferrofluid to climb all the way to the top and produce thick, well-defined spikes.

Photographic Technique

Approximate numbers for capturing the image are given in Table 1.

Field of View	14"
Distance from Object to Lens	16"
Lens Focal Length	18-55m
Type of Camera	Canon T3 DSLR
Final Picture Size	2744 x 3336 pixels
Exposure	Shutter Speed: 1/60th second Aperture: 4.0 ISO: 800
Post-Editing	Cropped, Sharpened, and Brightened Turned up saturation of Magenta, Cyan, Blue, and Green. Turned down saturation of Yellow and Red. Increased contrast

Table 1: Photographic Specs

Many of my images of the ferrofluid tree ended up having a reflection from the flash resulting in an oily rainbow effect on the ferrofluid spikes. The ferrofluid tree itself makes for some interesting images, but upon seeing the rainbows, I decided to turn these up a bit to make the photo more dramatic, hence the editing of color saturations. The original image is a little dark, which is why I brightened it slightly. In retrospect, I probably should have used a longer shutter speed or turned up the ISO, but some the reflections from the metal would have blown out certain areas. The f-stop chosen was to give a depth of field to the dish and the tree, which was in the center. I wanted to ensure that the entire tree was in focus, but it is not necessary to know what the tree is sitting in, and actually makes it a little more mysterious, if the viewer's attention is not drawn to the dish. The original image is given in Figure 4 for reference.

Figure 4: Original Image

Results

I am quite pleased with the results of my image. We set out to make ferrofluid look interesting and artistic, which I feel I accomplished, with a little luck with the rainbow effect. It was nice to approach the project from an artistic standpoint after so many months of technical work on the exhibits. If I were to do the project again, I may try to focus instead on a few spikes instead of the entire set up, as I have seen some really dramatic photos online doing just that. It makes for a really beautiful image, and perhaps demonstrates the normal-field instability better, as the viewer can closely inspect a few peaks and valleys. I think we all created some beautiful photos, however, and all in unique and original ways.

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[i] Blackstun, Brogna, Childress, Collegeman, Davis, Schwartz. *"ITLL Ferrofluid Exhibits."* May 2012. Integrated Teaching and Learning Laboratory at the University of Colorado at Boulder. April 2014.

[ii] Abou, Bérengère; Wesfreid, José-Eduardo; Roux, Stéphane; *"The normal field instability in ferrofluids: hexagon-square transition mechanism and wavenumber selection*." J. Fluid Mech. (2000), vol. 416, pp. 217-237. Printed in the United Kingdom. 2000 Cambridge University Press