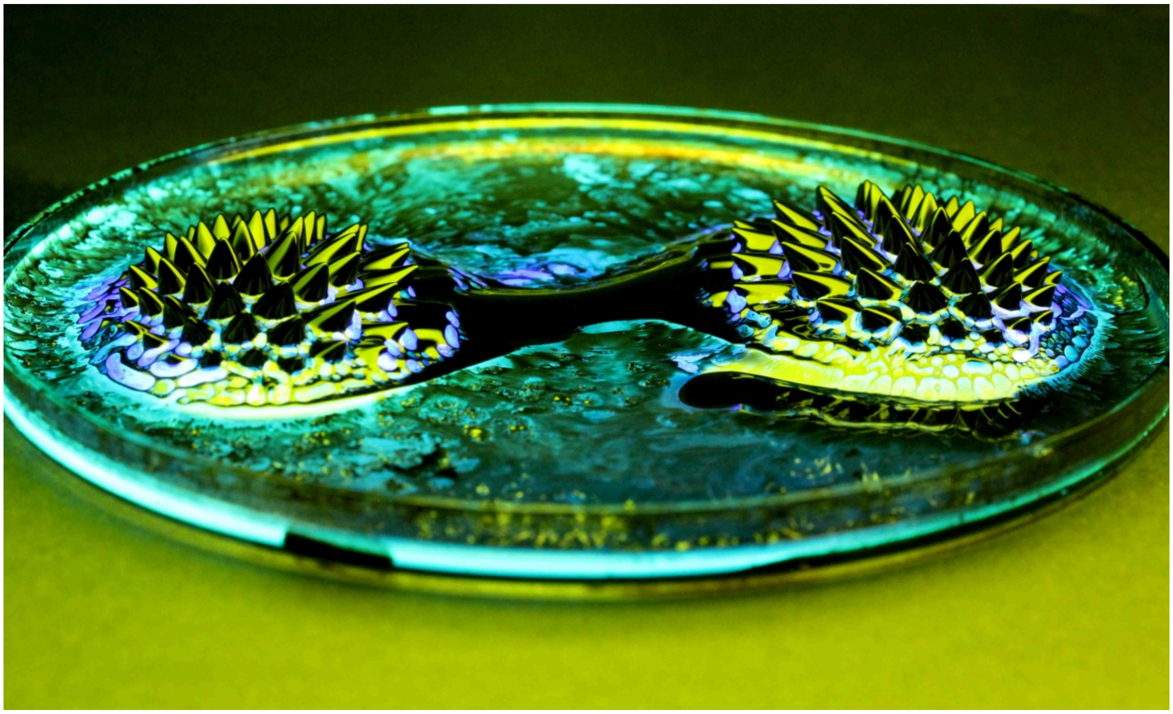


“Ferrofluid Fun”
Danny Maguire
MCEN 5151
Team 2: Danny Maguire, Erick Pena, Stefan Schultz

Introduction

The picture captured above was taken for class MCEN 5151, Flow Visualization, offered at the University of Colorado - Boulder. This third and final project with a group, “Group 3 Project”, is an assignment where we get to work with the same members of the class that we did in both Group 1 and Group 2 Projects, in an effort to come up with an aesthetically pleasing image that captures particular flow visualization phenomena. The project doesn’t have much limitation so the picture/video can be any number of items. Since we’re working in groups the assignment allows for us to come up with a fairly complex setup that allows us to capture our chosen phenomena. The two main objectives that the image is meant to capture is that it demonstrates some flow phenomena and that it’s a good, quality picture that offers some artistic relevance. For our final image, we decided to capture the unique shapes that ferrofluid produces within a petri dish while using glow stick fluid to illuminate the fluid itself. The colors and complex designs that are formed with the ferrofluid are very interesting and offered a great opportunity to capture a unique image. We felt this project offered enough difficulty in both image complexity and setup, and also offered the chance to capture a really unique and odd physical phenomenon. The other two members in my group were Erick Pena and Stefan Schultz. In general, the overall concept in getting this image was derived from a YouTube video uploaded by Physics Girl, called Amazing! Ferrofluid + Glow Sticks[1].

Setup

The overall setup of this particular project is a little complicated due to volatile state of the ferrofluid. We needed to be very careful that we didn't get any of the fluid on our hands or clothing because it has a tendency to stain relatively easily. It also is very magnetic, not surprisingly, so we needed to be sure to keep any magnets pretty far away from wherever we put the fluid. We decided to pour a small amount of the fluid into a 4" petri dish which is where we'd focus our photos when capturing the phenomena. The actual ferrofluid we used was supplied by Professor Hertzberg and had the following key characteristics based on the Material Specification Data Sheet pulled from their website and determined from the label off the bottle supplied by the professor[2]:

Manufacturer: Ferrotec
Catalog Number: EFN1
Lot Number: J102210A
Volume Ratio: Magnetite – 3-15% by volume
Oil Soluble Dispersant – 6-30 % by volume
Carrier Liquid – 55-91% by volume
Boiling Point (°F): 401-491
Specific Gravity: 0.92-1.47

We had a black, folded up piece of cardboard paper that acted as both a table top base and backdrop when taking the images. We placed the black paper on a cardboard box that had a hole cut out on the side that allowed us access to the top of the box. The reason we wanted/needed access was because we placed the magnet at this location, under the ferrofluid, petri dish, black cardboard paper and cardboard box stack up. The magnets were a series of 6 rectangular neodymium magnets, roughly 1" long x 0.25" wide x 0.25" tall. This allowed for a fairly strong magnetic interaction helping to emphasize the unique shapes that take place within the fluid when a magnetic field is present. This setup was all done in a closed garage at night with the lights off, so it resulted in a fairly dark space. We used warm glow stick fluid (green and blue) and dropped it into the ferrofluid with a small eye dropper. After taking a few pictures we realized we weren't quite getting the details of the conical shapes that the ferrofluid has, so we played around with waving the other glow stick colors (yellow and purple) over the top of the setup. Over a long exposure on the camera, this really helped shape the cones on the top of the fluid, and gave the final photos some real depth. The camera was roughly 6" away from the petri which allowed us to zoom in fairly well on the ferrofluid without getting too close to have complications with the magnetic properties of the fluid being attracted to anything on the camera. The tripod was tilted at roughly a 20° angle from the horizontal. A difficult aspect in this project was making sure the ferrofluid was well focused due to the small size of object and subtle details in the fluid itself. Due to this there were multiple times we'd take the pictures and have to look at it on the computer screen in order to determine the image came out clean. A sketch of this setup is shown below in Figure 1, along with the physical setup next to it.

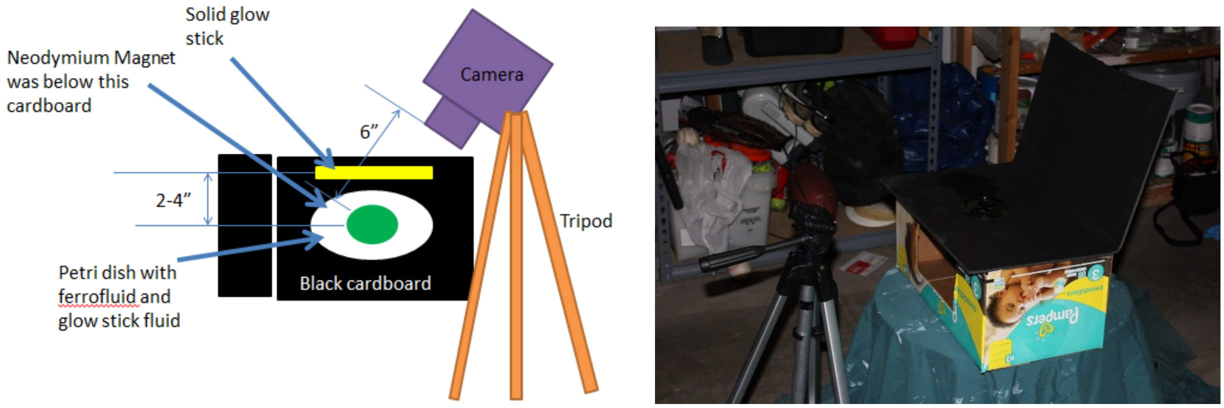


Figure 1: Group 3 Setup

Phenomena

The main phenomenon that is captured within the final image is the interaction of the ferrofluid and neodymium magnet. To truly understand why the unique phenomena captured in the final image takes place we need to first understand what ferrofluid really is. Ferrofluid is a series of ferromagnetic nanoparticles (magnetite in this case) that are collected in a carrier fluid[3]. The diameter of each of these particles is roughly 10 nanometers or less[3]. Due to these tiny particles and carrier liquid, when the fluid is exposed to magnetic field, some unique shapes are formed as seen in the final image.

The main explanation for these unique shapes and odd deformation is known as normal field instability, also known as the Rosensweig Instability. A combination of magnetic forces, surface tension, and gravity forces found within the system, uniquely form a set of peaks and valleys in the fluid along the magnetic field lines[4]. When the magnetic force exceeds the combination of the surface tension and gravity forces the peaks are formed. We noticed during our experimenting, and thru some trial and error, that when the magnet got closer to the petri dish the peaks became much more prevalent, visually recognizing that we were introducing a much stronger magnetic force into the system. The magnets being used, as mentioned above in the “Setup” section, are neodymium, which commonly are strong magnets compacted within a pretty small volume. Luckily, the combination of the strong magnets, small gap between the fluid/magnet and ability to zoom in on the fluid with the camera lens allowed us to capture this phenomenon rather clearly.

In one study of ferrofluid, a team of researchers examined ferrofluid in a reduced gravity environment in an effort to better understand the characteristics of ferrofluid. The team designed a payload to be flown on a rocket that contained a ferromagnetic fluid and a uniform magnetic field that could be adjusted. A video would capture how the fluid would react on orbit depending on the magnetic field being applied, and those visual results would be compared to the same setup back on Earth. The datasets would then be compared to gain a better understand of how a reduced gravity field alters the ferromagnetic characteristics[5].

Equation 1 below is what they used to theoretically calculate a critical magnetic field, the point at which no ferrofluid height is recorded[5]:

Equation 1:
$$H_{c,\infty} = \sqrt{\frac{(1+\chi)(2+\chi)\sqrt{g\rho\sigma}}{\chi^2\mu_0}}$$

The variables defined in the equation are the following; H is magnetic field, χ is magnetic susceptibility, g is gravitational constant, ρ is ferrofluid density, σ is the surface tension of ferrofluid, and μ_o is permeability of free space (a constant value). Based on this equation and the some assumptions they used for variables, the final critical magnetic field calculated was between 22.8-27.1 G

The team put together results for a 1G environment for a physical test case meant to be used to compare to the reduced gravity environment, recording data at various magnetic field strengths and recording the peak height the ferrofluid reaches. This data is shown below in Figure 2.

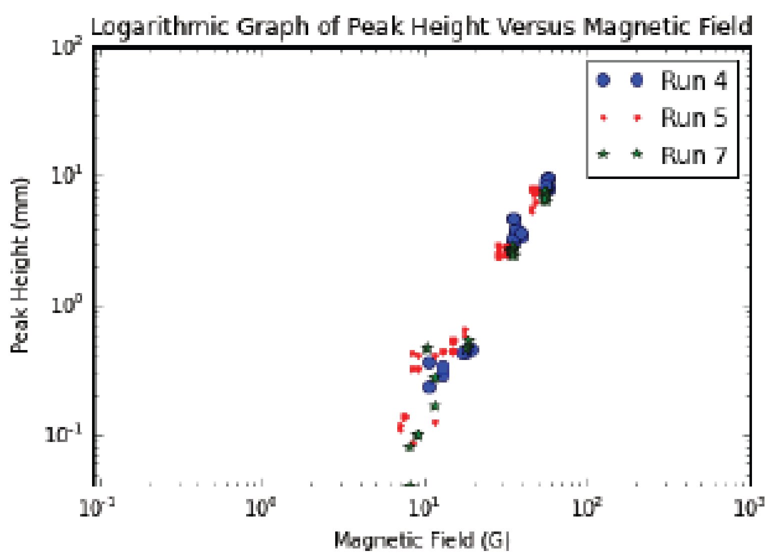


Figure 2: Peak Height based on Magnetic Field in 1G Environment [5]

As described in theory, and what we noticed in our trial and error session, as the magnetic field decreases the peak height of the ferrofluid also decreases. From the measured data in a 1G environment, the critical magnetic field on the ferrofluid is 15 G. Although the theoretical and tested differ, there are still many unknowns in the ferrofluid world, and I'm sure many of the variables used in the Equation 1 could be adjusted to better correlate the results. Unfortunately data for the reduced gravity environment was never recorded since the mission failed at launch, but nevertheless a lot was discovered about the ferrofluid within this research. One would expect in a reduced gravity environment, based on both Equation 1 (where g = 0) and common knowledge in how a ferrofluid works, that nearly any magnetic field would result in some sort of deformation on the fluid.

Visualization Technique

The main visualization technique used in this image is using the light of the glow stick to both illuminate within and reflect off the ferrofluid. The glow stick light from the top was mainly used to capture the cones that are formed at the peak of the ferrofluid shapes while the glow stick fluid that was injected into the fluid was used to brighten up the entire base of the ferrofluid. Before using the glow stick, they were dipped in hot water in order to brighten them up as much as possible, and provide enough light to capture this particular phenomenon. In the final image three different glow stick colors were used; green, blue and yellow. The green and blue fluid was placed in the ferrofluid while the yellow stick was kept encapsulated and used to brighten the top features of the fluid. To give you an idea of how dark the original photos were before using the glow stick, Figure 3 is shown below which is a photo from the earlier images taken before adding this step in the process.

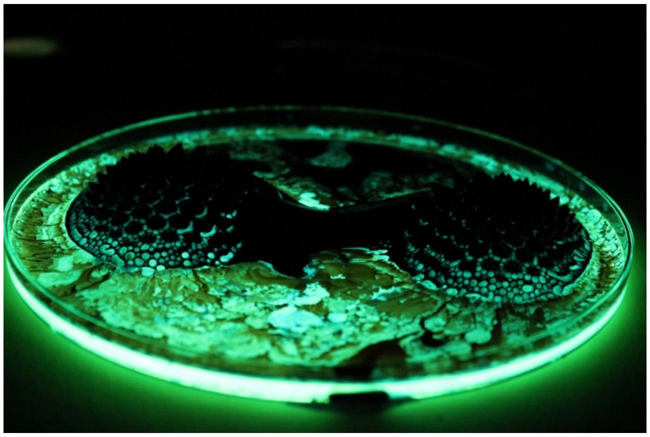


Figure 3: Ferrofluid without Light from Above

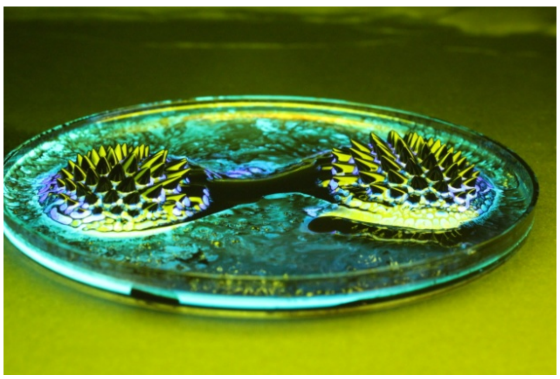
Photographic Technique

The main purpose of this setup was to get the most colorful and unique designs in the ferrofluid as possible. The settings of the camera became an important aspect when taking the picture. The manual mode was selected on our DSLR Canon T2i camera in order to adjust the aperture, exposure and ISO setting while using the manual focus setting on the lens itself to get the image in focus. Numerous angles, physical distances, zoom distances and camera settings (aperture, shutter speed, ISO) were experimented with in order to come up with the best image. The table below is a breakdown of the final settings that were used for the final image. The combination of an aperture setting of F14, an exposure time of 5 seconds and an ISO setting of 3200 (chosen automatically) produced a well-focused and clear image. An intermediate zoom was used between 18-55mm, roughly ~35mm, in order to capture the most amount of detail of the ferrofluid without losing the perspective of the entire petri dish. The original image was cropped down both laterally and vertically to a pixel size of 4912 x 2976 in order to center the petri dish. The image was in a .jpg format initially but was brought into GIMP and cropped down to a more ideal size. The colors were altered using the curves feature in GIMP in order to get a better contrast between the various colors and get some crisper detail of the ferrofluid characteristics.

The final image was exported as a .tif image. Both the original and final images are shown in Figure 4 below.

Table 1: Camera Settings

Setting Description	Setting Value
Aperture	F14
Shutter Speed	5
ISO	3200
Zoom/Focal Length	~35mm
Original Pixel Size	5184 x 3456
Cropped Pixel Size	4912 x 2976
Object/Image Size in Original Photo	4” x 4.5”



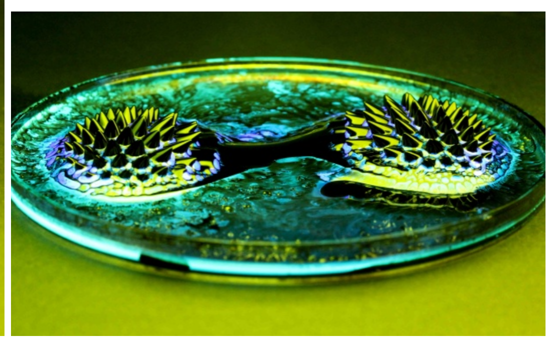


Figure 4: Original and Final Image

Conclusion

I really enjoyed working this final project and using a fluid I had never even heard of before. The fluid was a little hard to work with since it was so unstable, and the prep time was a little long in order to try and minimize the amount the fluid could stain in the garage, but the physics the fluid creates when exposed to a magnet was pretty incredible. I felt the glow sticks provided an eerie feel to the photo, but one that was still aesthetically pleasing to the eye. I also felt like I caught the fascinating details of the ferrofluid when exposed to a magnet fairly well, capturing the fine details of conical shapes that are formed at the top of the fluid, along with the very organized pattern that’s formed within the bubble. I wish I could’ve blacked out the background a little more, and maybe with a little more experience in GIMP, it could’ve been a little darker. I’m happy that I included the entire petri dish in the final image since I felt it gave some real perspective the scale we’re looking at. If I were to do it over again I would look into using more colors of glow sticks and possibly take a video instead of trying to capture this phenomenon with just a one shot photo. Overall, I really enjoyed working with my group and producing a very high quality image that captured the ferrofluid phenomena extremely well.

References:

[1] Cowern, Dianna. *Amazing! Ferrofluid + Glow Sticks*. October 20th, 2015. Retrieved at https://www.youtube.com/watch?v=RtBtD0_KZ9o

[2] *EFH Series Ferrofluid*; Ferrotec; Tokoyo, Japan; March 18th, 2009, Retrieved at https://www.ferrotec.com/downloads/efhmsds.pdf

[3] Wikipedia, *Ferrofluid*. Retrieved at https://en.wikipedia.org/wiki/Ferrofluid

[4] Engel, A. Langer, H. Chetverikov, V. *Non-linear analysis of the surface profile resulting from the one-dimensional Rosensweig instability*. Journal of Magnetism and Magnetic Materials 195 (1999) 212-219

[5] Krull, Brendan; Rundle, Tessa; LeCaptain, Kevin; Barhite, Justin; Gear, Amelia. *The Onset of Normal Field Instability in a Ferrofluid in a Reduced Gravity Environment*. September 14th, 2014.