Flow Visualization Team Project #1

Ferrofluids

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The purpose of this image was to capture the very unique phenomenon of ferrofluids reacting to magnetic fields. A ferrofluid is a substance that has fluid properties of a liquid and magnetic properties of a solid. To be more specific, the fluid contains very small particles (approximately 10 nanometers in diameter) of a magnetic solid in the liquid medium. This substance was discovered in the 1960's at NASA by scientists who were attempting to come up with methods to control liquids in space[2]. The benefits were obvious; you could control the fluid with a magnetic field and vary the strength of the field to control the force on the fluid which allows the liquid to flow as desired. In addition to this being a very interesting phenomenon to observe, ferrofluids are used in a few applications. They are used in rotating shaft seals as liquid O-rings that eliminate most friction produced by mechanical seals[2]. They are also used to improve the performance of some loud speakers as the electric coils are bathed in the fluid in order to dampen unwanted frequencies and dissipate heat[2]. Currently in the biomedical industry, researchers are attempting to design ferrofluids that can carry medications to specific parts of the body by applying magnetic fields[3]. The image my group captured shows a bolt and washer covered in a ferrofluid that is reacting to a magnet placed underneath the hardware. The arrays of spikes seen in the picture are from the fluid standing up along magnetic field lines. This concept can be seen in figure 1 below[1]. This is further explained by the Normal Field Instability which will be discussed in addition to photographic techniques and detailed descriptions of the experiment in this report.

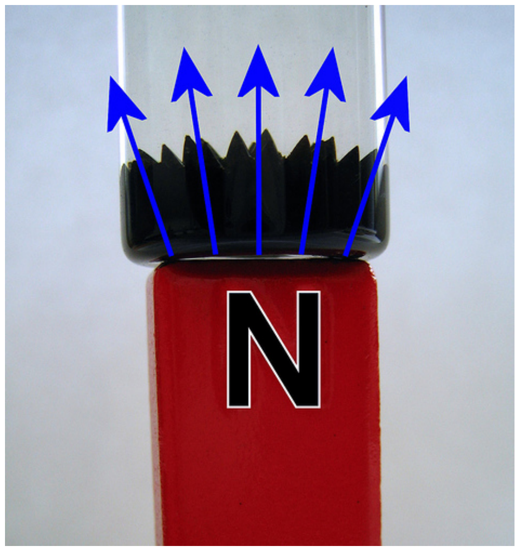


Figure 1 - Magnetic field lines shown by spikes in ferrofluid

In this experiment, a threaded bolt and flat washer were covered in the ferrofluid. A magnet was then placed under the materials hidden from view beneath a white plate. This caused the magnetic interaction between the magnet and ferrofluid to be observed by viewing the many spikes on the washer and top of the bolt. This perfectly symmetric balance and phenomenon observed of a ferrofluid occurs only when the ferrofluid is prepared correctly. The small particles suspended in the liquid medium that react to the magnet are magnetite[1] (Fe_3O_4). This compound can be prepared by combining an Fe(II) salt and an Fe(III) salt in basic solution which causes the mixed valance oxide, magnetite, to precipitate from solution[1]. The chemical reaction of this can be represented as:

$$2\ FeCl_3 + FeCl_2 + 8\ NH_3 + 4H_2O \dashrightarrow Fe_3O_4 + 8\ NH_4Cl$$

This reaction gives the desired particle, but the particle must be small to remain suspended in the liquid for the ferrofluid to function properly. This is because magnetic and Van der Waals bonds must be overcome to avoid particles from accumulating. One way to prevent particles from agglomerating is to keep the particles well-separated by adding a surfactant to the liquid which can generate either steric or electrostatic repulsions between the particles. A common surfactant used in ferrofluids is cis-oleic acid which causes a steric repulsion of the particles[1]. Cis-oleic acid is a long chained hydrocarbon with a polar head that is attracted to the magnetic particle. The long chains of tails then act as a repellent cushion and prevent particles from approaching one another. A diagram showing this process can be seen in figure 2[1].

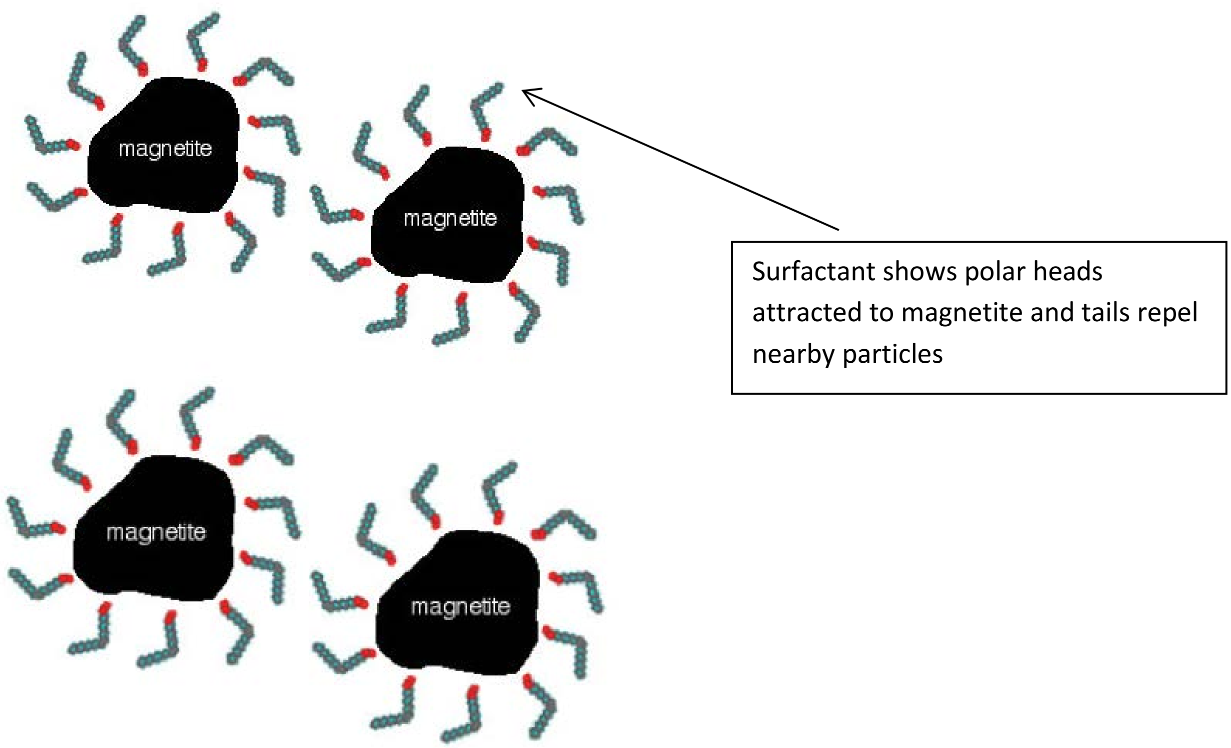


Figure 2 - Steric repulsion from interaction between surfactant and magnetite

The ability to maintain small magnetite particles allows the ferrofluid so effectively react to magnetic fields. When a ferrofluid layer is subjected to a uniform magnetic field, an interfacial instability occurs above a critical value of the magnetic field. This instability is called a Normal-Field Instability and gives rise of an array of hexagonal peaks. Increasing the strength of the magnetic field above the second threshold will result in a square array to be observed, but is not shown in the picture of this report. The critical value the magnetic field must be is of the order of 10^4 Am^{-1} for the phenomenon to be observed[2] and is represented by the equation:

$$H_{crit} = \left(\frac{2}{\mu_0} \frac{(\mu_0/\mu + 1)}{(\mu_0/\mu - 1)^2} \right)^{1/2} (\rho g \gamma)^{1/4};$$

where:

ρ = fluid density

g = acceleration of gravity

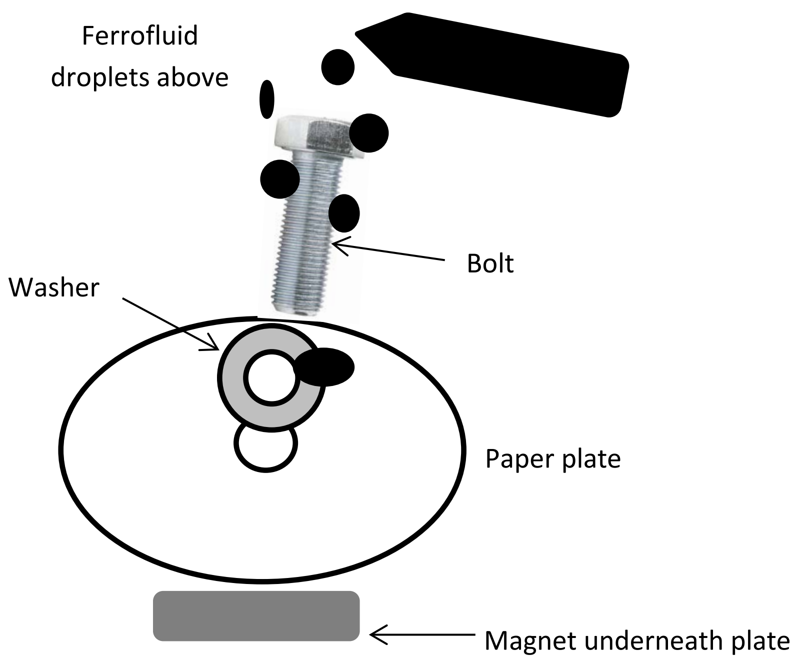
γ = surface tension

μ_o = permeability constant

μ = magnetic permeability

The values of these properties can be found from the ferrofluid technical data sheet on the course website and are referenced in the appendix of this report. When using these values, the calculated critical value was approximately 38227 Am^{-1}. The magnetic field applied from the magnet used in this experiment was of the necessary magnitude as the phenomenon of the Normal-Field Instability and spikes of the fluid are seen in the image shown at the beginning of the report.

The setup of the experiment was very simple. A paper plate was used as the base of the setup. The plate was then penetrated by the threaded bolt. The bolt was removed after making a clearance hole in the plate and a flat washer placed towards the head of the bolt. The assembly containing the washer and bolt was placed and stabilized in the hole of the paper plate. The ferrofluid was then poured directly over the top of the bolt and washer until the metal was submerged completely in the ferrofluid. A diagram of this setup can be seen below:



There was no direct lighting used to capture the photograph. The only light used was indirect bulbs that light the room normally. Since the experiment was performed inside, there were no relevant environmental conditions or details that should be noted.

The following photographic techniques were used to capture the image:

Size of field of view	12 inches across
Distance from object to lens	Approximately 8 inches
Focal length	55.0 mm
Type of camera	Canon EOS Rebel T3
Original/Final Image width	1536x1024 pixels
Aperture/ISO	F 5.7 / 800
Shutter Speed	1/60 s
Photoshop processing	Slightly increased the contrast

The aperture used was relatively large to capture a small depth of field. This feature in addition to a slower shutter speed allowed the subject of the image to be perfectly in focus, but the background to be a little blurred. I believe this allows the viewer to focus their attention completely on the ferrofluid and not on the surroundings in the image. A large ISO was used in order to allow the correct amount of light of the photograph and gives an extreme contrast between light and dark of the image. This contrast was slightly increased even more for the shapes and spikes made by the fluid to really stand out.

This image captured for my first team project does an excellent job at showing the physics behind ferrofluids. The Normal-Field Instability is clear in the photograph and magnetic field lines can be represented by the rising spikes of the ferrofluid. I really like how you can see the science behind the ferrofluid in the picture and also appreciate the artistic feel of the photograph as well. It is a very interesting phenomenon and raises a lot of curiosity to observing parties. I think the final image came out excellent and there is nothing significant I dislike about the photo. Our group took many photos using a few different materials and setups and the symmetry and beauty of this individual photo really jumped out at me. I would be interested in experimenting with this fluid even more using several other materials and different strengths of magnets to capture even more extreme instabilities. I also think that a video showing how the fluid reacts to magnets would help people further understand how it works and show the phenomenon more explicitly. Overall, I am very satisfied with the outcome of this project.

References

1. *A Materials Science Companion by A. B. Ellis, M. J. Geselbracht, B. J. Johnson, G. C. Lisensky, and W. R. Robinson. Copyright © 1993, American Chemical Society, Washington, DC*.
2. Abou, Berengere. "J. Fluid Mech." *The Normal Field Instability in Ferrofluids* 416 (2000): 217-37. Web. 5 Mar. 2013. <http://pages.csam.montclair.edu/~yecko/ferro/oldpapers/DIRECTORY_Normal_Field_Instability/AbouWesfreidRoux_NormFieldInst.pdf>.
3. "Ferrofluids." *Exploring the Nanoworld* (2008): n. pag. *National Science Foundation*. Web. 5 Mar. 2013. <http://education.mrsec.wisc.edu/background/ferrofluid/index.html>.

Appendix

Technical Data Sheet

Ferrofluid Type: EFH1

Physical Properties

Appearance	black-brown fluid
Carrier Liquid	light mineral oil
Saturation Magnetization	440 Gauss (44 mT)
Viscosity @ 27°C	6 cp (6 mPa·s)
Nominal Particle Diameter	10 nm
Initial Magnetic Susceptibility	2.58 Gauss/Oe (0.17 emu/g / Oe)
Relative Magnetic Permeability @ 20 Oe	2.6
Density	1.21 g/ml (1.21 X 10^3 kg/m^3)
Magnetic Particle Concentration	7.9% by Volume
Flash Point	92°C
Pour Point	-94°C
Surface Tension	29 dynes/cm (29 mN/m)
Volatility (1 hr @ 50°C)	9 %

For further technical data, please contact your local Ferrotec office:

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