IV 2: Normal Field Instability in Ferrofluid

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IV 2 - Team First
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Image Purpose and Context

This photo was taken with assistance in setting up the subject and adjusting lighting from Lucas Fesmire and Martin Allsbrook. We originally wanted to suspend ferrofluid in a glass container and generate vortexes using magnets attached to a hand drill, but the magnets we had barely perturbed the fluid in the jar. After regrouping, we decided we wanted to visualize the normal field instability and how it applies to the shapes generated by ferrofluid when a magnet is in close contact with it. Ferrofluid is a paramagnetic fluid whose surface forms regular patterns of peaks and valleys when it is subject to a strong magnetic field. I initially wanted a macro image of the peaks and valleys, but after experimenting with the fluid, I liked how our setup resembled the pupil and iris of an eye.

Image Circumstances

We began the experiment with a few ounces of ferrofluid (provided by Dr. Hertzberg) poured onto a minimally reflective, white ceramic plate to have a large contrast between the dish and the dark fluid. Magnets of varying strength were put underneath the plate to prevent the fluid from coming into direct contact with them, but have it still be affected by the generated magnetic field. This image was lit from the side with the RYOBI ONE+ 18V Hybrid 20 Watt LED Work Light. Any additional purple color projected onto the fluid came from LED strips that wrapped around the ceiling of the room. We initially had them turned off, but liked the additional color and reflectiveness it offered on the surface of the ferrofluid. We attempted to keep the ambient light in the room as low as possible and have the majority of the light come from the 20 Watt light, and for that reason I did not use the flash function on the camera. The photo was taken from above with the camera being slightly offset from parallel so it and myself were not visible in any reflection from the fluid in the final image. The orientation and set up of the image can be seen below in Figure 1.

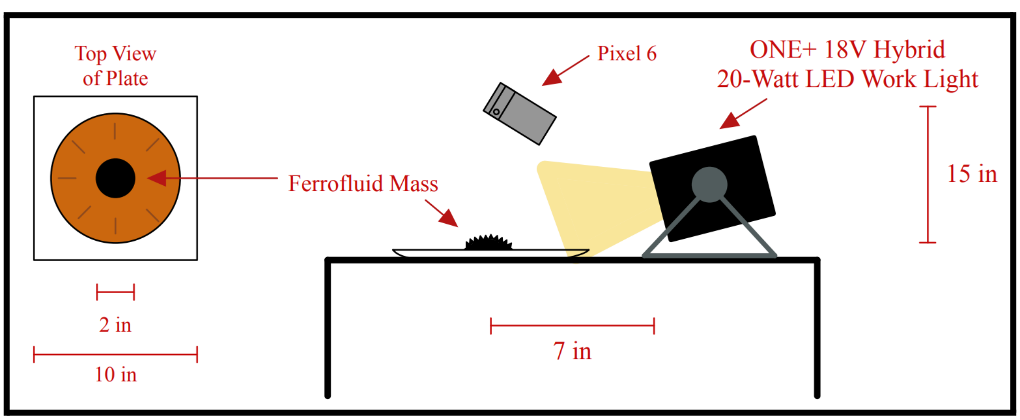

Figure 1: Experimental setup for recreating experiment and image

Ferrofluid is a liquid which becomes highly magnetized in the presence of a magnetic field, and the generated spiky shape of the magnetized fluid is caused by it wanting to find the most stable shape possible that minimizes the total energy of the system[1]. This effect is called the normal field or Rosensweig instability. Ferrofluids are colloidal fluids that consist of ferromagnetic particles in a carrier fluid, typically water or other organic solvents coated with a surfactant to prevent them from clumping in the carrier. Typical volume concentrations of the magnetic component are in the range of 5%-15%[II]. The fluid is more magnetic than its surrounding air, so in the presence of a magnet, it orients itself along the magnetic field lines, resulting in the peaks and valleys. The shapes of these peaks and valleys are resisted by gravity and surface tension. Incidentally, the generation of the corrugations (folds) decreases magnetic energy but increases the gravitational and surface free energy. The ultimate shape of these spikes come from the balance of these forces. In this photo, the magnet was in direct contact with the plate, separating it from the fluid by about 3 mm. Since the magnet field was weaker here, the spikes were smaller, but very clear and apparent.

The shapes generated by the magnetic field can be modeled using the critical value of the magnetic field for the onset of the instability (H_{crit}) and the critical wave number (k_{crit}):

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

Where ρ is the fluid density, γ is the surface tension, μ is the magnetic permeability, and g is the acceleration due to gravity[III]. On increasing the magnetic field, the smooth morphology of the surface transitions into a hexagonal or square orientation of spikes, depending on the magnetic threshold reached. We lack the necessary information about our system to reliably be able to perform these calculations, but an intuitive explanation will be provided. The spike magnitude and orientation depend on both of the values mentioned above, with a visual representation shown in Figure 2 from a Finnish research team from the Department of Bioproducts and Biosystems at Aalto University School of Chemical Engineering[IV]:

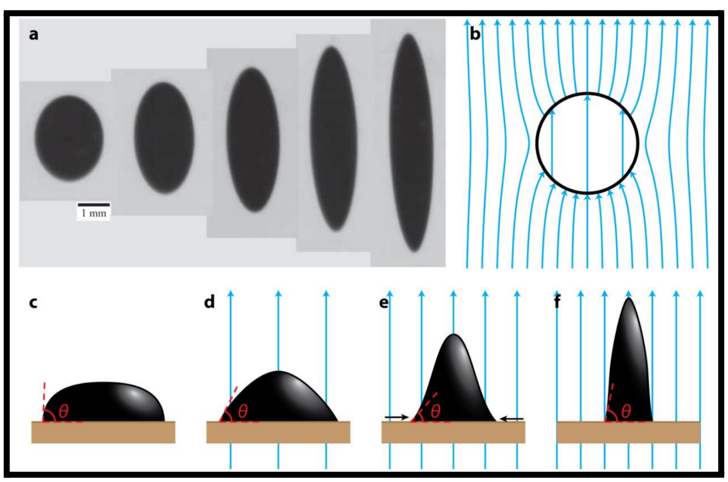

Figure 2: Finnish research team graphic: a) Side view of suspended ferrofluid under increasing vertical uniform fields from left to right. b) Magnetized sphere in magnetic field showing total field H. c-f) Schematic of ferrofluid droplet in increasing magnetic field strength

As you can see from the figure, the droplets shrink in width and elongate when larger magnetic forces are present. This is once again done so the droplets reach an energetically favorable state when subject to external uniform magnetic fields. The critical wave number comes into play with increased strength as well, since it models the spatial frequency of the wave (droplet width).

<u>Visualization Technique</u>

The ferrofluid starts as a dark mass on the white plate after being dropped, since it is not magnetized. We swirled the fluid around the plate to evenly distribute it across the surface before trying different magnet strengths, distances, and orientations and photographed different shapes and orientations of the spikes formed. I wanted to track individual particles of the ferrofluid when the magnet was introduced, and these field lines can be seen approaching the main mass that formed spikes from the edge of the plate in Figure 3.

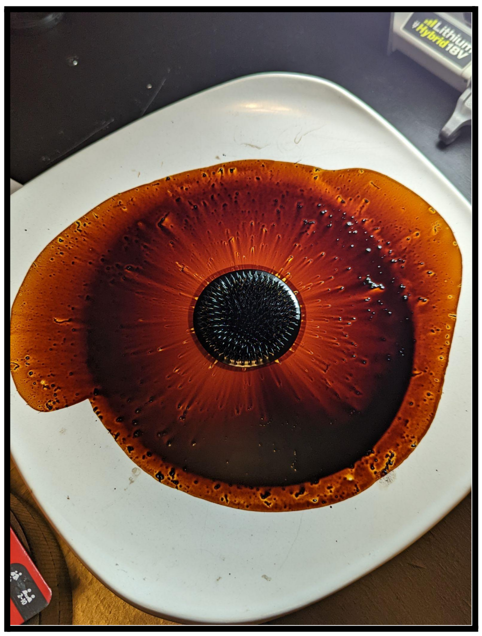

Figure 3: Unedited photo of ferrofluid trails leading to the spikes on the ceramic plate.

<u>Photographic Technique</u>

I took this photo using my Pixel 6's back camera, since it was better than my Canon Powershot SX10 IS at capturing details in macro images, and it felt like a smart choice given that the spikes were only millimeters tall. The image had a resolution of 3072 x 4080 pixels with a focal length of 6 mm and field of view ~9 inches wide. The camera was positioned ~15 inches away from the ferrofluid. I cannot give an exact value for camera position since my height and distance varied based on lighting and fluid conditions and this is one of many photos taken. The photo was zoomed in and focused by the phone with the following settings applied:

- Aperture: f/1.9
- Exposure: 1/120
- Focal Length: 6 mm

- Focus Distance: 0.32 m
- ISO: 63

I edited this photo in Dark Table, where I adjusted the contrast, saturation, brightness, and cropping. I edited the transfer function of the color to bring out the light and dark colors in the image. The contrast was increased to +0.3 and the brightness and saturation were both increased to +0.2. I added a pretty significant vignette to the image and cropped it (to 3020 x 2960 pixels) to remove some of the distracting things around the plate and to further emulate the eye aesthetic this image has.

Image Reveals

The photo visually demonstrates how ferrofluid reacts in the presence of a magnetic field. The white plate helped with the contrast of the darker, denser areas of the fluid and the lighter thinner layers of ferrofluid. If I were to perform this experiment again, I would do it with a round plate and try to have better control over the way the fluid was smeared, so I could have it better resemble a circle, to better emulate an iris. Aside from these artistic changes, I am very satisfied with how this experiment represented the normal field instability. Though it was a coincidence that I was able to capture this exact image and it was not the original intention, I feel that the pay off was well worth it.

References:

I. *Magcraft. (2015, January 31). What is a ferrofluid? MAGCRAFT Brand Rare Earth Magnets. Retrieved October 8, 2022, from https://www.magcraft.com/blog/what-is-a-ferrofluid*

II. *Altmeyer, S. A. (2020, December 25). Ferrofluids. Scholarpedia. Retrieved October 8, 2022, from http://www.scholarpedia.org/article/Ferrofluids#Structural_composition_and_configuration*

III. *Abou, B., Wesfreid, J., & Roux, S. (2000). The normal field instability in ferrofluids: Hexagon–square transition mechanism and wavenumber selection. Journal of Fluid Mechanics, 416, 217-237. doi:10.1017/S002211200000882X*

IV. *Latikka, M., Backholm, M., Timonen, J. V. I., & Ras, R. H. A. (2018, May 1). Wetting of ferrofluids: Phenomena and control. Current Opinion in Colloid & Interface Science. Retrieved October 8, 2022, from https://www.sciencedirect.com/science/article/pii/S1359029417301449*

Image Assessment Form
Flow Visualization
Spring 2013

Name(s) Isaac Martinez

Assignment: IV 2 Date: 10/10

Scale: +, ! = excellent √ = meets expectations; good. ~ = Ok, could be better. X = needs work. NA = not applicable

Art	Your assessment	Comments
Intent was realized	√	
Effective	√	
Impact	√	
Interesting	√	
Beautiful	√	
Dramatic	√	
Feel/texture	√	
No distracting elements	~	The smeared portion is not perfectly circular
Framing/cropping enhances image	√	Accomplishes "eye" aesthetics

Flow	Your assessment	Comments
Clearly illustrates phenomena	√	
Flow is understandable	√	
Physics revealed	√	Visible spikes & moving particles to center
Details visible	√	
Flow is reproducible	√	
Flow is controlled	~	
Creative flow or technique	√	I think the moving smear particles are unique
Publishable quality	√	

Photographic/video technique	Your assessment	Comments
Exposure: highlights detailed	√	
Exposure: shadows detailed	√	
Full contrast range	√	
Focus	√	Right in the center of the photo
Depth of field	√	
Time resolved	√	
Spatially resolved	√	After cropping, yes
Photoshop/ post-processing enhances intent	!	Creates eye aesthetic & performs color correction
Photoshop/ post-processing does not decrease important information	√	

Report		Your assessment	Comments
Collaborators acknowledged		✓	
Describes intent	Artistic	✓	
	Scientific	✓	
Describes fluid phenomena		✓	
Estimates appropriate scales	Reynolds number etc.	✓	
Calculation of time resolution etc.	How far did flow move during exposure?	✓	
References:	Web level	✓	
	Refereed journal level	!	Extensive research & graphics used
Clearly written		✓	
Information is organized		✓	
Good spelling and grammar		✓	
Professional language (publishable)		✓	
Provides information needed for reproducing flow	Fluid data, flow rates	✓	
	geometry	✓	
	timing	✓	
Provides information needed for reproducing vis technique	Method	✓	
	dilution	~	
	injection speed	✓	
	settings	✓	
lighting type	(strobe/tungsten, watts, number)	✓	
	light position, distance	✓	
Provides information for reproducing image	Camera type and model	✓	
	Camera-subject distance	✓	
	Field of view	✓	
	Focal length	✓	
	aperture	✓	
	shutter speed	✓	
	Frame rate, playback rate	✓	
	ISO setting	✓	
	# pixels (width X ht)	✓	
	Photoshop and post-processing techniques	✓	
	"before" Photoshop image	✓	