Normal-Field Instability in a Ferrofluid Covered with Small Droplets of India Ink

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Objective

The objective of the "Team First" assignment was to develop an idea for a flow visualization experiment, to collectively gather materials and design the experiment and then to photograph the results. The image should embody the essence of the art of flow visualization by striking a balance between revealing the physics of the flow and achieving an aesthetically appealing picture.

Background

Ferrofluids

Ferrofluids are a colloidal suspension of ferrite particles in a carrier fluid, frequently magnetite particles in oil. The solid particles are sufficiently small (on the order of 10nm or less) to be kept in suspension by thermal agitation i.e. Brownian motion [1, 2]. To keep the magnetite particles from clumping i.e. agglomerating a surfactant is added that counteracts the van der Waals forces that would otherwise draw particles together [2].

The ferrofluid used in this experiment was manufactured by Ferrotec and is designated EFH1. It is a suspension of magnetite particles in a light mineral oil (carrier fluid) with an oil soluble surfactant. The particles are iron oxide i.e. magnetite (Fe_3O_4) and have a 10nm nominal diameter. The proportions of these components by volume are 7.9% magnetite particles, 6-30% surfactant and 55-91% light oil [3,4]. At room temperature the ferrofluid is a black-brown liquid. Additional material properties for the ferrofluid can be found in Table 1.

Ferrofluid Type: EFH1	
Saturation Magnetization	44 mT
Viscosity @ 27°C	6 mPa.s
Nominal Particle Diameter	10 nm
Initial Magnetic Susceptibility	0.17 emu/g / Oe
Relative Magnetic Permeability @ 20 Oe	2.6
Density	1.21 X 103 kg/m3
Magnetic Particle Concentration	7.9% by volume
Surface Tension	29 mN/m

Table 1: Ferrofluid Material Properties [4]

Normal-field Instability

When a magnetic field is applied to a ferrofluid the suspended ferrite particles are subjected to a force which alters the shape of the free surface. Extremely small perturbations in the free surface change the distribution of ferrofluid and the magnetic field lines are focused where there are more ferromagnetic particles. The localized increase in the magnetic field draws more ferrofluid towards the points of higher magnetic flux creating small mounds of fluid, that in turn focus the magnetic field further. Spikes of ferrofluid develop at the fluid interface as this instability grows. This self-amplifying process is eventually counter-balanced by surface tension, which tends to flatten out the curves and points in the ferrofluid spikes, and gravity, which tends to drive the fluid to form a surface normal aligned with the gravity vector [1]. This interfacial instability is known as the normal-field instability. When a sufficiently large magnetic field is applied to a ferrofluid the interface at the free surface develops spikes organized in hexagonal patterns. If the magnetic field is increased further the fluid reaches a point where it becomes unstable and the spikes reorganize into square patterns due to a change in the relative energies for the two packing patterns [5]. When the magnetic field is removed the effects of surface tensions and gravity, which are no longer resisted by magnetic force, return the ferrofluid to its original state i.e. a pool of liquid.

Method

Experimental set-up

A large white plastic storage container lid was used as a surface for the ferrofluid to sit on because it was flat in the center and had a small lip around the edges to prevent the ferrofluid from flowing onto the floor. The lid was covered with a white shelf liner material to prevent the ferrofluid from staining the plastic. A stack of cylindrical ceramic magnets 31 mm in diameter and 19 mm tall was taped to the bottom of the lid. The magnets included a 9.5mm empty central hole. The ferrofluid was deposited onto the plastic lid above the location of the magnets using an irrigation syringe. The resulting mound of ferrofluid was 48 mm in diameter.

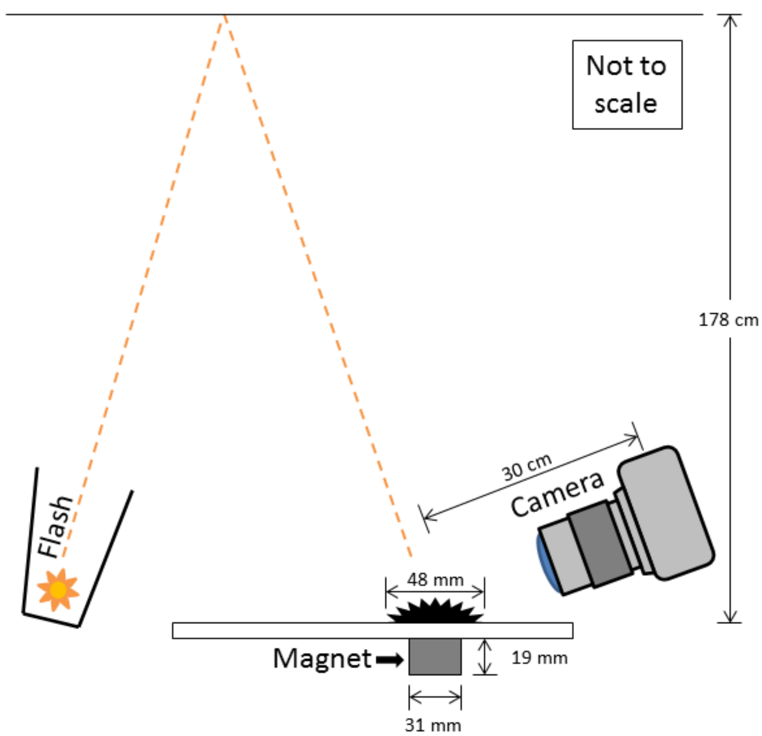

Figure 1: Experimental Set-up

The camera was mounted onto a tripod with the sensor plane roughly 30 cm from the center of the ferrofluid mound. A flash was mounted on a separate tripod that was placed on the opposite side of the lid and pointed upwards at the ceiling. A piece of fiber board with a glossy white finish was attached to the ceiling for the flash to bounce off of. Two 160 LED panel lights were set up on either side of the camera pointed at the subject and were used to manually focus the camera lens. While taking photographs the LED panel lights were turned off because they produced reflections on the mirror-like surface of the ferrofluid. Figure 1 provides a depiction of this experimental set-up.

Photo Settings

The photo was taken with a Canon 6D full frame camera and 24-70mm F2.8 lens. The lens was adjusted to a zoom of 57mm and an extension tube was attached because the subject was closer than the minimum focus distance. Lighting was provided by an off camera flash bounced light off of the ceiling. The camera was in aperture priority mode and the file was written to RAW format. Aperture was set to f/9 because that f-stop sits in the sharp range for the lens and provided enough depth of field for the scene. The ISO was set to 800 because some light is lost when the extension tube was added and the scene was not directly lit. The shutter speed of 1/160 seconds was computed by the camera to achieve a balanced exposure. Focus was set manually to get the ferrofluid peaks near the center of the disk in sharp focus. A summary of the photo settings with additional details can be found in Table 2.

Focal Length	57mm
Shutter Speed	1/160s
Aperture	f/9
ISO	800
Autofocus	On
White balance	Auto
Gamut	sRGB
Format	RAW
Pixels WxH	4180x2986

Table 2: Photo settings

Post processing

The original image was shot in Canon RAW format. A TIF file was written out using Canon's raw file post processor. The image was then edited in Photoshop Elements 5.0. The adjustments included cropping, adjusting lighting and contrast and increasing saturation. An unedited version of the original photo can be found in Appendix A for reference.

Results

The image produced in this experiment (Figure 2) displays the classic normal-field instability. An organized and symmetric pattern of spikes of ferrofluid can be seen across the free surface. These spikes serve as a way of visualizing the distribution and orientation of the magnetic field, which would otherwise be invisible, although, in the process the ferrofluid alters the field and is therefore not a passive visualization technique. Across the majority of the surface the spikes are organized into hexagon patterns. The two exceptions are the bottom edge of the pattern and the central axis spike. Along the bottom edge of the pattern some spikes do not have six adjacent spikes because the magnetic field has become too weak to produce the instability. At the central axis of the pattern the author hypothesizes that the hole in the permanent magnets below the fluid generates non-uniformity in the magnetic field that produces the heptagon pattern around the central spike.

Figure 2: Ferrofluid under the influence of a magnetic field and covered with droplets of India ink

The pattern of spikes in the ferrofluid separates the atomized droplets of the India ink preventing them from coalescing into a larger pool. The India ink sits in the troughs of the spike pattern due to gravity but stays on top of the ferrofluid because it is lower density than the ferrofluid. No mixing between the fluids occurred because the India ink is water based and the ferrofluid is oil based although some transfer of magnetite particles may have occurred between the two fluids. At the edge of the spike pattern the India ink did not slide down the side of the ferrofluid mound due to adhesion between the India ink and the ferrofluid. In a few spots on the side of the ferrofluid mound collections of India ink droplets highlight the presence of very subtle spikes that are otherwise difficult to see due to their minimal prominence.

Conclusions

The normal-field instability was successfully generated and photographed using ceramic magnets and a commercially available ferrofluid. The magnetic field was strong enough to produce spikes in the ferrofluid in hexagonal patterns. India ink was used to indicate the low spots in the spike pattern and also highlighted a few subtle spikes at the edge of the ferrofluid mound. The flow visualization and artistic intent of this experiment were therefore achieved.

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Literature Cited

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Appendix A: Unedited image