Flow Visualization
MCEN 5151

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Team Project 1

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Ferro fluid acted on by two attractive magnetic fields.

Figure 1, Example of a ferrofluid in a magnetic field above the critical magnetic strength.

Purpose: The main goal of the submitted movie was to capture interactions between the three main forces that act on a ferrofluid. These three forces are: gravity, surface tension, and magnetic attraction. Two magnetic fields were imposed on the fluid to see how the different forces balanced each other. One field was held constant both in position and in magnitude, while the other field decreased its strength and translated. This created a changing environment which allowed different segments of the fluid to be more affected by a different force. The effects were captured with a high-speed camera to give insight of the flow that could not be witnessed by the naked eye.

Flow Apparatus: The flow apparatus consisted of a white backdrop, two ceramic tiles, and several rare earth magnets. One tile was placed on the table with a magnet directly underneath it. Some Ferro fluid was poured on the tile and held there by the lower magnetic field. The second tile, with another magnet behind it, was held above the fluid. The distance between the tiles was reduced to allow some of the fluid to be captured by the above field. This created one magnetic field with two attractive concentration in field strength. Then the superior concentration of magnetic strength was moved side to side. The magnet was then displaced upward from the tile effectively reducing the magnetic field imposed on the fluid. The general geometry of the apparatus can be seen in figure 2.

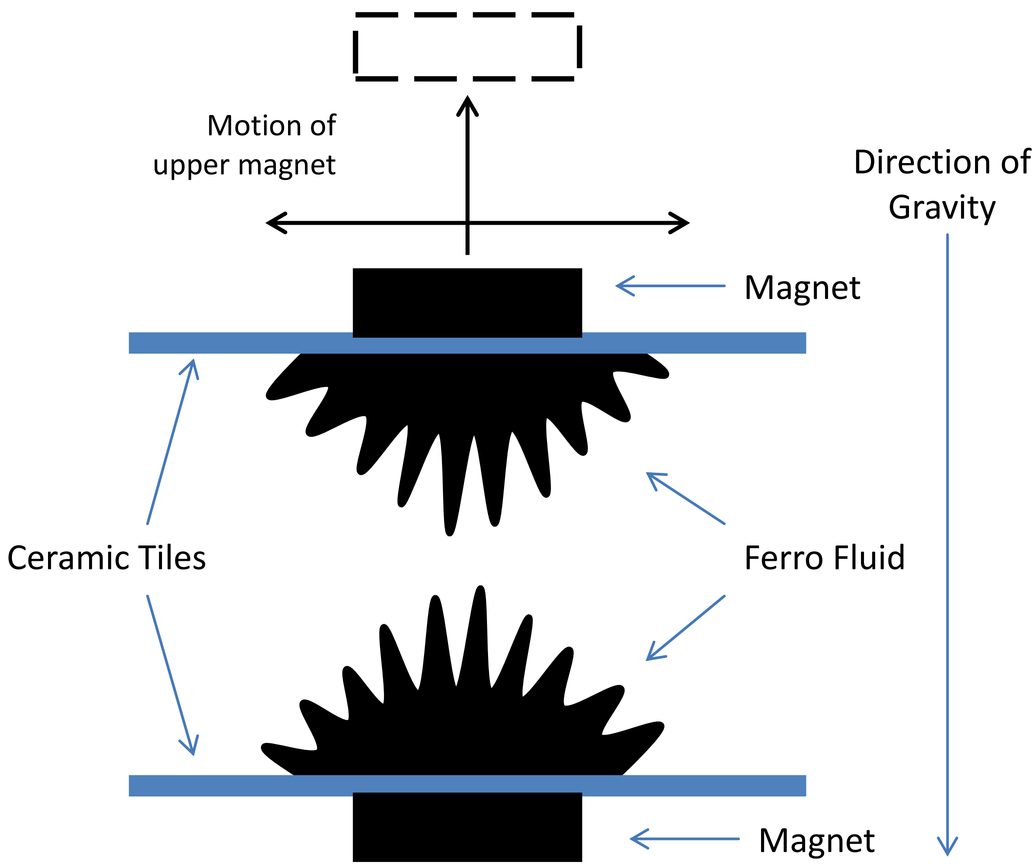

Figure 2, Geometry of the flow apparatus and possible motion of the upper magnet.
The displacement from the tile creates a weakened magnetic field concentration on the fluid.

Flow:

Background: Ferro fluid is a colloidal fluid composed of nano-sized ferro magnetic particles which are usually coated with some surfactant and suspended in a carrier fluid. The size and the surfactant allow the particles to be suspended by Brownian Motion and. [1] The magnetic attraction between the particles and the size of each particle is small enough to allow the van der Waals repulsion to dominate and prevents the particles from clumping and precipitating. [1]

The fluid used here is Ferrofuid Type EFH1. [2] 7.9% of the fluid volume is 10nm particles. [3] The carrier liquid is light mineral oil and composes 55-91% of the volume. [3] The exact surfactant type was not given but it encompasses 6-30% of the fluid volume. [2] This fluid is considered a proprietary item and therefore limited data was given as to its composition.

Patter Formation: The uniform spike pattern formation is a matter of the minimization of surface energy density. [4] It can be generalized by the energy density expression given by Gailitis which assumes an incompressible ferrofluid occupying the space below the surface of interest and three energy contributions: a gravitational force (hydrostatic energy), surface tension, and energy associated with the magnetic field. [4] With this Gailitis gives us the following equation: [4]

$$U(\xi) = \frac{1}{2}\rho g\langle \xi^2(x,y)\rangle + \sigma\langle\sqrt{1+\left(grad\xi(x,y)\right)^2}\rangle + \frac{1}{2\mu_0\mu}\langle\int_{-\infty}^{\infty} B^2(x,y,z)dz\rangle$$

The spikes concentrate the magnetic flux. [4] There is some critical value of strength of the magnetic field which causes the initial formation of spikes. This instability between a smooth surface to a spiked surface was analyzed by Cowley & Rosenweig in 1967 and called the Rosenweig Instability. The critical values for the onset of the instability a can be fround be finding the critical wave number k_{crit} and the H_{crit} [5,6] These parameters can be found with the following equations:

$$k_{crit} = \left(\frac{\rho g}{\gamma}\right)^{\frac{1}{2}}$$

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

This number can then be used to solve for a critical magnetic field strength. Above this critical field strength the spikes will continue to grow in length as the magnetic field strength increases. [4]A second instability was found that changed the spikes from hexagonal orientation to square patter. This is again the result of the minimizing the surface energy density. [5,6]

For the ferrofluid used, the above equations were can be solved for the critical wave number and the magnetic strength. Given the fluid properties of [3]: density $\rho = 1.21 * 10^3\,\frac{kg}{m^3}$, surface tension

$\gamma = 29 * 10^{-3} \frac{N}{m}$, magnetic permeability $\mu = 3.268 \frac{\mu H}{m}$, and constants: μ_0 is the vacuum permeability, and g acceleration due to gravity. The following values were calculated: $k_{crit} = 6.398 cm^{-1}$ corresponding to a critical wave length of $\lambda_{crit} = 0.98\ cm$ and $H_{crit} = 1.041 * 10^4 \frac{A}{m}$.

There is a simple relation to determine the strength of the magnetic field created by a magnet and a ferro fluid. The relation is:

$$H = \frac{\mu}{B}$$

Where μ is the ferrofluid's particle permeability and B is the remanence of the magnet. The remanence of the neodymium 40 magnet was found to be $B = 1.27\ T$ [7] Using that equation the actual field strength was approximated to be $H_{actual} = 3.451 * 10^5 \frac{A}{m}$. Becuase $H_{actual} > H_{crit}$ the formation of the spikes is expected.

Flow Observations: As seen below we have two separate concentration of magnetic field. One area is sitting on a horizontal tile, the other is hanging from a horizontal tile. This image progression shows the continuing tendency to balance all the three forces (weight, surface tension, and the magnetic force) as the above magnetic field is reduced slightly. The areas of interest are showing in figure 3 and circled.

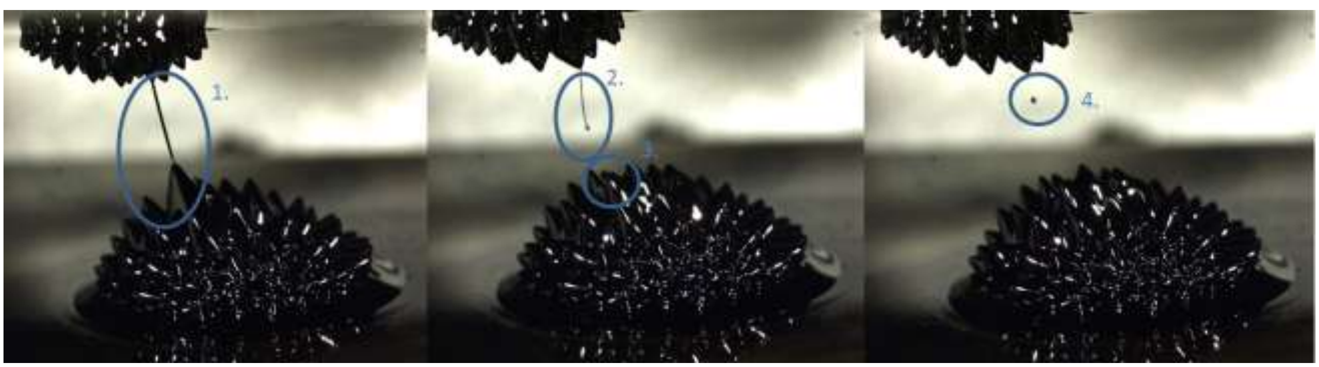

Figure 3, Transition of dominating forces while the upper magnetic field decreases.
1. The Surface tension dominates pinching the ligament.
2. The magnetic force dominates and pulls the ligament upwards.
Bottom of initial ligament is indistinguishable from other spikes. .3
4. While traveling upward surface tension dominates and forms a spherical droplet

Below is a qualitative analysis of the dominating forces acting on the ferrofluid in the sequence shown in figure 3.

1. As the upper magnetic field decreases the connecting ligament thins. Initially the ligament has an hourglass shape but notice at circle 1 there is apparent necking of the ligament. This is where gravity and the bottom magnetic field pulls the fluid in the ligament and surface tension then dominates and pinches the ligament. Ultimately it is surface tension that cuts the ligament.

2. After the ligament is separated from the bottom fluid the upper magnetic force begins to dominate pulling the ligament upwards. Surface tension is still at work forming a droplet at the bottom of the ligament.
3. At this point the bottom half of the initial ligament in the bottom accumulation of fluid has formed a spike and is indistinguishable for the other spikes seen in the bottom accumulation.
4. Halfway down the ligament separates from the upper fluid. Surface tension forms a droplet which continues upwards against gravity. While the other section of the ligament, which is no longer shown was force upwards by the magnetic field to the upper fluid.

All three of the phenomena shown is due to the minimization of surface energy density. Natures driving force and governing laws state that energy is always reduce as much as possible given the excitation. As seen it can cause some strange and interesting physical events.

Visualization Technique: This movie was filmed with the high speed Phantom v710 camera. Two lights illuminated the apparatus and reflected off the white back drop supplying ample light to the fluid. The camera was shot at 2000 frames per second. Each frame was captured after a 400µs exposure on a period of 500µs with a resolution of 1280x800 pixels.

Editing Process: The editing done to the movie was fairly simple. Cropping was done to focus the film on the ferrofluid alone. The film was made to be black and white. This drastically reduced the file size and because the fluid was black, the backdrop was white, and the tile was dark no information especially pertaining to the fluid was lost. An intro slide and ending slide was added to the movie to give it context. All of this was done with a free video editing program, VideoPad Video Editor.

Movie: The movie depicts the battle of balancing the three main forces acting on the ferrofluid. The event of the droplet flying up into the upper field was exactly what I was looking for when I started this project. The sequence in figure 3 chosen depicts that event well. It becomes apparent that the whole environment is always changing and nothing is static. I feel the video portrays that realistically. The high speed camera was well resolved both in focus and in time. I believe the high speed c amera gave light to events that could not have been witnessed otherwise. I do wish there were more video editing resources available to us. This would have allowed for a much better video. However despite this limiting fact the video turned out to very well.

Citations:

[1] A. Y. Zubarecv, L. Y. Iskakova, “Rheological properties of ferrofluids with microstructures,” Journal of physics: Condensed Matter, 18 (2006) S2771-S2784

[2] Material Safety Data Sheet. FerroTec. March 18, 2009 p.1

[3] Technical Data Sheet, Ferrofluid Type: EFH1. FerroTec. EFH1 092120

[4] S. Bohlius, H. Pleiner, & H. R. Grand, “Pattern formation in ferrogels: analysis of the Rosenweig instability using the energy method,” Journal of Physics: Condensed Matter 18 (2006) S2671-S26784

[5] B. Abou, J. Wesfreid,& S. Roux, “The normal field instability in ferrofluids: hexagon-square transition mechanism and wavenumber selection,” Journal of Fluid Mechanics 416 (2000) pp.217-237

[6] S. K. Malik, M. Singh, “Rosensweig Instability with Surface Adsorption,” Int. J. Engng Sci Vol 33 No. 4 (1995) pp 524-533

[7] “Magnetic Property of Neodymium magnet,” Armstrong Magnetics Inc. http://www.armsmag.com/neodymium.htm