IV2 – Ferrofluid Flows

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INTRODUCTION

The purpose of this report is to discuss the fluid physics and artistic techniques involved in an experiment with a magnetic fluid, or ferrofluid, which is an oil or water suspension of magnetic nanoparticles [1]. My team elected to explore the interesting characteristics of magnetic fluids for our second assignment and to strive to understand the physical mechanisms behind their behavior. I created an experiment with a large magnet attached to the shaft of a speed-control motor and observed how the rotating magnet created flow in a pool of ferrofluid above. The video I captured shows the ferrofluid swirling around in a vortex created by the rotating magnetic field produced by the magnet.

EXPERIMENTAL SETUP

Equipment used for the experiment consisted of an opaque plastic container filled with ferrofluid, a 1x2x4cm magnet, a 1/3 horsepower AC speed control motor with 0-1800 rpm range, a Sony Alpha a6300 with 16-50mm lens, and a video light panel with adjustable brightness and color temperature. To setup the experiment, I placed the AC motor on the table with the shaft oriented vertically. Then, I placed the magnet on the shaft horizontally to create a strong magnetic field upward through the ferrofluid. I filled the plastic container with approximately 10 mL of ferrofluid and held it about 1mm above the magnet. Next, I set up my tripod over the test setup so the camera could face directly downwards into the open plastic container and attached a light panel to the top of the camera to get sufficient light, discussed below, to capture the movement of the ferrofluid. A detailed depiction of the experimental setup is shown in Figure 1 of Appendix A. After setup was complete, I powered on the motor and began filming the ferrofluid. I varied the speed to observe the ferrofluid's behavior and found the most interesting visual effects to occur in the lower end of the range of motor speeds. I have no way to directly measure the motor speed, but I would estimate the speeds used for the final video to range from 50–150 rpm.

RESULTS AND ANALYSIS

To understand the flow phenomenon exemplified here, I had to take a closer look at the composition of ferrofluid to uncover some of its material properties. Ferrofluid is the colloidal suspension of ~10-micron magnetite particles. The viscosity of the fluid suspending the tiny particles combined with their constant motion keeps them from settling out, and the particles are coated with a surfactant to keep them from clumping together [1]. Normally, the magnetite in the ferrofluid would be permanently magnetic, but because of the scale of the particles in suspension, ferrofluid is considered paramagnetic, meaning it only behaves magnetically in the presence of a magnetic field, making it useful for some interesting applications, including sealing, damping, and medical imaging [1]. What is happening to the ferrofluid in my video? In the presence of a magnetic field, the ferrofluid becomes highly magnetized and moves to form the position with the lowest energy state, also known as the normal-field instability [2]. The spikes seen in the video are the result of the magnetite in the ferrofluid aligning with the magnetic field produced by the magnet, with gravity and surface tension limiting their height.

But the spikes do not form across the entire pool of ferrofluid. The normal field instability only occurs above the critical magnetization value, M_c, which can be expressed without dimensions as:

$$\frac{\mu_0 M_c^2}{\sqrt{g \Delta\rho_m \sigma}} = 2\left(1 + \frac{1}{r_p}\right) \tag{1}$$

where μ_0 represents the permeability of a vacuum, g the gravitational constant, $\Delta\rho_m$ the difference in densities of fluids across the ferrofluid-air interface, σ is the surface tension, and r_p is the dimensionless permeability ratio, described as

$$r_p = \sqrt{\frac{\mu_c \mu_t}{\mu_0}} \tag{2}$$

where μ_c and μ_t are the chord permeability and tangent permeability, respectively [2]. These equations apply to the ideal case with a uniform, vertical magnetic field, and they let us predict the boundary where the ferrofluid will form distinct peaks and where it will lie flat. We can also predict the distance between peaks, λ, as

$$\lambda = 2\pi \sqrt{\frac{\sigma}{g \rho_m}} \tag{3}$$

which is the capillary length between fluids, the scaling factor that relates gravity and surface tension [2]. Assuming the ferrofluid had a similar density and surface tension as canola oil [3], I calculated the capillary length to be approximately 1.6 mm, which is on the same order of magnitude as I would estimate the spacing of the peaks in my video. If my ferrofluid is actually made of something other than vegetable oil, its density and surface tension would likely yield a capillary length more accurate to the spacing I observed. Of course, I was rotating the magnetic field underneath the pool of ferrofluid, causing other flow effects I don't have the tools to evaluate analytically, but in general, I would wager my manipulation of the magnetic field isn't causing anything indescribable.

VISUALIZATION TECHNIQUES

Visualizing the motion of the ferrofluid is straightforward because of how opaque it is already. Dr. Hertzberg provided my team the ferrofluid, and I assume it to be an oil-based suspension. I do not know the concentration of the suspended magnetic particles, but we did not have to dilute it. To illuminate the setup, I used a Pixel G1s video light panel attached to the top of my camera. I set it to 3700 K and 100% brightness yielding the full power of the light.

PHOTOGRAPHIC TECHNIQUES

The camera setup was important to capture the flow. I used a Sony a6300 Mirrorless digital camera with a 16-50mm lens and set the video resolution to 1920x1080 px, which is retained in my edited video. The camera was placed approximately 1 foot above the ferrofluid and zoomed to 44 mm. I used an aperture of f/11 to keep all parts of the fluid in focus, and an

ISO of 400 to keep the image crisp as there was plenty of light. I recorded the ferrofluid at 30 fps which I retained in the final version. As far as video editing, I was happy with the appearance of the raw video and didn't have to do any cropping or image enhancements besides changing the playback speed.

REVELATIONS

Frankly, this video is better appreciated as an artistic endeavor rather than a scientific one. I can't claim this experiment has any real impact on my understanding of fluid physics or ferrofluid specifically, but I don't regret doing it. I think I fulfilled my intent by creating something beautiful with the ferrofluid and finally finding an opportunity to use the cool AC motor I was given more than a year ago, but I could improve upon the design. My choice to put the magnet on the tip of the motor shaft was not my original intention. At first, I had designed, and 3D printed a carrier for a set of eight small donut magnets distributed radially along the edge of a 5" diameter disc. The carrier pressed onto the shaft of the motor and was meant to create an interesting pattern in the ferrofluid as it rotated. The magnets weren't strong enough and the motor spun too fast to get the desired effect, but with more time I could redesign the carrier to try something else. Another idea would be to use an electromagnet to vary the strength of the magnetic field acting on the ferrofluid. These are things I hope to try in the future.

REFERENCES/BIBLIOGRAPY

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APPENDIX A: FIGURES

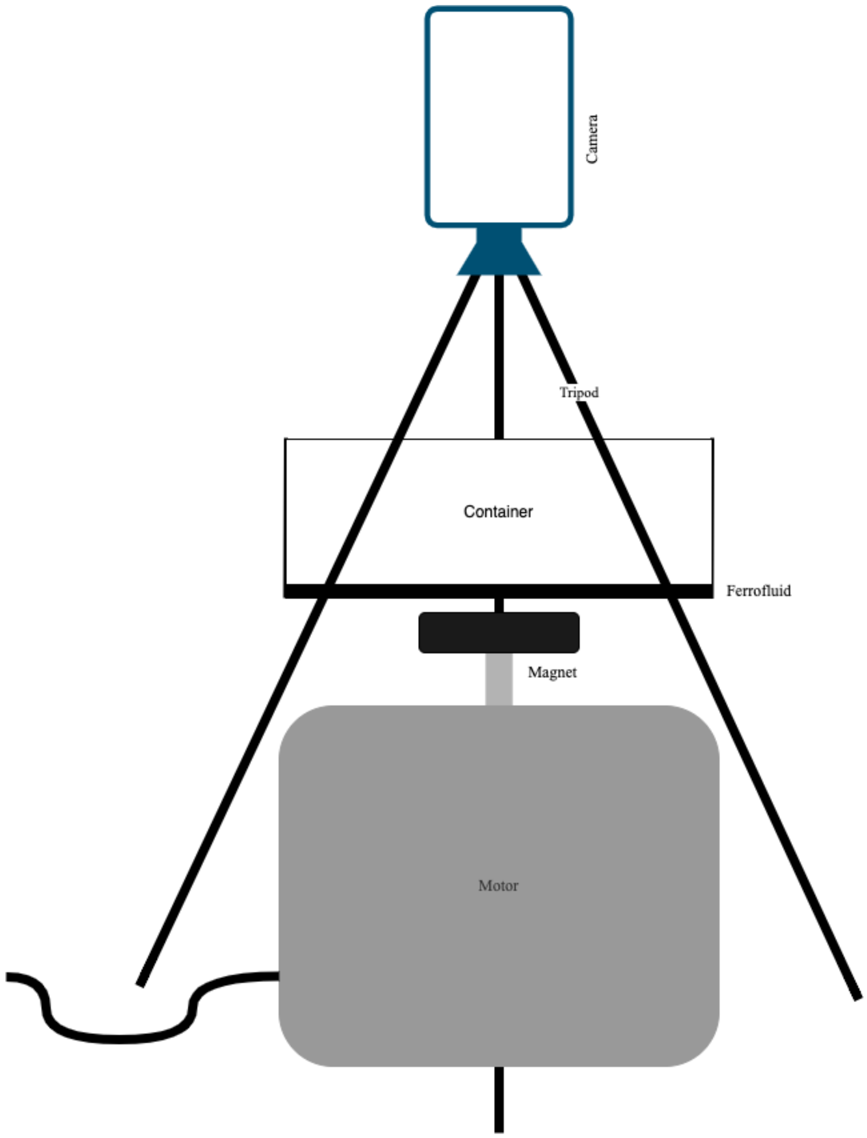

Figure 1: Experimental setup for ferrofluid flow capture.