Max Armstrong

Team Second Image Report

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Gravity Swirls – Ferrofluid Experiment

Supported by: Robert Giannella, Aaron Zetley,

Byron Pullutasig, Evan Blake, Professor Hertzberg

Figure 1: Screen capture from team second video

The above image is a screen capture from the team second video for the Flow Visualization course at University of Colorado at Boulder. The idea behind the video was simply to capture some of the unique behaviors of ferrofluid. The main phenomenon that was recorded was the interesting vorticity that results from the fluid being drawn towards the magnet against the force of gravity, and the momentum that it gains on the path to the magnet. Capturing this video wouldn't have been possible without the help of Robbie Guianella, who lent me his camera and skillfully moved the magnets to get this shot, and Byron Pullutasig and professor Hertzberg who provided ferrofluid for the experiment. This phenomenon wasn't what I had originally set out to record, but was something I had observed in the process of helping a teammate capture their video. If I had known that this phenomenon existed before my group and I started recording, I would have gotten a high speed camera, because even shooting at 240 fps was not sufficient to eliminate motion blur. Even so, I feel that the phenomenon that I captured is both beautiful and interesting.

Fluid Flow Calculations and Explanation

Figure 2 shows the relatively simple experimental setup for recording the behavior of the ferrofluid. The phenomenon consisted of the fluid starting in a pool on the bottom of a sideways laying graduated glass beaker. A sheet of white paper was placed behind the beaker, with the sun overhead. The paper was in place to block the view of the magnet behind the glass, as well as to provide a diffuse background. Behind the paper, was a magnet pulled from a stud finder, so it was a fairly strong and small magnet, which made moving the fluid easy.

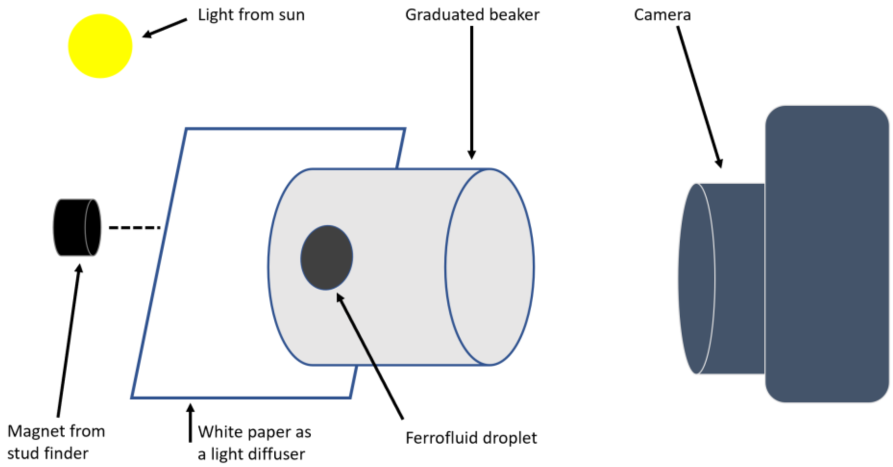

Figure 2: Diagram of experimental setup

The flow can be broken into 3 phases, all of which are explained by dominating forces and interactions. These phases are broken down and analyzed in terms of their dominant fluid interactions in the following sections. Because fluid properties of ferrofluid can vary depending on the presence of magnetism, ferrofluid properties have to be approximated as those of oil, which is used to suspend the iron nanoparticles:

Density: ρ $\left[{}^{kg}/_{m^3}\right]$	Dynamic Viscosity: μ $\left[{}^{kg}/_{m \cdot s}\right]$	Kinematic viscosity: ν $\left[{}^{m^2}/_{s}\right]$
888.1	0.8374	$9.429 \cdot 10^{-4}$

Table 1: Fluid mechanic properties of clean motor oil @ 20 ℃ (best approximation) [1]

Phase 1: Initial vertical flow

Figure 3: Flow phase 1, frame 0 left, frame 5 right

By comparing the fluid heights in the two frames shown above, we can determine the fluid velocity between the two frames. The heights are calculated by measuring the fluid height with respect to the 4” diameter graduated beaker.

$$\Delta H = H_5 - H_0 = 0.65\text{"} - 0.40\text{"} = 0.25\text{"}$$

$$\Delta t = 5\, frames \cdot \left(240\, \frac{frames}{s}\right)^{-1} = 0.021\, s$$

$$V = \frac{\Delta H}{T} = \frac{0.25\text{"}}{0.021s} \cdot \left(\frac{1\ m/s}{39.4\ in/s}\right) = 0.30\, \frac{m}{s}$$

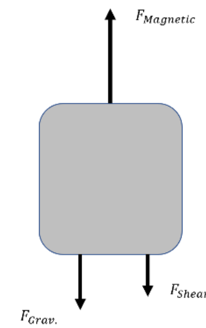

Figure 4: Fluid element free body diagram

Assuming a constant force and therefore constant acceleration on this body of fluid, we can calculate magnitude of the net forces acting on the ferrofluid:

$$V = \Delta t \cdot a \rightarrow a = \frac{0.30\, \frac{m}{s}}{0.021\, s} \rightarrow a_{Net} = 14.3\, \frac{m}{s^2}$$

Given that acceleration due to gravity is 9.81 $^m/_{s^2}$ and that net acceleration is nearly 1.5 times that of gravity, we can see that the force from the magnet is very strong. This magnetic force for a fluid element of 1 mL is calculated as follows:

$$v = 1\, mL = 1\ \cdot 10^{-6}\, m^3 \rightarrow m = v \cdot \rho = 1\ \cdot 10^{-6}\, m^3\ \cdot 888.1\ {}^{kg}/_{m^3} \ \rightarrow\ m = 8.881\ \cdot 10^{-4}\, kg$$

$$F_{Net} = m\ \cdot a_{Net}\ \rightarrow\ F_{Net} =\ 8.881\ \cdot 10^{-4}\, kg\ \cdot\ 14.3\, \frac{m}{s^2}\ \rightarrow F_{Net} = 0.013\, N$$

Now we can find the gravitational force:

$$F_{Grav} = -9.81 \frac{m}{s^2}\ \cdot\ 8.881\ \cdot 10^{-4}\, kg\ \rightarrow\ F_{Grav} = -0.0087\, N$$

Next, we can look at the Reynolds number to determine if the flow is laminar or turbulent, to help us determine whether surface roughness or shear stresses are dominating forces.

$$d:\ v = \frac{4}{3}\pi r^3\ \rightarrow r = \sqrt[3]{{}^3/_{4\,\pi}\ v}\ \rightarrow d = 2\ \cdot\ \sqrt[3]{{}^3/_{4\,\pi}\ \cdot 10^{-6}\, m^3}\ \rightarrow d = 0.01\, m$$

$$Re = \frac{\rho\, V\, d}{\mu}\ \rightarrow\ Re = \frac{888.1\ {}^{kg}/_{m^3} \cdot\ 0.30\, \frac{m}{s}\ \cdot\ 0.01\, m}{0.8374\ {}^{kg}/_{m\,\cdot\, s}} \rightarrow Re = 3.182$$

From here we can tell that the flow is well within the laminar flow regime. Next is to calculate the effects of shear stress. Shear stress is simply approximated by:

$$\tau = \mu\, \frac{d\gamma}{dt}$$

Where $d\gamma$ is the velocity in our upwards direction.

$$\tau = -\left(0.8374\, {}^{kg}/_{m\,\cdot\, s}\right)\ (0.30\ {}^{m}/_{s})\ \rightarrow\ \tau = -0.251\ {}^{N}/_{m^2}$$

Finally, we can calculate the magnetic force on this fluid element by comparing it to the net force:

$$F_{Net} = F_{Grav.} + F_{Mag.} + \tau \cdot v$$

$$F_{Mag.} = F_{Net} - F_{Grav.} - \tau$$

$$F_{Mag.} = 0.013\,N - (-0.0087\,N) - (-0.251\,N/m^2) \cdot (\pi\,(0.005\,m)^2)$$

$$F_{Mag.} = 0.0217\,N$$

This force may seem small, but it is actually sizeable when we consider that it is acting only on a small fluid element. This explains the rapid acceleration of the body of fluid as a whole. Additionally, it helps explain the difficulty that I had capturing the motion of the fluid.

Phase 2: Upper limit of flow

Now we can look at the upper limit of the flow and the relationship that this has with the momentum of the fluid.

$$\sum \vec{F} = \frac{d}{dt} \int_{CV} \rho \vec{V}\, dV + \int_{CS} \rho \vec{V} (\vec{V} \cdot \vec{n}) dA$$

The equation says that: the sum of external forces acting on a control volume is equal to the rate of change of linear momentum within the control volume plus the net flow of momentum leaving the control surface. [1]

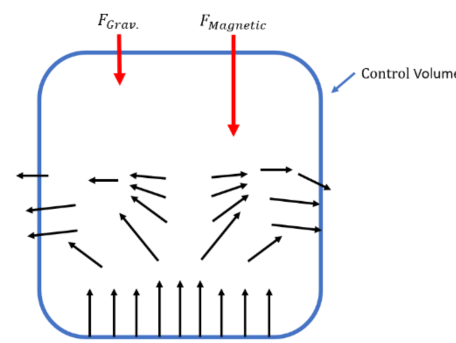

Figure 5: Control volume at top of flow

The implications of this equation are that the momentum in the vertical direction is what carries the fluid up through the control volume until it loses sufficient momentum to continue moving further upwards (because of the forces acting in the downward direction). Because there is still fluid travelling vertically below this now momentum-less fluid, it is now forced out of the way, so it gains horizontal momentum. Another implication of this equation is that because there are no forces acting in the horizontal direction, the fluid must maintain equilibrium of momentum when leaving the control volume. This means that the fluid cannot leave the volume with uneven momentum, which explains the equal motion to either direction. This equal side to side motion, coupled with the centripetal force of the magnet at the center of the flow is what causes the formation of the vortexes seen in the video. These vortices are the main phenomenon that I set out to capture.

Phase 3: Stationary

This is the point where the fluid has stopped its rotation about the magnet, and is instead held stationary by the magnet. The fluid then shows the spikes and troughs typical of the 'normal field instability' [3] seen with ferrofluids in magnetic fields. This instability can be seen in figure 5. The stopping of the fluid motion is explained mainly by the significant shear stress that each small element of fluid experiences due to the thin fluid thicknesses and the no slip condition against the glass.


Figure 6: Normal Field Instability

Photography Techniques

The flow was visualized by recording the specular reflection off of the ferrofluid. Because the fluid has a very high specular reflectivity, and dark color, it is difficult to photograph in many lightings. For this reason, it is important to have a diffuse lighting source, because a spotlight would be reflected off of the body of the fluid, over-exposing the reflecting area and leaving the rest of the flow obscured. In the video, approximately 20 mL of fluid was placed in a cleaned glass beaker. The background was provided by a thick sheet of white butcher paper folded in half to help obscure the hand moving the magnet.

The field of view in the video contains the 4" diameter beaker and the fluid contained inside. The camera was Robbie's Google Pixel 3 set to record in 'super slow' motion. I had initially been using a Nikon D3300 to record the phenomenon, but the focus was difficult to maintain with a small subject relatively close to the lens. On top of that, the Nikon camera could not shoot at a high enough framerates to capture the effect. The camera was held 2" from the top lip of the beaker, making the distance from subject to camera approximately 7". Because the frame rate was at 240 fps, the quality of the video was slightly lowered, and was therefore shot at 720 x 1280 px. Because the video was shot on automatic settings, the exposure statistics were dynamic and changed throughout the filming. The final video was edited in Filmora 9 and involved the following: cropping to enhance the focus of the video on the fluid itself, slightly increasing brightness, and slowing the footage down to 40% of the already slowed speed. Because the original footage was recorded at 240 fps and played at 30 fps and then further reduced to 40, every second of the final video is 1/20th of a second in real time.

Wrapping Up

To me, this video hints at some really interesting fluid physics and reveals the complexity of the behavior of ferrofluids when they are being acted upon by magnetic fields. I really like the way that the video turned out, but would have liked to see the fluid motion slowed down even further. The motion of the fluid was so fast, that it made capturing the phenomenon very difficult. I fulfilled the intent that I went into this project with and think that playing with ferro fluid is a really interesting subject of a photography project. To potentially develop this idea further, I could use a more diffuse light source and shoot the video inside with more light.

References

[1] Çengel, Yunus A.; Cimbala, John M.; Fluid Mechanics: Fundamentals And Applications, Third Edition; *McGraw Hill* 2014 ISBN 978-0-07-338032-2

[2] Pierno, Matteo; Mistura, Giampaolo; Talbot, Delphine; Massart, René; Bacri, Jean-Claude; Abou-Hassan, Ali Static; Magnetowetting of Ferrofluid Drops; *Langmuir* 2016, 32, 30, 7639-7646 Publication Date: July 6, 2016 https://doi-org.colorado.idm.oclc.org/10.1021/acs.langmuir.6b01934

[3] 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