Ferrofluid Flows

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Introduction

The purpose of this paper is to document and describe the experimental process that was followed to produce a flow visualization photo that was captured as a requirement for the first team assignment of MCEN 5151 - Flow Visualization called Team First. The original post can be found at http://www.flowvis.org/2019/09/17/matt-knickerbocker-2/. The task of the assignment was to capture a photo of fluids that both (1) clearly demonstrate the phenomenon being observed and (2) is a good photo. The intent of the photo for this assignment was to observe the interaction of magnetic forces and a ferrofluid that was seeded with ink. The collaboration done to produce the photo included Faisal Alsumairi, Blake Chin, Robert Drevno, and Abhishek Kumar who are all members of group 5. Robert provided the containers that held the experiment and Dr. Hertzberg provided the ferrofluid.

Flow Description

The apparatus used in this flow experiment involved a magnetic ferrofluid, a household magnet, a glass container, and several colors of India ink. A Canon EOS T7 Rebel DSLR camera was held by hand to capture the photo as shown in the experimental setup below (Figure 1). The glass container was filled with ferrofluid and several different colors of ink were dropped into the fluid. Simultaneously, the magnet was held to the bottom of the container such that the magnetic forces acted on the fluid, causing it to deform with the magnetic field. The magnet was then moved away from the container until the force appeared to dissipate. This motion was repeated several times which caused the ferrofluid and the ink to mix and flow together.

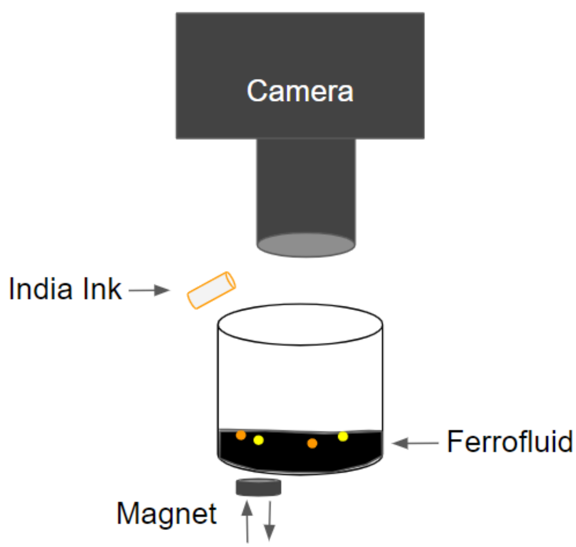

Figure 1: Experimental Setup.

After the mixing of several colors had occurred, the container was left sitting on top of the magnet when the photo of this assignment was captured. Due to this, there were small motions in the ink to the left of the magnet, but the fluid was largely at rest. The main phenomenon being observed is known as the normal-field instability which occurs when a ferrofluid is subject to a strong magnetic field. In the photo, this can be seen in the dark circular region on the right side of the fluid where there are peaks of ferrofluid protruding from the surface. The green and white ink visible around the peaks is filling the valleys between the spikes. The glass container and the magnet had diameters of roughly 4 inches and 1 inch, respectively. Since the magnetic field diameter roughly matches that of the magnet diameter, the resulting impact on the fluid is of the same scale. Since the fluid was mainly static, a Reynolds number and other flow parameters cannot be estimated. The image is however, the result of several magnet motions over time which occurred at an average of one cycle per second.

As stated above, the fluid flow is a result of the normal-field instability since the ferrofluid is composed of nanoscale ferromagnetic particles. The ferrofluid is acted upon by the magnetic field of the external magnet which pulls the fluid in the direction of the field lines, causing the visible peaks. The fluid rides along the direction of the field lines until the magnetic force is balanced by gravity and surface tension, setting the height of the peaks. This follows from the idea that the fluid is changing shape in order to minimize the total energy of the system [1]. Another explanation is that the "magnetic field induces a magnetic dipole moment in each droplet. When the dipole-dipole interaction energy exceeds the thermal energy, a phase transition occurs as the fluid of randomly dispersed droplets changes to a solid of nearly equally sized and spaced columns" (Liu et al., 1995, p.1) [2]. An interesting note is that since the ferrofluid used in this experiment does not remain magnetized (visible spikes) after the magnet is moved away such that the external field is no longer present, the proper term would be superparamagnetic rather than ferromagnetic [3].

Flow Visualization Technique

As mentioned above, the flow visualization technique used in this experiment was ferrofluid seeded with ink being acted on by magnetic forces. Due to the nanoscale ferromagnetic particles in the fluid, a magnetic field can be visualized with the fluid. The spikes seen in the fluid are due to the normal-field instability where the magnetic field is concentrated which causes the fluid to deform. Adding the ink provided contrasting colors to this effect which enhanced the visibility and the art aesthetic. Additionally, the ink provided a visualization of the mixing that occurred over time between the different ink colors and the ferrofluid. The specific colors added for my photo were green, yellow, orange, and white. Roughly 3 ounces of ferrofluid was used and 5 to 10 drops of each color were added. The ferrofluid was borrowed from Dr. Hertzberg, the magnets were generic and were purchased from Amazon, and the India inks were Dr. Ph. Martens and also purchased from Amazon. In an effort to enhance the visibility of the flow, the built-in flash on the camera was used.

Photographic Technique

The camera used to produce the photo was a hand-held Canon EOS T7 Rebel DSLR. The photo was shot with a resolution of 6012 x 4008 pixels at a lens zoom of 55 mm. The field of view was roughly 4 inches by 4 inches with the camera lens positioned about 12 inches from the ferrofluid. The lens used was a Canon 18-55 mm zoom lens with an aperture range of 1:3.5-5.6. The exposure was produced using an aperture value of f/5.6, an ISO of 1600, and a shutter speed of 1/200 of a second.

Minimal post-processing of the photo was performed, and screenshots of the original and final photo can be seen below in Figures 2 and 3, respectively. The photo was slightly cropped (5216 x 3672) and the white balance along with the contrast were slightly adjusted in order to lighten the background and enhance the appearance of the ink colors. Additionally, a small glare towards the upper left corner of the fluid was modified to be less distracting. All of these edits were performed through the use of the GNU Image Manipulation Program (GIMP).

Figure 2: Original Photo.

Figure 3: Final Photo.

Conclusion

The photo produced in this experiment reveals the nature of magnetic fields and fluid mixing. The physics of the magnetic forces acting on the ferrofluid is clearly shown with the visible spikes and valleys in the image. The different ink colors highlight the fluid motions and interactions over time in an elegant manner. I personally enjoy the range of contrasting colors in addition to the visible magnetic spikes protruding from the surface of the fluid. I find the image to be aesthetically pleasing in the way that I'm reminded of cream mixing in coffee, an alien eyeball, or perhaps the chaotic and stormy surface of Jupiter. I certainly fulfilled my intent with this photo and am very happy with the result however, I think it would be interesting to experiment further with multiple magnets, different colors, and different points of view.

References

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