Measurement of Ferrofluid Dynamics in Undergraduate Physics Laboratory

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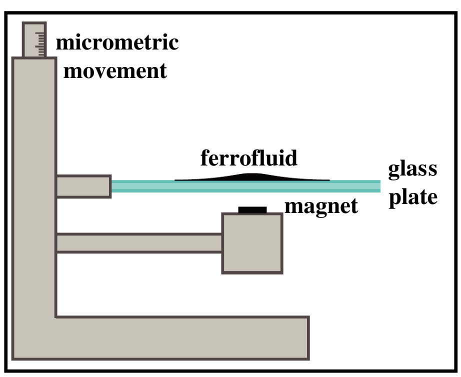
Abstract— We present an activity performed in the second-year Physics Laboratory of the undergraduate course in Physics at the University of Insubria (Como, Italy). The work is focused on the characterization of a ferrofluid sample in an external magnetic field. The didactic approach to the experiment was to leave the students free to choose the experimental procedure and the measurements to perform. The measurements were performed by taking pictures of the structures at the different distances. The images were processed to extract the dimensions and shape of the structures, which were fitted with some models for the shape of the peaks.

1. INTRODUCTION

Ferrofluids are suspensions of small-sized ferromagnetic particles (10 nm) in a non-magnetic liquid (oil or water). Beside their many relevant applications, ferrofluids are interesting for didactics because they display peculiar behaviors in the presence of an external magnetic field, such as instabilities which produce new structures on the surface of the fluid [1]. Due to the dipole-dipole interaction between the ferromagnetic nanoparticles, aggregates can be formed, so that the ferrofluids can exhibit magnetization effects, including hysteresis [2].

In the second-year Physics Laboratory of the undergraduate course in Physics at the University of Insubria (Como, Italy), we characterized a ferrofluid sample in an external magnetic field. The didactic approach to the experiment was to leave the students free to choose the experimental procedure and the measurements to perform. Two groups of students were involved in the work in two different Academic Years. Both groups decided to measure the dynamics of birth and growth of the first structure developing from a layer of ferrofluid lying on a flat surface as a function of the distance between a neodymium magnet and the fluid surface. The measurements were performed by taking pictures of the structures at the different distances. The images were processed to extract the dimensions and shape of the structures, which were fitted to different mathematical models for the shape of the peaks.



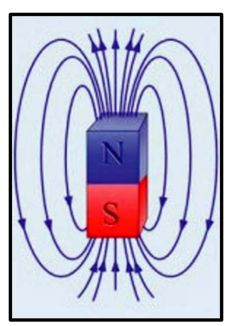


Figure 1: Sketch of the experimental setup to measure the ferrofluid dynamics. Diagram of the field lines generated by a permanent magnet.

2. EXPERIMENTAL SETUP

Ferrofluids are a complex system in which both the properties of the fluid and the magnetic properties of the particles in the suspension must be taken into account in the description of the sample behavior. The behavior of a ferrofluid in a magnetic field depends on its weight, surface tension and viscosity. Moreover, depending on the value of the applied magnetic field, peak structures appear on the surface of the fluid. The peaks arrange along the lines of the magnetic field when the field overcomes the stabilizing effects caused by the weight and surface tension of ferrofluids. As the sample to be investigated, we used a commercial ferrofluid material [3], made of Magnetite (Fe_3O_4, 3%–15% in volume), surfactant oil (6%–30% in volume) and water (55%–91% in volume). Unfortunately the exact composition of the fluid was unknown.

The experimental setup was quite simple (see Fig. 1): some drops of ferrofluid are located on a flat glass surface. Below the plate, a Neodymium magnet is fixed to a movable post. The magnet can be moved in micrometric steps towards the plate. When the distance from the plate is sufficiently large, the ferrofluid surface remains unaffected, but as the distance shortens, a peak emerges quite suddenly and further peaks emerge when getting closer till the entire surface of the liquid is organized in peaks (about 20 peaks were observed). As apparent from the pictures in Fig. 2, the peaks emerge on the top of the profile of the unperturbed fluid.

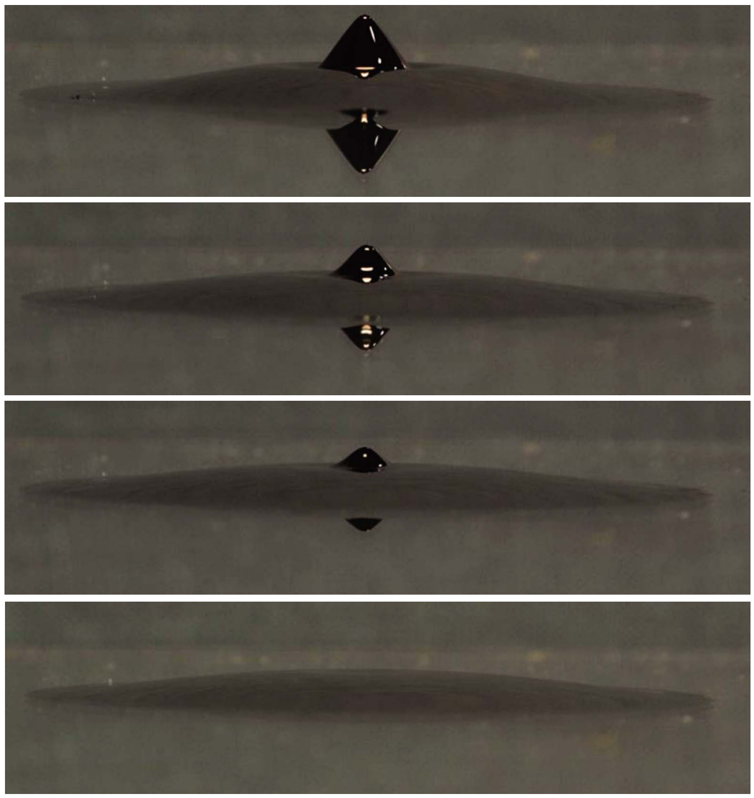


Figure 2: Sequence of pictures of the profile of the ferrofluid surface at different distances of the magnet from the glass plate. Note that the lower peaks are reflections by the surface of the glass plate.

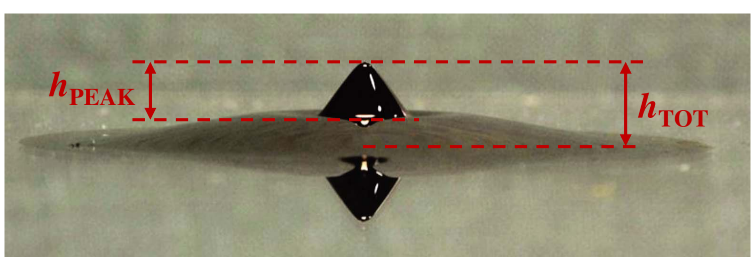


Figure 3: Scheme of the analysis of the pictures.

To observe the birth and the growth of the structures, we used a camera to take pictures of the surface profile at subsequent steps of the micrometric movement. We focused on the interval in which only one peak was present and we made measurements for two different values of the ferrofluid volume (1.5 ml and 4 ml). To obtain images useful for the analysis, we took pictures with a a uniform contrasting background (see Fig. 2). The analysis of the images was performed with Matlab® to recover the total heights of the peaks, h_{TOT}, and that of the part emerging from the underlying structure, h_{PEAK}, as a function of the distance of the magnet from the plate (see Fig. 3).

3. RESULTS

The pictures were elaborated in Matlab®, to obtain the profile of a sharpened image. In Fig. 4 we plot the measurement of the maximum value, the total height, of the peaks for two different volumes of fluid, as a function of the distance of the magnet from the glass plate. The data in Fig. 4 are plotted in different colors to underline the recording procedure: red and blue dots represent the data taken when the magnet approaches the plate (growing peak), while black and green dots are the data taken when the magnet moves away (decreasing peak). We point out the presence of hysteresis in the behavior since the peak persists for larger distances (lower values of the magnetic field), beyond the initial values. The behavior is expected from the formation of magnetic aggregates in the fluid [2].

To determine the value of the peak at the top of the structure, we implemented a fitting procedure based on the assumption that the surface profile could be reproduced by a sum of two gaussian

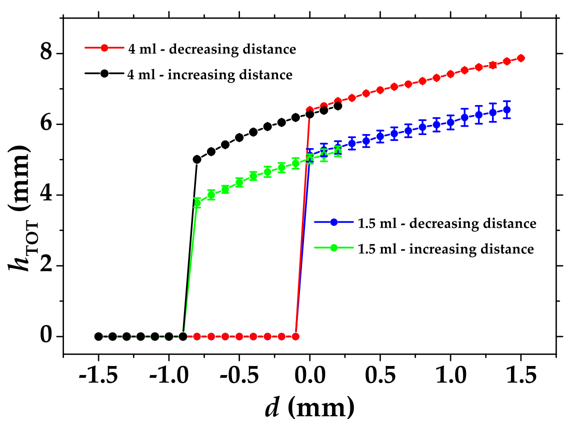


Figure 4: Total height of the fluid as a function of the distance of the magnet from the plate. The abscissa, d, is set to zero at the distance at which the first peak emerges when the magnet approaches the plate.

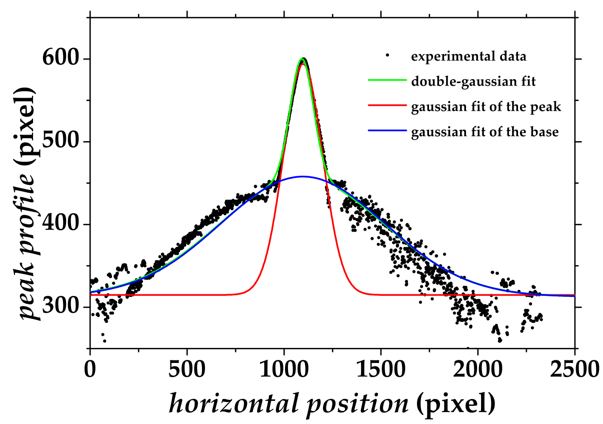


Figure 5: Experimental profile of the ferrofluid surface in the presence of an external magnetici field (black dots) and plot the double-gaussian fit (green line). Red and blue line are the calculated gaussian functions interpolating the peak and the base,respectively.

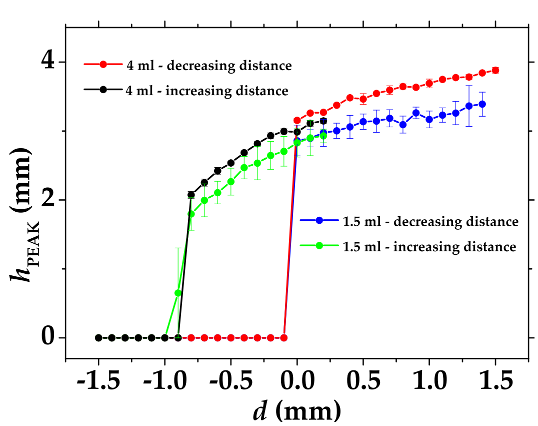


Figure 6: Height of the fluid as a function of the distance of the magnet from the plate.

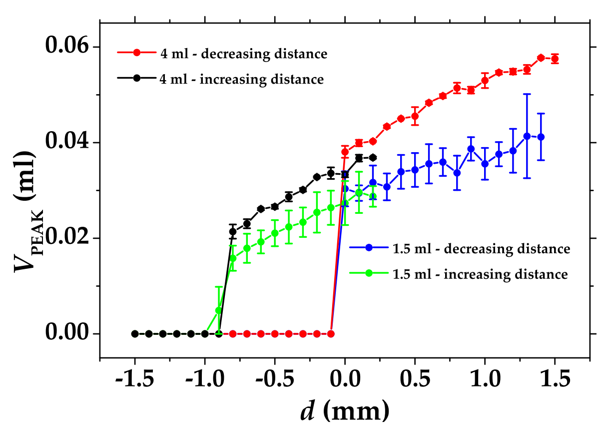


Figure 7: Volume of the fluid as a function of the distance of the magnet from the plate.

functions

$$f(x) = A_{\text{PEAK}} \exp\left[-\frac{(x-x_0)^2}{2\sigma_{\text{PEAK}}^2}\right] + (A_{\text{TOT}} - A_{\text{PEAK}}) \exp\left[-\frac{(x-x_0')^2}{2\sigma_{\text{BASE}}^2}\right] + K. \tag{1}$$

The results of the fitting procedure are displayed in Fig. 5, where, together with the experimental data (black dots), we plot the overall fit according to Eq. (1) (green line) and the two calculated gaussian functions interpolating the peak and the base (red and blue line, respectively). From the fit, we can easily extract the value of the peak height and perform an estimation of the peak volume.

In Fig. 6 we display the values of A_{PEAK} evaluated from the fit, showing, as expected, a behavior very similar to that of the overall height in Fig. 4. Finally, in Fig. 7, we plot the estimated volume of the peak, evaluated by assuming a 3D gaussian shape. We note a dynamics very similar to that of the peak.

4. CONCLUSION

The implemented experimental procedure was effective to extract physical information from the pictures and the obtained data seem to be good enough to be compared to some theoretical model. A full theoretical analysis of the behavior of a ferrofluid is extremely complicated and goes beyond the scope of an undergraduate laboratory and, unfortunately, no simple model exist for the complex dynamics of the fluid [4, 5]. For this reason, the students focused their attention on the most evident features displayed by the fluid surface, namely the single peak. Other features, such as the number of the generated peaks and the dependence of the evolution on the ferrofluid volume, were also investigated but not reported here.

The next step will be a more quantitative approach to try to model the experimental data and new experimental observations [6].

ACKNOWLEDGMENT

M. B. acknowledges Andrea "Pinci" Caldiroli for helping with the data.

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