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WAVES FORMATION IN CAPILLARY VOLUMES OF MAGNETIC FLUID

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A.Ya. Simonovskii[1,2,*], N.A. Shatalov[1,3], P.A. Assorov[1], A.R. Zakinyan[1]

[1]North-Caucasus Federal University, Stavropol, Russia
[2]Stavropol State Agrarian University, Stavropol, Russia
[3]Stavropol College of Communications named after V.A. Petrov, Stavropol, Russia

Abstract:
This paper presents experimental studies of the influence of an alternating magnetic field on the separation of magnetic liquid droplets from a capillary hole. The formation of waves on the surface of capillary volumes of a magnetic fluid flowing out of a capillary hole in a horizontal non-magnetic plate under the action of gravity in external alternating magnetic field is detected. Spherical, dumbbell-shaped, jet-shaped, and comb-shaped droplet geometries were observed. It is established that the shape of the waves formed could vary from waves running and standing on the surface of a growing drop to bending oscillations of a vertical fluid jet. The magnetic field parameters at which different instability patterns are observed were determined.

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Magnetic fluid, Droplets separation, Jets, Surface waves, Instability

1. INTRODUCTION

In modern literature the manifestations of several different capillary, hydrostatic, electro- and magnetostatic instabilities that take place at the interface of magnetic colloid (magnetic fluid) with other media under the influence of external force fields are known and intensively studied [1-9]. In the development of physics of magnetic colloids, much attention is traditionally paid to the problems of equilibrium shapes of their limited volumes determined by the action of magnetic interaction forces and surface tension. In recent years, a large number of works have appeared that investigate the behavior of individual droplets and microdroplets of magnetic colloids subjected to the action of constant and rotating magnetic fields [10-15]. Attempts have been made to study various equilibrium shapes and nonequilibrium states of such droplets. It should be noted that when studying the instability and shape dynamics of layers and droplets of magnetic fluids, the layers and droplets bounded from below by some substrates are usually considered.

The application of magnetic colloids in microfluidic devices (so-called "micro-magnetofluidic" devices), which has been formed in recent years, has opened new prospects for such research. Such developments at the intersection of electromagnetism and fluid dynamics have made it possible to achieve a significant improvement and expansion of functionality of microfluidic technologies and devices based on them. In the last few years, several devices (medical, analytical, chemical-technological, etc.) have been proposed in which magnetic colloids act as detectors, manipulators, actuators, sensors, etc. [16-18]. However, it should be noted that these studies are currently only at the initial stage, and having already demonstrated their great potential to the scientific community, they have raised several new scientific problems of fundamental character, the solution of which is necessary for further development of the mentioned branches of knowledge and technology. Thus, one of the problems in this field is controlling the shape and motion of finite volumes of magnetic colloid by means of external force fields [19-21].

*CONTACT: A.Ya. Simonovskii, e-mail: simonovchkij@mail.ru

In the context of the stated problems, it is important to study formation of droplets and jets when magnetic fluid flows out of capillary hole. In particular, the effect of a stationary magnetic field on the volume and shape of detached droplets, as well as on the length of a continuous section of the jet at different flow rates was studied [22-26]. In contrast to previous studies, this paper considers the process of flow of magnetic fluid from a capillary outlet hole under the influence of an external alternating magnetic field. The difference of this work from previous studies is also the consideration of the shape dynamics and instability of droplets of magnetic fluids, for which the bounding surface is located on top.

2. MATERIALS AND METHODS

In our experiments, we used a magnetic fluid representing magnetite particles with a mean diameter of 10 nm dispersed in kerosene with oleic acid as a stabilizer. The density of the magnetic fluid was 1400 kg/m^3; its saturation magnetization 55.4 kA/m; initial magnetic sucseptibility was 3. The surface tension coefficient at the fluid–air interface was 0.028 N/m. Experiments were conducted at room temperature (23°C).

A drop of magnetic fluid flowed out of a capillary hole on the surface of a horizontal non-magnetic plate hanging in the air and located in a uniform external magnetic field created by Helmholtz coils. The alternating magnetic field in the Helmholtz coils was provided by an alternating current generator. The magnetic field varied widely in frequency and intensity. The scheme of the setup for monitoring the behavior of a drop of magnetic fluid hanging on a horizontal non-magnetic plate in a magnetic field is shown in Fig. 1.

The pressure and flow rate of the fluid from the reservoir were monitored using a syringe connected to an automated pressure device. Recording of drop geometry for the purpose of subsequent processing was carried out using a digital video camera.

3. EXPERIMENTAL RESULTS

As a result of the observations, it was found that the capillary volume of a magnetic fluid hanging and simultaneously growing on a horizontal surface having a size significantly larger than the size of a hanging drop, significantly changes its geometric characteristics depending on the direction, magnitude and frequency of the applied magnetic field. A drop of magnetic fluid, without the magnetic field action, had an axisymmetric shape with a vertical axis of symmetry. At a certain magnitude of the horizontal magnetic field (H_{max}>3 kA/m), the neck of the drop increased significantly, and the drop itself significantly elongated in the direction of the applied magnetic field and oscillated with various frequencies and amplitudes. With a further increase in the field (H_{max}>6 kA/m), the drop, without the formation of a neck, spread along the solid surface. At the same time, traveling waves of various amplitudes and frequencies appeared on the surface of the droplet. These traveling waves, as a result of reflection from the boundary of a droplet conjugated with a solid surface, subsequently formed standing waves with a certain distribution of amplitudes and wavelengths, which will be demonstrated further.

The change in the frequency and intensity of the magnetic field led to a change in the characteristics of both traveling and standing waves. In addition to these phenomena, with an increase in the field strength, the character of growth, the shape and duration of the droplet outflow from the hole changed significantly.

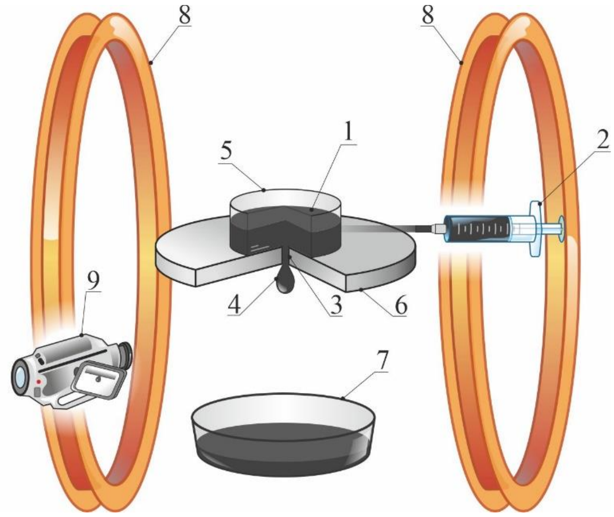


Fig. 1. The scheme of the experimental setup: 1 – magnetic fluid; 2 – syringe with a magnetic fluid; 3 – a hole with a diameter of d = 1 mm; 4 – a drop of magnetic fluid; 5 – a cylindrical plastic container; 6 – a copper disk; 7 – a container for collecting magnetic fluid; 8 – Helmholtz coils; 8 – a high-speed video camera

Fig. 2 shows images of the shapes of a drop flowing out of a hole made in a horizontal plate at low intensity and different frequencies of the magnetic field. Fluid outflow rate is 0.1 ml/s. As is seen from Fig. 2, in the field H_{max} = 1 kA/m, the drop is a sphere suspended on a thin column of liquid with a base fixed on a horizontal solid plate. The retention of the droplet on the horizontal surface is carried out due to capillary forces. It is also seen that the shape of the droplet does not depend on the frequency of the applied magnetic field, at its low intensity.

a b c

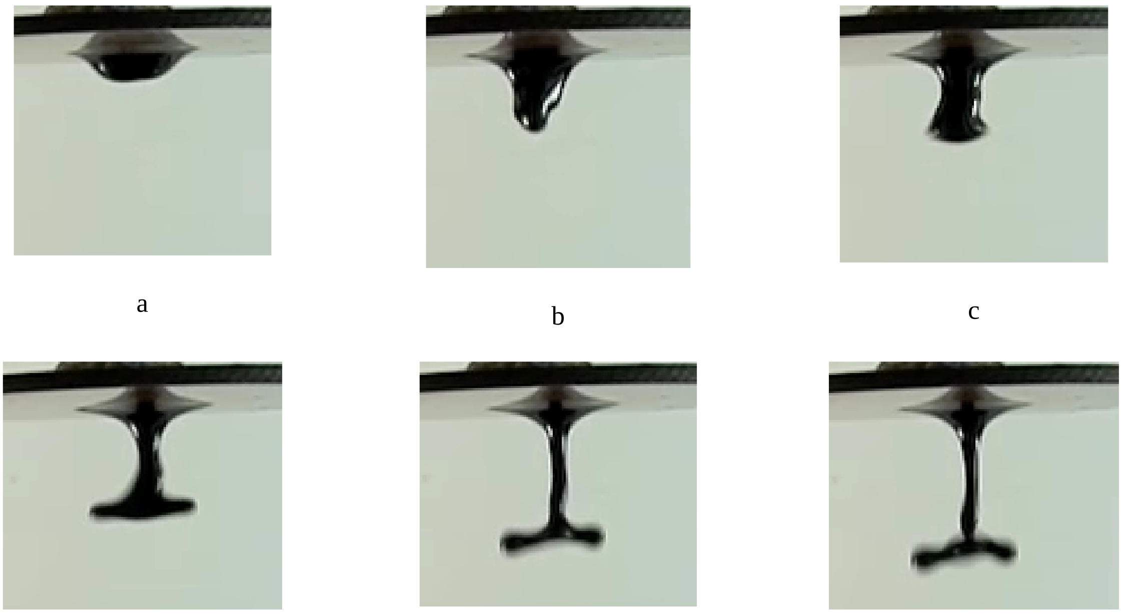
Fig. 2. Snapshots of separation of a drop of magnetic fluid in an alternating magnetic field with a strength of H_{max} = 1 kA/m: a – 10 Hz; b – 12 Hz; c – 15 Hz

Fig. 3 shows a series of photo of a drop growing in a horizontal magnetic field H_{max}= 4.6 kA/m. Fluid outflow rate is 0.1 ml/s. The time points of the drop expiration from the beginning of observation are indicated in the Fig. 3. It can be seen that a drop from a spherical shape turns into an elongated dumbbell-like shape suspended on a vertical column of liquid.

The behavior of the droplet shown in Fig. 2 and 3 changed significantly with increasing of the outflow (>5 ml/s) of the droplet from the hole by increasing pressure applied to the surface of the magnetic fluid in a cylindrical container. Namely, there was a significant elongation of the vertical column of liquid suspended on the horizontal surface of the plate, as shown in Fig. 4. In fact, the drop turns into a jet of magnetic fluid.

It can be seen from the Fig. 4 that with an increase in the expiration time of the column of liquid from the hole on the horizontal plate, this column is elongated until its decay. The axial line of the column undergoes transverse oscillations in the direction of the applied magnetic field. Fluid outflow rate is 0.5 ml/s in this case.

Note that such instability of a magnetic fluid jet in a perpendicular magnetic field was previously analytically investigated in [25, 26]. With an increase in the field strength, as shown in Fig. 5, the liquid column disintegrated into cylindrical parts of approximately the same height, each of which separately oscillated in the direction of the external applied magnetic field. Fluid outflow rate for the case shown in Fig. 5 is 0.5 ml/s.



a b c

d e f

Fig. 3. Growth and oscillations of a drop of magnetic fluid in an alternating magnetic field with a strength H_{max} = 4.6 kA/m and frequency of 12 Hz at time points: a – 0.6165 s; b – 2.9924 s; c – 3.0033 s; d – 3.0165 s; e – 3.0264 s, f – 3.0297 s

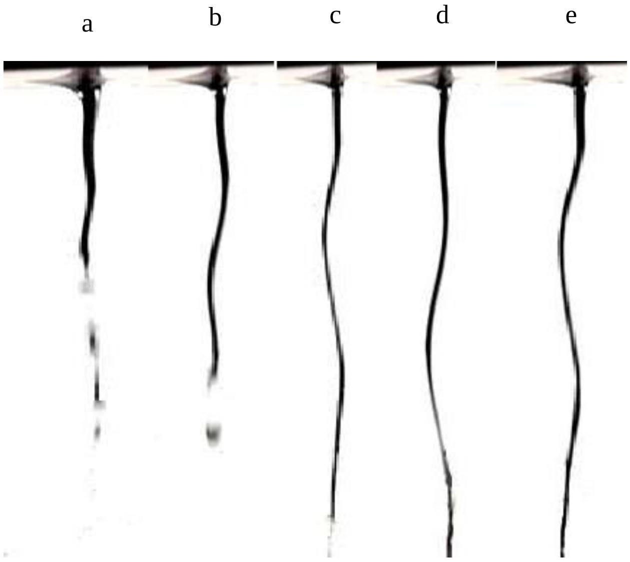


Fig. 4. A jet of magnetic fluid in an alternating magnetic field with a frequency of 10 Hz and an amplitude of strength 4.6 kA/m at time points from the beginning of the experiment: a – 0.0792 s; b – 0.1132 s; c – 0.1528 s; d – 0.1726 s; e – 0.2066 s

Fig. 5. A jet of magnetic fluid in an alternating magnetic field with a frequency of 10 Hz and a strength amplitude of 6.3 kA/m at time points from the beginning of the experiment: a – 0.3330 s; b – 0.3429 s; c – 0.3561 s; d – 0.3660 s

The formation of standing waves on the surface of a magnetic fluid flowing from a hole in a horizontal plate is shown in Fig. 6. Waves arise in an alternating magnetic field with a strength of at least H_{max}=7 kA/m and at a field frequency over 30 Hz. Fluid outflow rate is 0.2 ml/s. It can be seen from the Fig. 6 that with an increase in the frequency of the applied magnetic field, the length of the train of surface waves increases significantly. In this case, both the amplitude and the wavelength change.

Fig. 6. Spreading of a drop of magnetic fluid in an alternating magnetic field with an amplitude of strength H_{max}=7 kA/m and at different frequencies: a – 30 Hz; b – 50 Hz; c – 60 Hz

The waveforms presented above appear oscillatory, but they are more complex than a simple sine wave, indicating the presence of additional waves. To demonstrate that the instability phenomena are composed of a sum of individual oscillatory components, a harmonic decomposition analysis of the considered wave patterns was carried out. Thus, Fig. 7a,b presents the results of Fourier series decomposition of a set of experimental coordinates of the surface of a magnetic fluid jet, previously presented in Fig. 4e.

Fig. 7b,d shows the decomposition results for the coordinates of the surface of a drop of magnetic fluid in the case of the formation of a standing wave in an alternating magnetic field, presented in Fig. 6b. Dots in Fig. 7a,c correspond to the Cartesian coordinates of fluid surface points obtained from image analysis and measured in dimensionless arbitrary units. Solid lines in Fig. 7a,c correspond to the harmonic approximation of experimental data. The frequencies of the corresponding harmonics are demonstrated in Fig. 7b,d.

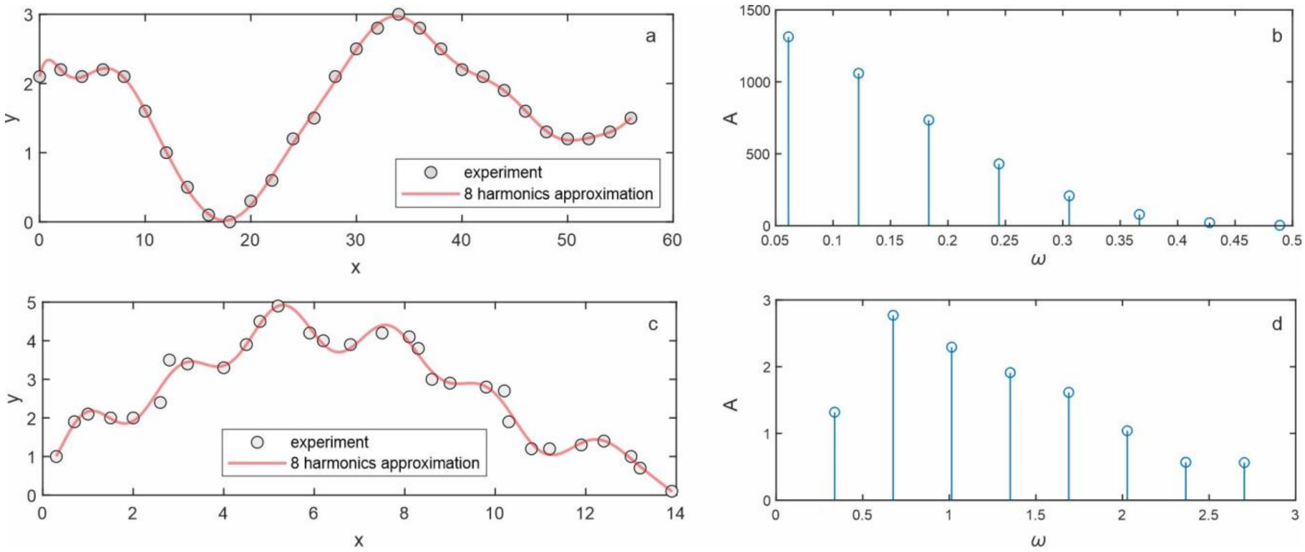


Fig. 7. Results of harmonic decomposition of experimental data of magnetic fluid surface coordinates at wave instability of a jet (a,b) and a drop (c,d) in an alternating magnetic field

4. CONCLUSION

In this work, based on the observation of the behavior of a drop of magnetic fluid flowing out of a hole in a horizontal non-magnetic surface in an alternating homogeneous external magnetic field, the formation of surface waves on the liquid-gas interface was detected. The dependence of the characteristics of surface waves on the frequency and intensity of the applied magnetic field is determined. The appearance of both traveling and standing waves on the surface of a growing magnetic fluid droplet in an external alternating magnetic field with different characteristics is shown. Bending waves of capillary jets of magnetic fluid are found. Such behavior and discovered patterns of instability of flowing droplets of magnetic fluid in an alternating magnetic field have not been previously investigated and are new compared to previous works. The difference of the obtained results from the results of previous studies is the consideration of the dynamics of the shape and instability of droplets of magnetic fluids, for which the bounding surface is located on top, as well as the study of the effect of an alternating field on the instability of drops and jets when they flow from the hole. The results obtained may be of interest for inkjet printing technology and microfluidic devices development.

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