Investigating dynamics of the interface between air and magnetic fluid in the so-called magnetic vacuum within an annular magnet

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Abstract. Magnetic, acoustic, and thermophysical phenomena in magnetic fluid systems have found application in the design of magnetic fluid seals, shock absorbers, sensitive three-axis accelerometers, density meters, and a number of other advanced devices. This explains the interest in studying these effects. Lately, due to the rapid development of microfluidics, more and more works have appeared that deal with magnetic fluid dynamics in channels of various shapes when various external physical fields affect them. However, several aspects have only been studied superficially, although they are potentially of great scientific and practical interest; these are levitating gas cavity properties and magnetic, acoustic and thermophysical phenomena accompanying dynamic gas cavity and bubble displacement in a magnetic fluid. This paper investigates the dynamics of bubble trapping in magnetic fluid located in the so-called magnetic vacuum region of an annular magnet. We obtained data on effects of centrifugation and magnetic fluid structure on the strength of magnetic fluid bridges subjected to external pressure. This information may be useful for developing a test bench for magnetic fluids used in seals, where fluids undergo similar effects. We used two samples of magnetic fluid to perform an experiment which involved compressing the air cavity, eventually leading to gas bubbles detaching from the samples. We draw conclusions concerning the effects of physical parameters of magnetic fluids and magnetic field configuration on the diameter of the resulting bubbles.

1. Introduction
Currently, systems based on magnetic fluids (MF) interacting with gas inclusions are used for a wide range of applications [1]. Such systems are used in magnetic fluid seals [2, 3], where a driven element separates gas volumes; the element consists of magnetic fluid located in a non-uniform field of a system of magnets. In tilt sensors [4, 5] the working fluid is a magnetic fluid moving in the annular magnet field, and the signal is recorded by measuring coils. Lately, due to the rapid development of microfluidics, more and more works have appeared that deal with magnetic fluid dynamics in channels of various shapes when various external physical fields affect them [6–8]. Investigating the effect of physical properties of magnetic fluids on system parameters is of particular interest, for example, concerning tensile strength of magnetic fluid bridges in MF seals [9] or vibration damping efficiency in MF shock absorbers [10-13]. A promising direction is using magnetic fluids to create gas metering devices, that is, so-called flowmeters [14].
2. Sample properties and the idea of the experiment

We studied three samples of magnetic fluid. Table 1 lists their physical and chemical parameters.

| Sample  | Carrier fluid | ρ, kg/m³ | φ, % | χ | Ms, kA/m | η, mPa·s |
|---------|---------------|----------|------|---|----------|---------|
| MF-1    | Kerosene      | 1.245    | 10   | 1.8| 39.5     | 34.8    |
| MF-2    | Kerosene      | 1.348    | 12.3 | 4.2| 68.2     | 8.75    |
| MF-3    | Kerosene      | 1.498    | 15.7 | 4.7| 70.6     | 11.5    |

The MF-1 sample was provided by the Problem Scientific Research Laboratory of Applied Ferrohydrodynamics, Ivanovo State Power University. The MF-2 sample was prepared using chemical condensation at the Department of Nanotechnology, General and Applied Physics, South-West State University. The MF-3 sample was obtained by centrifuging the MF-2 sample.

The idea of the experiment is as follows: if an annular magnet is brought from below into a tube filled with magnetic fluid, then at a certain distance between the surface of the fluid and the surface of the annular magnet the fluid traps a portion of gas (figure 1a). Raising the magnet slowly (~ 0.02 mm/s) further leads to capture of gas bubbles and formation of a larger cavity, the sealing of which is then broken (figure 1b). This process is similar to the process of failure in a magnetic fluid seal. Subsequently lowering the magnet results in the cavity wall being restored (sealing the cavity). While the magnet is lowered at a constant rate of ~ 0.8 mm/s, the cavity wall turns into a continuous column due to the MF flow (figure 1c). Upon lowering the magnet further so that it begins to move past the bottom of the tube, a non-uniform magnetic field pushes the air cavity down to the bottom (figure 1d); and when the magnet is underneath it, the gas bubbles detach.

Figure 1. The process of an air cavity being captured by a magnetic fluid.

3. Study of the dynamics of magnetic fluid capturing an air cavity and its splitting into bubbles of controlled size.

We investigated a MF sample based on highly dispersed magnetite stabilized by an oleic acid surfactant. Kerosene was used as the carrier fluid. The density of the sample under study is ρ = 1580 kg/m³. The saturation magnetization is Ms = 56.7 kA/m. In the processes under study, the fluid is Newtonian, its shear viscosity is measured on a Brookfield DV2T viscometer; its value is η = 16.45 mPa at a spindle speed of 60 rpm. The study employed a neodymium annular magnet with a size of 60x24x10 mm. We considered the section of the magnetic field of the annular magnet that surrounds the point where the direction of the magnetic induction reverses; the intensity H is zero, and the intensity gradients are oppositely directed.
Figure 2 shows the diagram of the setup created for the experiment. A glass tube with a bottom 1.25 cm deep is filled with MF2 (the height of the liquid column is 15 cm) and rigidly fixed to an aluminium structure with fixtures made of acrylic glass. The annular magnet 3 and the inductor 4 recording magnetic oscillations are mounted coaxially to the tube. The piezoelectric element 5 is used to record acoustic oscillations. Amplifiers 6 and 7 amplify sensor signals, which the ADC 8 then transmits to a PC for further processing. A helical gear with a stepper motor 9 is used to move the annular magnet and the inductor at a speed of 0.05 - 45 mm/s. In the initial position, the annular magnet is located below the bottom of the tube. A cavity 10 is formed as the magnet is lifted.

![Diagram of the experimental setup](image)

**Figure 2.** Block diagram of the experimental setup.

When an air bubble punctures the magnetic fluid, there occurs a perturbation in the magnetic field, which is caused by a non-magnetic bubble with oscillating walls moving in the magnetic field detected by the measuring coil. Figure 3 presents the oscillogram recorded as the MF bridge fails and an air cavity is captured. The top graph is the signal received from the piezoelectric element; the bottom one comes from the inductor. Then, as the magnet rises, we observe that this stage repeats; at each repetition, the volume of the trapped air cavity is replenished.

The oscilloscope was set up in such a way that it recorded only the signals generated when the bubbles were captured; the absolute oscillogram recording time was simultaneously tracked, which makes it possible to restore the time and frequency of the bubbles puncturing the fluid and evaluate the relationship between the properties of the fluid and the puncture dynamics. Figure 4 shows the ordinal number of the bubble $N$ as a function of the puncture time $t$ for samples MF-1 to MF-3. In these experiments, the annular magnet moved upward at a speed of 3.6 mm/s.

We can infer from the graph and the table that initially the bubble capture dynamics in the MF-2 and MF-3 samples are similar. Later, 56 seconds after the first puncture, the air cavity wall in MF-2 ruptures when the 14th bubble is captured. For the MF-3 sample, which was obtained by centrifuging the MF-2 sample, bubble capture lasts 107 seconds and the air cavity captures 39 bubbles, which is almost two times than that for the non-centrifuged MF-2 sample.
Figure 4. Bubble number $N$ as a function of the puncture time $t$ for the MF1 ($\square$), MF-2 ($\circ$), MF-3 (+) samples.

As for the MF-1 sample, the air cavity wall retains its integrity the longest, for 123 s, capturing only 15 air bubbles, which indicates the ability of magnetic-fluid bridges based on this particular magnetic fluid to maintain their strength characteristics under external pressure.

4. Experiment on compressing an air cavity in magnetic fluid

We also carried out an experiment to study the interaction of physical fields when a non-uniform field of an annular magnet presses down on an air cavity in magnetic fluid, the block diagram of which is shown in Figure 5.

Figure 5. Block diagram of the experimental setup. Figure 6. An example of an oscillogram recorded when a bubble punctures the fluid.

Elements 1-9 are the same as those presented in section 3 in Figure 2. While the cavity 10 is compressed (Figure 1 in the previous section shows the capture mechanism), air bubbles 11 detach. Electromagnetic oscillations and signals from the piezoelectric element are recorded. Figure 6 presents an example oscillogram.

The bottom signal is received from the inductor, the one above comes from the piezoelectric element. The oscillograms show that the signals have the same basic frequency, the presence of which can be explained by the fact that when a bubble detaches from an air cavity in magnetic fluid, its walls oscillate radially at the frequency given by the well-known expression
\[ \nu = \frac{1}{2\pi R_0} \sqrt{\frac{3\gamma P_0}{\rho}}, \]  

(1)

where \( R_0 \) is the bubble radius, \( P_0 \) is the hydrostatic pressure, \( \gamma = C_p/C_v \) is the ratio of specific heat capacities in the bubble, and \( \rho \) is the magnetic fluid density.

The radius \( \overline{R} \) is calculated as the arithmetic average of the values given by

\[ R_0 = \frac{1}{2\pi \nu} \sqrt{\frac{3\gamma P_0}{\rho}}. \]  

(2)

For the case under consideration, we take into account that

\[ R_0 = 2\sigma/R_0 \]  

(3)

(\( \sigma \) is the coefficient of MF surface tension).

Figures 7 and 8 show the gas bubble size distribution histograms obtained for the MF-1 and MF-2 fluids. For the MF-1 sample, the expected value is 2.68 mm, the variance is 0.29; for MF-2 these are 2.7 mm and 0.17, respectively.

We can see from the histograms that the most probable bubble size is the same for both fluids, equalling 2.8 mm. For MF-2, there is a smaller variance of bubble diameters, which can be explained by its particle size distribution.

5. Conclusion

We investigated the dynamics of bubble trapping in magnetic fluid located in the so-called magnetic vacuum region of an annular magnet. We obtained data on effects of centrifugation and magnetic fluid structure on the strength of magnetic fluid bridges subjected to external pressure. This information may be useful for developing a test bench for magnetic fluids used in seals, where fluids undergo similar effects.

To obtain a detailed mechanism of air cavity formation in the so-called magnetic vacuum region of an annular magnet, we performed an experiment with video recording of the interface between gas and magnetic fluid. We considered the stages of the MF surface distorting while affected by a non-uniform magnet field, and those of instability formation in the form of peaks and cavities, the latter being precursors to gas microbubbles forming the initial air cavity.

We used two samples of magnetic fluid to perform an experiment which involved compressing the air cavity, eventually leading to gas bubbles detaching from the samples. The most probable bubble size is the same for both fluids and equals 2.8 mm, which demonstrates that the size of the bubbles is
determined by the magnetic field configuration of the annular magnet. For MF-2, the variation in the bubble diameter may be explained by its particle size distribution.

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