Dynamics of the Gas Bubbles in the Magnetic Fluid in the Non-Uniform Magnetic Field

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Abstract. This work presents a study of the hydrodynamics of gas bubbles in a magnetic fluid which is in a flat channel with a thickness of 2 mm, placed in the non-uniform field of the rare-earth annular permanent magnet. The peculiarity of the magnetic field configuration of this magnet is as follows: at a distance of 9 mm from the surface of the magnet there are two symmetric regions where the magnetic field is zero, the so-called 'magnetic vacuum' regions. The specified configuration of the magnetic field allows capturing and holding gas cavities when the magnet moves; while pressing the cavity to the bottom of the channel, gas bubbles separate. An experimental setup was created to study the hydrodynamics of gas inclusions; using this setup studies on the concentration series of four magnetic fluids based on kerosene with a volume concentration of 10.56%; 6.32%; 3.93%; and 2.08% were conducted. The mechanism of gas bubbles capturing and gas cavity formation in a magnetic fluid in the magnetic vacuum region of an annular magnet is investigated. The process of the separation of the bubbles from the air cavity when it is pressed down to the bottom of the channel by a non-uniform magnetic field is studied.

1. Introduction

Studies of gas inclusions (bubbles and cavities) in a magnetic fluid is of great interest due to the possibility of controlling by means of an external magnetic field. The scope of experimental research is the influence of the magnetic field on the bubbles shape, speed of movement, and the gas jets decay [1-3]. In theoretical terms, the popular technique for interpreting such systems is a method called the Volume of Fluid (VOF) [4-6] which was applied to theoretically simulate the shapes of gas bubbles in a magnetic field, including external uniform magnetic fields. A theoretical model of nonlinear movement and oscillations of a bubble wall in a magnetic fluid in a uniform magnetic field when exposed to an acoustic signal and a variable magnetic field is presented in [7]. Most of these works consider interaction of magneto-fluid systems with gas inclusions with uniform magnetic fields. Only [1] studies the influence of a non-uniform magnetic field created by an annular electromagnet on the deformation and velocity of the bubbles in a magnetic fluid. From the practical viewpoint, it is of interest to use such systems for gas flow control systems. In [8–9], a gas microflow rate sensor was proposed; in this sensor gas bubbles float onto the surface in the magnetic field in a uniform magnetic field, passing through a cylindrical measuring coil; when passing through it a gas bubble perturbs magnetic field, which leads to the EMF induced in the coil.

In the previous work [10], the dynamics of gas inclusions in the magnetic fluid in the cylindrical tube with the diameter of 12 mm in a non-uniform magnetic field was studied. An original acousto-magnetic mechanism for recording oscillations of the gas bubble wall in a magnetic fluid is proposed. Estimation of the sizes of gas bubbles was carried out. A theoretical interpretation of the mechanism of gas cavity capturing, transporting and pressing in the magnetic fluid in the non-uniform magnetic field of the annular magnet was presented. However, the experiments were carried out in an optically non-transparent system, which made it difficult to experimentally interpret the results obtained.
2. Experimental results and their interpretation

The idea of the experiment is as follows: if an annular magnet is brought from below into the tube filled with a magnetic fluid, then at a certain distance between the surface of the fluid and the surface of the annular magnet a portion of the gas is trapped into the fluid (Figure 1a). A further slow rise of the magnet (~ 0.02 mm/s) leads to the capture of gas bubbles and the formation of a larger cavity, the sealing of which is then broken (Fig. 1b). This process is similar to the process of breakdown of the magneto-liquid sealer. Jumper recovery (sealing cavity) occurs during the subsequent lowering of the magnet. In the process of lowering the magnet at a constant speed of ~ 0.8 mm/s, the jumper turns into a solid column due to the flow of the MF (Fig. 1c). Upon further lowering of the magnet to the level ‘below the tube with the MF’, the air cavity is pressed by the non-uniform magnetic field to the bottom (Fig. 1d) and when lowering below it, the gas bubbles separate [10].

![Figure 1. The process of capturing air cavity by the magnetic fluid](image)

The experimental setup is shown in Figure 2. A flat channel 1 with a thickness of 2 mm and a width of 10 mm filled with magnetic fluid 2 is rigidly fixed to an aluminum structure with fixtures made of plexiglas. The annular magnet 3 and the inductor coil 4, used to register magnetic oscillations, are mounted coaxially to the tube. The signals from it are amplified by means of the amplifier 5 and transmitted by means of the digital oscilloscope 6 to PC for further processing. A helical gear with a stepper motor 7 is used to move the annular magnet of the inductor coil at a speed of 0.05-45 mm/s. In the initial position, the ring magnet is located below the bottom of the tube. A cavity 8 is formed while lifting the magnet. For video recording, a LED controlled luminaire 9 and a high-speed camera 10 configured for recording in the transmitted light are used. Figure 3 shows the result of video recording of the air cavity in the magnetic fluid MF-1 in the flat channel. The air cavity is near the bottom of the flat channel and is superimposed on the isoline pattern of the module of the magnetic field intensity. The figure demonstrates that the upper part of the gas-fluid interphase boundary follows the isolines of the magnetic field intensity module equal to 35 kA/m.
A concentration series obtained by diluting MF-1 sample based on kerosene was studied. The physical parameters of the samples are presented in table 1.

| Sample | MF Density | Volume Concentration φ, % | Saturation Magnetization Ms, kA/m | Magnetic Concentration φm, % | MF Viscosity, mPa·s |
|--------|------------|----------------------------|-----------------------------------|----------------------------|---------------------|
| MF-4   | 870        | 2.08                       | 9.2                               | 1.93                       | 1.8                 |
| MF-3   | 952        | 3.93                       | 12.9                              | 2.70                       | 2.45                |
| MF-2   | 1,058      | 6.32                       | 20.7                              | 4.34                       | 4.15                |
| MF-1   | 1,245      | 10.56                      | 43.3                              | 9.08                       | 31.8                |

To analyze video recorded data in the NI LabView environment, a program for controlling and processing machine vision data and determining physical parameters of gas inclusions in the magnetic fluid (volume, surface shape evolution and their velocity) was developed. Figure 4 shows a graph of the dependence of the air cavity volume on the time; the time when the air cavity touches the bottom of the flat channel is taken as a reference point.

On the graph, the vertical segments demonstrate the moment of a sharp change in the gas cavity volume, associated with the gas bubble separation. It can be seen from the graph that for magnetic fluids with lower concentration, bubble separation occurs earlier. Based on the graph data, table 2 was created; the table presents the sizes of the bubbles in the order of their numbers for each sample of magnetic fluid.
fluid. The table shows that in low concentrated MFs a smaller number of gas bubbles of larger diameter is formed; on the contrary, concentrated MFs are characterized by the formation of a large number of the bubbles of small diameter.

Table 2. Bubble sizes

| Number of the bubble | MF-4 | MF-3 | MF-2 | MF-1 |
|----------------------|------|------|------|------|
|                      | time of separation | bubble volume | time of separation | bubble volume | time of separation | bubble volume | time of separation | bubble volume |
| 1                    | 11.14 | 28.89 | 12.21 | 29.95 | 12.97 | 14.31 | 13.41 | 2.29 |
| 2                    | 20.79 | 20.83 | 20.28 | 26.27 | 18.03 | 9.43  | 16.83 | 2.32 |
| 3                    | -     | -     | 28.38 | 17.49 | 22.41 | 6.73  | 19.31 | 2.40 |
| 4                    | -     | -     | -     | -     | 27.79 | 5.50  | 22.48 | 2.36 |
| 5                    | -     | -     | -     | -     | 33.38 | 1.92  | 25.72 | 2.23 |
| 6                    | -     | -     | -     | -     | -     | 28.41 | -     | 1.69 |

The data obtained for the MF-1 sample, coincide with the data obtained in [10] using acoustomagnetic display for the setup with a cylindrical tube filled with MF.

3. Conclusions

The dynamics of bubble trapping by magnetic fluid in the ‘magnetic vacuum’ region of the annular magnet is investigated. The data concerning the influence of concentration on the strength of magnetofluid bridges under the influence of external pressure are obtained. This information may be useful for the development of a test bench for magnetic fluids used in sealers, where fluids experience similar effects.

To obtain a detailed mechanism of air cavity formation in the ‘magnetic vacuum’ region of the annular magnet, an experiment with video recording of the gas-magnetic fluid interface in the flat thin channel was performed. An experiment on the air cavity pressing was performed, as a result of which gas bubbles separated from the MF samples. It is shown that in low-concentrated MF’s, bubbles separation occurs earlier, with the formation of a small number of gas bubbles of large diameter. The data obtained for the most concentrated MF-1 sample coincide with the data obtained in [10] using an acoustomagnetic display for the setup with a cylindrical tube filled with MF.

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