Experimental study of gas inclusions dynamics in the magnetic fluid in the inhomogeneous magnetic field

Petr Ryapolov*, *Vyacheslav* Polunin, *Anatoly* Ivanov, and *Kirill* Ryabcev

South-West State University 305040, Kursk, ul. 50 October, 94

Abstract. The results of an experimental study of the capture, transport, and subsequent destruction of the air cavity into bubbles by the magnetic fluid in the area of the 'magnetic vacuum' of the annular magnet are discussed. The study was performed using video recording and recording of electromagnetic and acoustic signals.

1 Introduction

Magnetic fluids are a colloidal stable system of the nanoscale single-domain magnetite particles coated with the stabilizing shell dispersed in the carrier fluid. The unique combination of magnetic fluid (MF) capability to interact with magnetic field and its fluidity are not only of scientific interest, but also the basis for numerous applications. In particular, micro-and nano-disperse MFs are used to solve the problems of vibration damping controlled by magnetic field, magnetic fluid sealing of gas, dosed feeding of small portions of gas into reactor, choppers and valves in microgaps [1-3].

In this work, to expand the capabilities to control the gas-liquid system based on MF by using a magnetic field the magnetic field section of the annular magnet surrounding the point of change of the magnetic field induction direction, i.e. the "magnetic vacuum" area is applied; video recording and recording of electromagnetic and acoustic signals are used as techniques of studying the process of air cavity capturing by MF and gas bubbles tunneling.

2 Physical and chemical properties of magnetic fluid, experimental setup and measurement technique

In this work, an MF sample based on highly dispersed magnetite stabilized by an oleic acid surfactant was investigated. Kerosene was used as a dispersion medium. The density of the sample under study is $\rho = 1580$ kg/m^3. The saturation magnetization is $M_s = 56.7$ 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 is 16.45 mPa at a spindle speed of 60 rpm. In the current study, a neodymium annular magnet with a size of 60x24x10 mm was applied. A section of the magnetic field of the annular magnet, which surrounds the point of change

* Corresponding author: r-piter@yandex.ru

of the induction direction, is considered; the intensity H is zero, and the intensity gradients are oppositely directed.

The diagram of the setup created for the experiment is shown in Figure 1

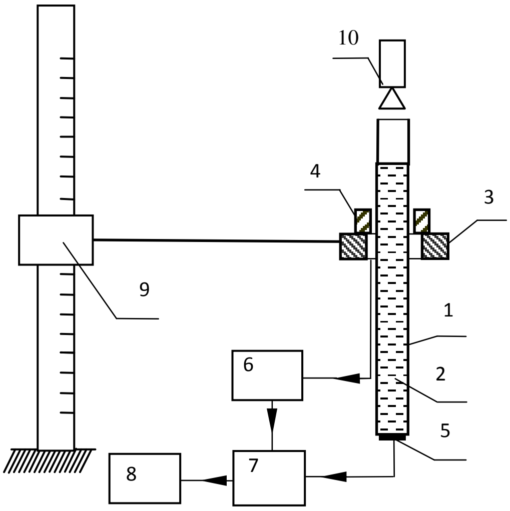


Fig. 1. Block diagram of the experimental setup.

The glass tube with the bottom 1, 25 cm long, filled with MF 2 (the height of a liquid column is 15 cm), is rigidly fixed to the 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. To fix the acoustic oscillations, the piezoelectric element 5 is used. Signals from the sensors are amplified by means of amplifiers 6,7 and transmitted by means of ADC 8 to PC for further processing. A helical gear with a stepper motor 9 is used to move annular magnet the inductor coil at a speed of 0.05 - 45 mm/s. In the initial position, the annular magnet is located below the bottom of the tube. The video recording of the breakdown process is carried out using the high-speed camera 10 with a specially manufactured SMD LED annular illuminator with dimming unit.

Fig. 2 shows the main points of this process. To eliminate the occurrence of air bubbles when filling the MF tube, the magnet is placed and subsequently lifted from the distance of 50-60 mm below the bottom. Figure 2a shows the position of the magnet in the course of

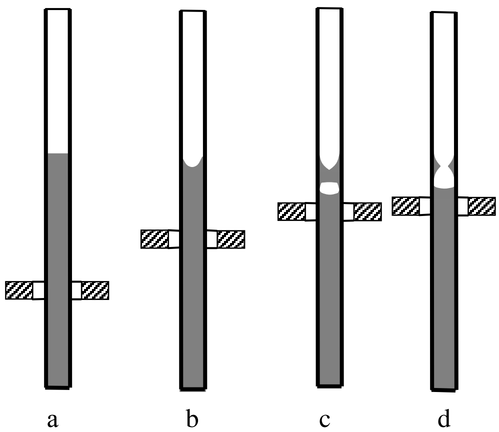
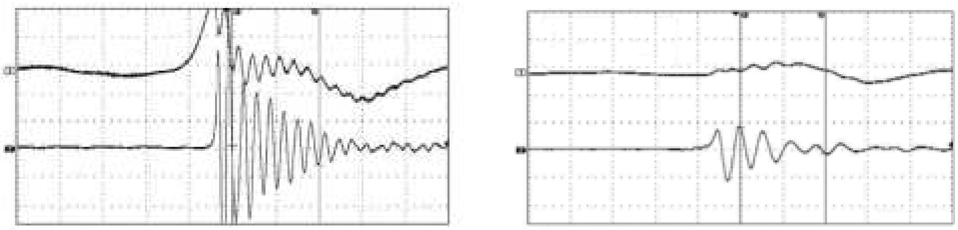


Fig. 2. The process of capturing the air cavity with a magnetic fluid

movement from its initial position. To eliminate the occurrence of air bubbles when filling the MF tube, the magnet is placed and subsequently lifted from the distance of 50-60 mm below the bottom. Figure 2a shows the position of the magnet in the course of movement from its initial position. The magnet is lifted with the constant speed of 0.8 mm/s upwards. With a reduction in the distance from the magnet surface to the free surface of the MF column, the surface of the fluid starts to bend under the action of the magnetic field (Fig. 2b). Further slow (~ 0.02 mm/s) magnet lifting leads to the formation of a larger cavity (Fig. 2c), the sealing of which breaks later (Fig. 2d).

3 The experiment and interpretation of results

The oscillogram obtained during MF breakdown and air cavity capturing, obtained by moving the magnet upward, have the form shown in Figure 3. Until the moment of breakdown (Fig. 2d), 12–15 portions of gas are captured. Fig. 3a shows the waveform for the first breakdown, and Fig. 3b for the last. The upper graph depicts the signal obtained from the piezoelectric element, the lower one represents the signal from the inductor.



a (portion 1, frequency 614,4 Hz) b (portion 2, frequency 353,4 Hz)

Fig. 3. Oscillograms of the magnetic fluid breakdown

Assuming the applicability in this case of the formula for the oscillation frequency of the harmonic oscillator $\omega = \sqrt{k_g / \rho S h_f}$ and considering that the coefficient of elasticity of the gas [4]: $k_g = \gamma \pi d^2 P_0 / 4h_0$, write down: $(h_{0n} / h_{01}) \cdot (h_{fn} / h_{f1}) = \omega_1^2 / \omega_n^2$ (designations: ω_1 - membrane frequency after passing a single portion of air; ω_n – n-th portion; indexes at h_0 and h_f meet the same condition). In particular, according to our data for n=15 we have $\omega_1^2 / \omega_n^2 =$ 3. The peculiarity of the stage-by-stage filling of the air cavity in the vicinity of the “magnetic vacuum” of the magnetic field is the ratio of increasing the volume of the air cavity “a” times and reducing the jumper volume by “b” times, and in this case a / b = 3.

The total force that determines the condition of the non-magnetic body motion in a non-viscous magnetized magnetic fluid in the approximation of a ‘weakly magnetic’ medium can be represented a follows [5]:

$$\vec{F} = (\rho_s - \rho)V\vec{g} - \mu_0 MV\nabla H\,, \qquad (1)$$

where ρ_s and V are the density and the volume of a nonmagnetic body, M and ρ are the magnetization and the density of magnetic fluid, H is the magnetic field strength, μ_0 is the magnetic constant. In this case, for the air cavity (bubble) in the MF with

$$\rho\,|\,\vec{g}\,| > \mu_0 M\,|\,\nabla H\,|, \qquad (2)$$

the cavity (bubble) floats, and when

$$\rho\,|\,\vec{g}\,| < \mu_0 M\,|\,\nabla H\,|, \qquad (3)$$

the cavity is moving down. Note, that the vector $\boldsymbol{M}$ in both cases under study is directed downwards, and its module is written in the expressions.

If the magnet is lifted ‘bottom-top’ to the surface of the MF and approaches to it at the distance of z > 25 mm (Fig. 1), an air bubble that appears in the MF, for example, when extruded from the capillary, experiences a pushing effect in accordance with the formula formula (2). At the point of the curve maximum (z ≈ 25 mm), and the movement is carried out by the archimedes force. With the further magnet lifting, the magnetic field gradient becomes much larger than before. When z <25 mm due to a sufficiently large value of $M\,|\nabla H\,|$ condition (3) is satisfied, which leads to air bubble submergence.

During magnetic fluid breakdown and bubble capture, instabilities in the form of peaks and cavities occur on the surface which can be considered as the neck of a bubble in the fluid. In the approximation of the ‘weakly magnetic’ liquid medium in the gradient magnetic field, this radius can be obtained from the expression:

$$r_b = 2\mu_0 M \nabla H R_b^3 / 3\sigma\,,$$

where σ is the coefficient of MF surface tension.

Taking for the gradient in fig. 1directed from bottom to top, the order of $4 \bullet 10^6$ A/m^2, M = 10 kA/m, R_b = 0.3 mm, $\sigma = 28\cdot10^{-3}$ N/m, we get: $r_b \approx 30$ μm.

Fig. 4 shows the photographs of the surface of the MF column, the first three of which relate to the next breakdown, and the fourth one – to the beginning of the breakdown repetition, following the jump-like change of the picture and the clapping of the damper.

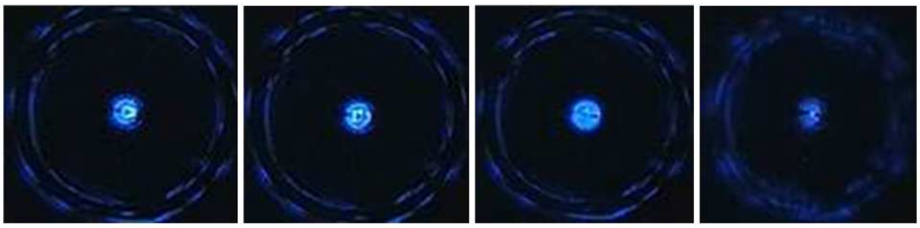


Fig. 4. Photographs of the MF surface during the next breakdown stage (No a-d from L to R)

The figures are distinguished by instabilities in the form of a funnel in the center, the size of which increases from Fig. 4a to Fig. 4b, after breaking through the funnel is missing (Fig. 4c), then the process repeats again (Fig. 4d). Since the surface relief of the magnetic fluid is tied to the magnetic field at the surface, its complete repetition, both in this breakdown and in all subsequent breaks, indicates a periodicity in the change of the magnetic field during magnet lifting. Due to this, the conditions for the resumption of the flow of bubbles into the region of ‘magnetic vacuum’ occur and the replenishment of the volume of the trapped air cavity.

In this work, the dynamics of gas inclusions in a magnetic fluid in a non-uniform magnetic field of a ring magnet, in which micro-bubbles magnetophoresis and liquid breakdown occur, is investigated. An assessment of the diameters of microbubbles was made ($r_b \approx 30$ μm), the process of changing the volume of the gas cavity before the breakdown of magnetic fluid layer was investigated, and the condition for the movement of gas inclusions in a magnetic fluid was proposed.

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