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CAVITATION PHENOMENA IN MAGNETIC LIQUIDS

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Investigations of acoustic cavitation in magnetic liquids subjected to the action of inhomogeneous magnetic fields were carried out for the first time. Possible mechanisms of the effect of the fields on the dynamics of single bubbles, cavitation threshold, and cavitation-induced erosion are considered. The effect of intense ultrasound vibrations on samples of magnetic liquids with a kerosene base are studied experimentally with and without gradient magnetic fields. It is shown that for magnetic liquids prepared with the optimum content of stabilizing substance and subjected to centrifugation in fields of $6 \cdot 10^3 g$ the action of powerful oscillations does not affect adversely their performance properties and structure, which supports the use of magnetic liquids as technological media. An increase-induced in cavitation-induced erosion of test samples after application of a gradient magnetic field is revealed.

Introduction. Magnetic liquids are colloidal solutions with suspended magnetic particles of $(0.2-2) \cdot 10^{-8}$ m. Stabilization of dispersed particles is attained by adsorption of ions on their surface with the formation of ionic bilayers or using surface-active substances (SAS) [1]. SAS molecules form adsorption layers with a certain orientation of polar groups on particles, which leads to a potential barrier that hinders coagulation of particles upon molecular and magnetic interaction. Magnetite, nickel, and iron are usually used as magnetics. Oleic acid or sodium oleate can serve as a stabilizer, whereas water, kerosene, various kinds of oils, molten metals, mercury, etc. can be used as a dispersion medium.

Presently, samples of magnetic liquids obtained under the laboratory conditions reach a saturation magnetization equal to 150 kA/m and retain their physicochemical properties over several years [1, 2, 6]. Owing to the ponderomotive interaction of suspended magnetic particles with magnetic fields, magnetic liquids are easily controlled in space. The presence of unique properties has provided wide applications of magnetic liquids in various branches of technology [1-8] and opens up wide prospects in future, in particular, in technical acoustics [2-5]. Therefore nonlinear effects produced in magnetic liquids by the simultaneous action of magnetic and high-intensity ultrasound fields, such as cavitation phenomena, are of great scientific and practical interest.

Owing to its dual nature, cavitation can play both a positive role (e.g., in the combined method of capillary defectoscopy [5, 11], cavitation increases the penetration depth of the penetrant into the capillary channel) and a negative rolem – causing erosion of the walls of magnetoliquid devices and disrupting the sound conductivity of the magnetic liquid being used as an acoustic contact [4] or in focusing of high-intensity ultrasound by magnetoliquid lenses [3].

1. Qualitative Analysis of a Effect of the Magnetic Field on Cavitation Phenomena in a Magnetic Liquid. Let us consider acoustic cavitation in a magnetic liquid under the action of the magnetic field.

When a magnetic liquid is placed in a magnetic field, a volume-distributed field of mass forces arises in the liquid. In this case, a nonmagnetic probe sphere of radius r will experience the force

$$\mathrm{F} = - M \nabla H \frac{4}{3} \pi r^3 , \tag{1}$$

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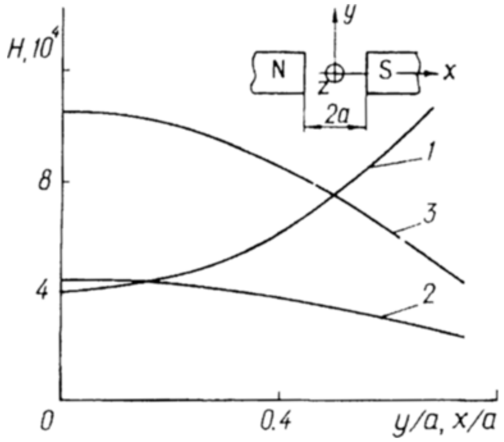

Fig. 1. Field strength H as a function of x: $y = z = 0$ (1) and as a function of y: $x = 5.5 \cdot 10^{-2}$ (2), $14.4 \cdot 10^{-2}$ m (3). H, A/m.

where M is the magnetization of the volume of magnetic liquid, H is the magnetic field intensity. Therefore, a cavitation bubble will move in the volume of magnetic liquid. In view of (1), the velocity of this transport in the field of gravity forces is as follows:

$$6\pi \cdot \mathrm{u} \sim \frac{1}{r\eta} (M\nabla H + \rho \mathrm{g}) . \tag{2}$$

Here η is the shear viscosity of the magnetic liquid, ρ being its density, and g is the free fall acceleration. Estimates obtained with expression (2) show that in a rather intense magnetic field the velocity can reach several cm/sec, which exceeds substantially the transport velocity in the gravity field when the magnetic field is absent. Thus, along with fast acoustic Eckart-type flows formed as a result of cavitation [9], the aforementioned transport can contribute substantially to the migration of cavitation bubbles in the magnetic liquid, which is extremely important in technical applications. In addition, the action of the magnetic field should cause a substantial variation in the spherical shape of the cavitation bubbles, by stretching them along the field lines. This is due to a pressure jump ΔP resulting from the different densities of the lines of magnetic induction on the surface of a sphere placed in an inhomogeneous magnetic field [12]. Most likely, the effect of this phenomenon is greatest when

$$\Delta p \; \mathrm{J} \; \mu_0 M^2 \sim 2\sigma / r ,$$

where σ is the surface tension coefficient of the liquid.

These ellipsoidal bubbles, both in the free volume and near solid walls, collapse in a manner quite different from that of spherical bubbles, separating into parts upon collapsing [10, 13].

The factors specified – the transport and breakdown of cavitation bubbles in a magnetic liquid under the action of a magnetic field – can, most likely, change the threshold of acoustic cavitation in the magnetic liquid as a result of variation of the local concentration of cavitation nuclei, which determines in many respects the value of the cavitation threshold [7, 9].

Inasmuch as the magnetic field causes excess pressure in the magnetic liquid, an increase in the collapse rate of cavitation bubbles and, consequently, an enhancement of cavitation erosion should be expected. For example, at $\Delta H = 0.5T$, $M = 50$ kA/m the excess pressure $P_M = 0.25 \cdot 10^5$ Pa. When the magnetic field is pulsed, the value P_M can reach several atmospheres.

Thus, the above analysis of cavitation phenomena in magnetic liquids under the simultaneous action of magnetic and high-intensity ultrasound fields points to the existence of a unique mechanism of contactless cavitation control in the magnetic liquid.

2. Experimental Investigation of Cavitation in Magnetic Liquids. In order to verify the possibility of using magnetic liquids as technological sound-conducting media and controlling cavitation processes, we developed a method and an experimental installation.

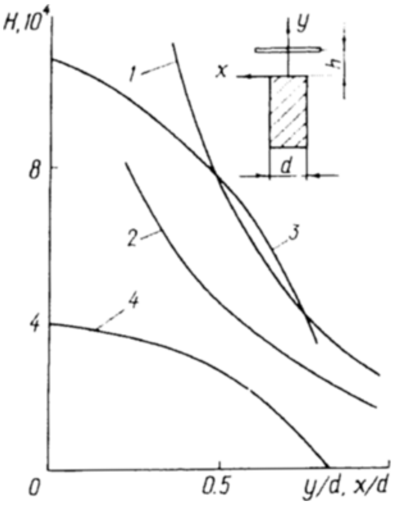

Fig. 2. Dependence of distribution of field-strength component on coordinates y (1, 2) and x (3, 4) relative to the magnetic surface. $x/d \simeq 0.38$ (3), 0.7 (4).

Two identical piezoelectric transducers with a working frequency of 5 MHz are placed in a cylindric cell with the magnetic liquid with their acoustic axes in the horizontal plane. The transducers are connected, respectively, to a generator and receiver of pulses of the probing signal. The output of the receiver is connected to an N341 recorder.

Intense ultrasound vibrations in the magnetic liquid are excited by an ultrasound emitter with a working frequency of 22 kHz. Temperature monitoring is realized by means of a thermocouple connected to a voltmeter.

The magnetic field in the working volume is created by Sm–Co magnets $20 \cdot 10^{-3}$ m in diameter. To mount the magnets conveniently and increase the concentration of the magnetic flux, a supporting plate on a coordinate table is attached to the reverse side of each of the magnets. The cell with a sound absorber on its bottom is attached to a turntable. The coordinate table and turntable are mounted on a supporting rail.

Several parameters of the magnetic field created within the working volume are presented in Fig. 1.

In order to study the effect of the magnetic field on cavitation erosion, we used special test samples produced from aluminum foil coated with a special adhesive powder layer 0.2 mm thick, which had an enhanced ability to disintegrate. In this case a hollow Plexiglas cylinder was placed in the cell coaxially with the emitter; the test sample was held at the upper base of the cylinder by a clamping ring.

For the analysis of the cavitation zone immediately within the working volume (between the test sample and the emitter of the low-frequency ultrasound) two transducers for a frequency of 3 MHz with dimensions of $4 \times 4 \cdot 10^{-6}$ m designed for the shadow mode of operation were placed coaxially on the outer side walls of the cylinder. The distance between the surface of the emitter and the test sample was fixed with an accuracy of 10 μm. To prevent pinching of the bubbles special slits were cut in the supporting cylinder from the opposite side of the test sample. The sonic-irradiation time of the test samples varied from 10 to 60 sec.

Heating of the magnetic liquid during the sonic-irradiation process did not exceed 3–5°C. When erosion tests were carried out, the samples were weighed on an electronic balance with an accuracy of 0.1 mg. We used a ponderomotive method of weighingto take into account the weight of the magnetic particles that were left on the surface of the test sample. For each measurement, we used 4–5 test samples, and the decrease was found from averaged data.

In studies of erosion, a magnetic field was created that was equivalent to that of a band $8 \cdot 10^{-3}$ m in width with the current flowing tangentially to the emitter surface at a distance of $6.2 \cdot 10^{-3}$ m from it. Curves of the magnetic-field parameters are presented in Fig. 2.

In order to analyze qualitatively processes that take place in the magnetic liquid an inductance coil was introduced coaxially in its volume and was connected to a balanced bridge, whose output was connected to a PPD-2

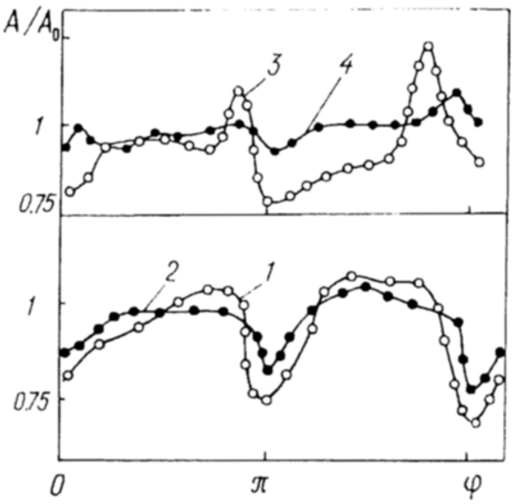

Fig. 3. Dependence of relative amplitude A/A_0 of the probe signal on the angle φ between the principal axis of magnets and the wave vector; 1, 3, the liquid is not sound-irradiated; 2, 4, the liquid is sound-irradiated; $M = 54$ kA/m (1, 2), 29 (3, 4). φ, rad.

plotter. When large gas formations were present in the working volume, the amplitude of the output signal from the coil changed as a result of the variation in the content of the magnetic substance.

Four kerosene-based liquids with saturation magnetizations M = 12, 29, 39, and 54 kA/m produced by peptization with an optimum content of stabilizing surface-active substance and centrifugation in a gravity field of $6 \cdot 10^3$ g were used as magnetic liquids. In addition, one of the samples (M = 31 kA/m) was manufactured with the lowered stabilizer content.

The first stage consisted of an investigation of the effect of cavitation on the structural properties of magnetic liquids. To do this, samples of the magnetic liquid 50 cm^3 in volume were sound-irradiated at a temperature of 90–100°C for 25 min with the oscillation amplitude of the emitter equal to $26 \cdot 10^{-6}$ m.

Comparison of the results of the action of cavitation on the structural properties of magnetic liquids was carried out by analysis of the anisotropic acoustic parameters of the probe signal. Some of them are presented in Fig. 3. It should be noted that the amplitude dependence $A(\varphi)$ in an inhomogeneous field is rather sensitive to processes of aggregation and sedimentation stability of magnetic liquids. The presence of associates leads to additional losses of ultrasound energy due to a number of relaxational processes [14].

An increase in particle size and a change in particle concentration in space are accompanied, as a rule, by a variation in the amplitude of the acoustic signal. And the greater this variation, the less stable the magnetic liquid. As is evident from the data presented, the dependence $A(\varphi)$ has especially pronounced extrema in the vicinity of $\varphi = 0, \pi, 2\pi$, i.e., when the principal axis of the magnets is parallel to the wave-vector.

Acoustic investigations carried out with samples of magnetic liquid of optimum composition which were subjected to centrifugation make it possible to conclude that the action of cavitation does not affect adversely the structural properties of the liquids. Moreover, it should be noted (Fig. 3, curves 3, 4) that in certain cases the value of the variation $\Delta A/A_0$ even decreased substantially after acoustic irradiation. One of the possible reasons of such a change is the mechanism of cavitation-induced fragmentation of aggregates of particles, which are present in virtually any liquid in one concentration or another. Measurements carried out using the ballistic method on the BU-3 setup have not revealed within the limits of experimental error, variations in the magnetization parameters of sound-irradiated and nonsound-irradiated liquids.

It should be noted that the action of cavitation can cause deterioration of the structural properties of a magnetic liquid if the amount of SAS adsorbed on the particles is insufficient. Thus, investigations of the magnetic liquid sample with M = 31 kA/m have shown that the maximum value of variation $\Delta A/A_0$ increased after sound-irradiation from 0.5 to 0.8.

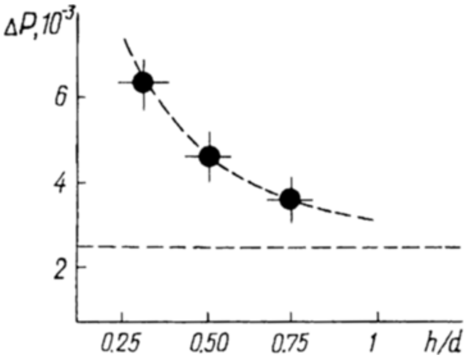

Fig. 4. Decrease in weight of test sample as a function of distance between magnet and sample. ΔP, kg/m^2.

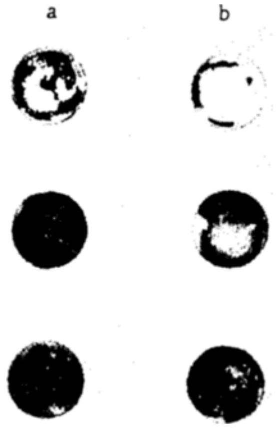

Fig. 5. Erosion of test samples in the absence (a) and in the presence of the applied magnetic field (b) as a function of time.

Most likely, one of the reasons of this phenomenon is desorption of the surface-active substance from the magnetic particles as a result of the microimpact action of collapsing cavitation bubbles. In this case SAS molecules either form new chemical compounds (the chemical action of cavitation) [1] or go into solution. In the latter case SAS-free particles integrate into larger associates. A similar effect takes place upon dilution of the magnetic liquid by the dispersion base. To obtain more detailed data on the structure of the magnetic liquid and the mechanism of the action of cavitation on the liquid, comprehensive methods of investigation of the frequency response of magnetic permeability and optical microscopy must be used.

Figures 4 and 5 presents results of the investigation of the effect of the magnetic field on the decrease in the weight of test samples under the action of intense vibrations with an amplitude of $20 \cdot 10^{-6}$ m. As is evident from the figure, a change in the strength of the magnetic field by placing the source of the field at different distances from the test sample is accompanied by a variation in the weight decrease. It should be noted in this case that similar investigations carried out with a cavitating kerosene medium did not reveal an effect of the field on cavitation activity.

As follows from the results of the investigations, the above assumptions on the possibility of controlling cavitation by means of ponderomotive actions agree well to the data presented.

First of all, it should be noted that the magnetic field probably affects the structure of the cavitation region and its dynamics, which is indicated by oscillograms of the probe signal (Fig. 6). With a decrease in the distance between the magnet and the emitter of ultrasound vibrations, the amplitude of the probe signal increases, and the value of the variation ΔA decreases, which is probably indicative of an increase in the sound conductivity of the zone as a result of shifting of the function of the size spectrum of cavitation bubbles towards lower values. This is supported by the fact that with an inductive sensor that covers the cavitation zone, the number of spikes resulting from formation of large bubbles decreases sharply.

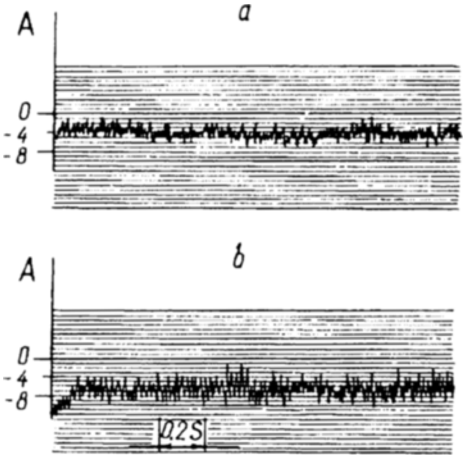

Fig. 6. Oscillograms of dependence of probe-signal amplitude A within the working zone of cavitation in the presence (a) and in the absence (b) of a magnetic field. A, dB.

It should be noted that for both the modeling of cavitation processes and the development of novel ultrasound technologies, problems of introduction of powerful ultrasound vibrations into local (small) volumes of magnetic liquid with a developed free surface and a high density of acoustic energy confined in an arbitrary spatial arrangement are of topical interest. The use of conventional nonmagnetic media for these purposes is virtually impossible. As is known, the interaction of powerful ultrasound with the free surface of a liquid leads to the fountain effect, spraying, and pulverizing, which result from the capillary-wave instability mechanism [12].

As is shown by the investigations carried out, the best conditions for increasing the critical threshold of the specified instability, which is determined by the Bond number $B_m = \nu_0 M \nabla H l^2/\sigma$, where l is the length of characteristic perturbations of the surface, occur when the field lines are directed tangentially with respect to the free surface, and the gradient of the field intensity is directed normally. When the normal component of the field is present Rayleigh instability [1], which is accompanied a peak structure that weakens the mechanism of suppression of liquid spraying, is possible.

Conditions for the stable confinement of a magnetic liquid with a volume of ~20 cm^3 upon excitation of vibrations with an amplitude of 25 μm and a frequency of 22 kHz in the liquid were modeled experimentally. The source of the magnetic field confined the magnetic liquid on both the horizontal and vertical surfaces and was placed opposite the surface that emitted the ultrasound. A sample of liquid with saturation magnetization $M \simeq 40$ kA/m and a kerosene base was used as a cavitating medium. In practice, when a magnetic field with strength $H \simeq 2 \cdot 10^5$ $\mathrm{A/m^2}$, $\nabla H \sim 10^6 - 10^7$ $\mathrm{A/m^2}$ was created, and at temperatures of 80–90°C, effects of spraying of the liquid are absent.

It should be noted that heating of the liquid lowers the threshold values of the intensity of vibrations introduced as a result of a decrease in magnetization, surface tension, and viscosity of the liquid, which determine the complex mechanism of acoustohydrodynamic and surface interactions.

Conclusions

1. It is shown by qualitative analysis of the effect of a magnetic field on acoustic cavitation in magnetic liquids that a magnetic field can cause additional migration of cavitation bubbles from the working volume, variation of their spherical shape, and an increase in their collapse rate.

2. Studies of the anisotropy of ultrasound propagation through magnetic liquids with a kerosene base and magnetization of from 0 to 54 kA/m have shown that the action of high-intensity ultrasound vibrations at temperatures of 80–90°C does not lead to an increase in variation in the attenuation coefficient. No variation in the saturation magnetization of the magnetic liquid or its performance properties was observed either. This shows that these media can be used in ultrasound technology.

3. It was found experimentally that the action of an inhomogeneous magnetic field can result in an increase in the cavitation-induvced erosion of test samples. The possibility in principle of confinement of local volumes of a

cavitating magnetic liquid with a free surface in various spatial configurations with the use of magnetic fields is established.

4. The experimental results show the possibility in principle of efficient contactless control of cavitation phenomena in magnetic liquids by means of applied magnetic fields.

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