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Features of the Behavior of a Plane Axisymmetric Magnetic Fluid Drop in a Nonmagnetic Solvent and a Uniform Magnetic Field

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Abstract. The work is devoted to an experimental study of the process of dissolution of a magnetic fluid in a nonmagnetic solvent under the action of a uniform magnetic field. It is experimentally established that in a volume of magnetic fluid surrounded by a miscible solvent fluid, under the action of a uniform magnetic field, a mechanical movement arises, triggering deformation of this volume. Initially, the axisymmetric volume of the fluid takes an ellipsoidal shape, lengthening along the magnetic field direction. The main reason for this movement is the pressure differences in the magnetic fluid, caused by jumps and nonuniformities of the magnetic field at the interface between magnetic and nonmagnetic media. Simultaneously with the mechanical motion, the diffusion dissolution of the magnetic fluid occurs, which is also accompanied by the motion of the diffusion front at the interface between the fluids. The concentration gradients of magnetic particles that arise in this case cause gradients of the magnetization of the fluid and, as a consequence, gradients of the magnetic field intensity. Together, this triggers the appearance of a bulk magnetic force in the magnetic fluid, and the pressure gradients associated with it. The main regularities of this process have been established, viz. the dependence of change of the geometric characteristics of the volume and its deformation rate on time. It is shown that at the initial stage of the process, the rates of mechanical movement of the boundaries of the magnetic fluid volume are much higher than the rates of movement of the diffusion front. Thus, the initial rate of mechanical elongation of the droplet under the experimental conditions is 0.25 mm/min, and the diffusion front rate is 0.08 mm/min. Over time, these processes slow down and stop when the volume of the magnetic fluid is completely dissolved. Herewith, the mechanical elongation of the drop is the first to stop and, in the case under consideration, takes about ten minutes.

Keywords: magnetic fluid, nonmagnetic solvent, diffusion, droplet dissolution, uniform magnetic field, magnetic pressure drop, droplet deformation

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Особенности поведения плоской осесимметричной капли магнитной жидкости в немагнитном растворителе в однородном магнитном поле

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Реферат. Работа посвящена экспериментальному исследованию процесса растворения магнитной жидкости в немагнитном растворителе под действием однородного магнитного поля. Экспериментально установлено, что в объеме магнитной жидкости, окруженном смешивающейся с ней жидкостью-растворителем, под действием однородного магнитного поля возникает механическое движение, приводящее к деформации этого объема. Первоначально осесимметричный объем жидкости принимает эллипсоидальную форму и удлиняется вдоль направления магнитного поля. Основной причиной этого движения являются перепады давления в магнитной жидкости, вызванные скачками и неравномерностями магнитного поля на границе раздела магнитных и немагнитных сред. Одновременно с механическим движением происходит диффузионное растворение магнитной жидкости, которое также сопровождается движением диффузионного фронта на границе раздела жидкостей. Возникающие при этом градиенты концентрации магнитных частиц вызывают градиенты намагниченности жидкости и, как следствие, градиенты напряженности магнитного поля. В совокупности это приводит к возникновению объемной магнитной силы в магнитной жидкости и связанных с ней градиентах давления. Установлены основные закономерности этого процесса: зависимость изменения геометрических характеристик объема и скорости его деформации от времени. Показано, что на начальном этапе процесса скорость механического движения границ объема магнитной жидкости значительно превышает скорость движения диффузионного фронта. Так, начальная скорость механического удлинения капли в условиях эксперимента составляет 0,25 мм/мин, а скорость распространения диффузионного фронта 0,08 мм/мин. Со временем эти процессы замедляются и прекращаются, когда объем магнитной жидкости полностью растворяется. При этом механическое удлинение капли прекращается первым и в рассматриваемом случае занимает порядка десятка минут.

Ключевые слова: магнитная жидкость, немагнитный растворитель, диффузия, растворение капли, однородное магнитное поле, магнитный скачок давления, деформация капли

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Introduction

In connection with the development of technologies that use magnetic fluids [1–4] for heat transfer, chemical, and medical applications for water purification from harmful impurities [5–6], and many other purposes, the relevant issues are the interaction of limited free volumes of a magnetic fluid with a nonmagnetic fluid or gaseous environment. This becomes especially important when creating magnetic fluid emulsions and gas-liquid systems.

To date, the bulk of the work in this direction is associated with the study of the behavior of magnetic fluid droplets placed in a nonmagnetic fluid that is immiscible with them, when surface tension forces act on their interface.

The most interesting in this case is that under the action of an applied uniform magnetic field, the droplets are deformed, which is expressed in their elongation along the field. This fact was first noted based on theoretical calculations in [7] and experimentally observed in [8, 9]. Such change in the shape of an initially spherical droplet of magnetic fluid is due to the fact that its presence distorts the applied uniform magnetic field and causes the appearance of forces that tend to change the shape of the droplet in such a way as to minimize these distortions and the associated increase in the energy of the system. This minimization is ensured by elongation of the droplet along the direction of the magnetic field with a corresponding decrease in that part of the drop surface that is perpendicular to the field intensity vector and on which field jumps occur. Thus, a magnetic fluid droplet tends to form its surface so that the magnetic field is on the maximum possible area tangent to it, where, as is known from electrodynamics, the field intensity is continuous when passing through the interface between magnetic and nonmagnetic media.

The most impressive results of numerical simulation of this process in terms of accuracy are presented in a recent paper [10], where the authors achieved a detailed description of the process.

Such a deformation of magnetic fluid droplet volumes creates effective control mechanisms for multicomponent magnetic fluid systems for heat exchange technologies, including those accompanied by boiling [11, 12], bubbling [13], and magnetic fluid droplet impacts with the surface of its large volume [14], in lubrication systems [15].

A large number of works are devoted to the study of magnetic fluid droplet volumes of various geometries, including semi-bounded and flat droplets [16, 17].

Another large class of problems is associated with the situation when a magnetic fluid droplet is surrounded by a nonmagnetic fluid that mixes with it and dissolves it. In this case, the surface tension disappears at the interface between these media, but the processes of diffusion dissolution of the magnetic fluid come into play. At the moment, the most interesting investigated effects accompanying this situation are the instability of the boundary of the diffusion layer in a uniform magnetic field [18], as well as the labyrinth instability of a flat drop in a magnetic field normal to its plane [19]. In addition, as shown in [20], an alternating uniform magnetic field can create mechanism for mixing of fluids.

However, the existing viewpoints allow us to expect that in this case, in a constant uniform external magnetic field, mechanical motion can occur in the volume of the droplet, which provides an additional mechanism for its mixing.

The present work is devoted to the experimental study of the processes occurring in a plane axisymmetric magnetic fluid droplet surrounded by a nonmagnetic miscible fluid-solvent in a uniform magnetic field $\vec{H}$ parallel to the plane of the droplet, as shown in Fig. 1.

Consider the physical prerequisites for the expected results of this study. As it is known, at the interface between magnetic and nonmagnetic fluids, a magnetic pressure jump Δp arises, which is proportional to the square of the fluid magnetization component normal to the boundary M_n: $\Delta p = (1/2)\mu_0 M_n^2$, ($\mu_0 = 1,26 \cdot 10^{-6}$ H/m is the magnetic permeability of the vacuum) [1].

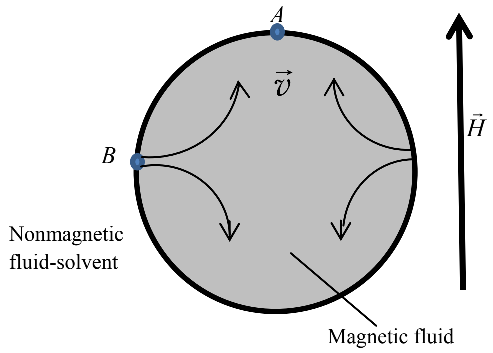

Fig. 1. Geometry of the problem

By this value, the pressure in the magnetic fluid is less than the pressure in the surrounding nonmagnetic fluid. At those points where the magnetic field is tangent to the interface, such a pressure jump does not occur and the pressure in the magnetic fluid is equal to the pressure in the nonmagnetic fluid. With regard to the situation considered in Fig. 1, the above means that when a magnetic field is applied, the pressure p_A at the top of the droplet at point A will be less by the value of this jump than the pressure p_B at the side point B. Under the action of this pressure difference in the droplet, the fluid will begin to flow from the area with a higher pressure to the area with a lower pressure, that is, from the side points to the peaks. The result of such fluid overflow will be the elongation of the fluid droplet along the vector of magnetic field intensity. The droplet from spherical will turn into ellipsoidal. As mentioned earlier, for a droplet of magnetic fluid surrounded by an immiscible nonmagnetic fluid, this process has been studied in sufficient detail both experimentally and theoretically. In this case, when the droplet is elongated, the curvature of its surface changes at the top and side points considered above, as a result of which different capillary pressure jumps arise at these points, triggering corresponding pressure differences in the fluid, which compensate for the pressure differences caused by magnetic pressure jumps. Because of this, the droplet takes some stable stationary shape.

In the situation considered in this paper, when the magnetic fluid and its nonmagnetic environment are miscible fluids and there is no surface tension between them, such a compensating action for the magnetic pressure jump does not occur and the elongation of the droplet cannot reach a stationary value. However, in this case, the diffusion dissolution of the magnetic fluid into the surrounding solvent and the corresponding blurring of the interface between the fluids will necessarily take place. It will turn into some kind of diffusion boundary layer with a smoothly changing concentration of the magnetic fluid and an increase in thickness with time. The magnetic fluid concentration gradient is accompanied by the appearance of a magnetization gradient ∇M and, in its turn, causes a magnetic field intensity gradient ∇H. Thus, over time, pressure differences in the magnetic fluid caused by the magnetic pressure jumps are transformed into pressure gradients caused by the volume magnetic force $\mu_0 M \nabla H$ in a nonuniform magnetic field, which will provide a further elongation of the droplet. However, over time, as the droplet dissolves, the diffusion rate decreases, the thickness of the diffusion boundary layer increases, and the gradients of concentration, magnetization, and magnetic field intensity decrease. Accordingly, the process of elongation of the droplet will slow down and stop when the droplet is completely dissolved.

Thus, in the case under consideration, the mixing of a magnetic fluid droplet with a nonmagnetic surrounding solvent will be provided by two mechanisms: diffusion dissolution and mechanical motion due to pressure differences associated with jumps and gradients of its magnetization.

Experimental studies

In the experiments performed, a cylindrical droplet of magnetic fluid is formed in a thin layer between the glass plates of the Hele-Shaw cell and placed in a uniform magnetic field parallel to the plane of the plates. The remaining volume between the plates is filled with a transparent nonmagnetic fluid, into which the droplet dissolves. The small thickness of the layer makes it possible to carry out optical observation of the ongoing processes and the distribution of the magnetic fluid concentration over time, as well as their photography and filming. In the experiments carried out, magnetic fluids based on transformer oil were used, with magnetite as a dispersed phase of various concentrations and oleic acid as a stabilizer. Characteristics of magnetic fluids samples are given in Tab. 1.

Table 1

The main properties of used magnetic fluids

Type of the fluid	Magnetization of saturation, kA/m	Density, kg/m^3	Volume concentration of magnetite, %	Viscosity, P·c
MMT-32	32.1	1313	0.105	0.0395
MMT-8	7.90	988	0.025	0.0248
Transformer oil	0	886	0	0.0210

The fluid that is the basis of the magnetic fluid, i. e. pure transformer oil, was used as the solvent surrounding the droplet. The thickness of the studied droplets was 0.14 mm, and their radius was 4.5 mm. A uniform magnetic field was generated by Helmholtz coils with a working zone diameter of 200 mm. The experiments were carried out at a magnetic field intensity of 12.6 kA/m and in its absence. During the experiment, photography and filming were carried out with subsequent image processing using Photoshop. Visual typical results of the experiment are presented in Fig. 2.

As expected, in the absence of a magnetic field, the initially cylindrical droplet of magnetic fluid with radius $r_0 = 4.5$ mm retained axial symmetry and monotonically increased its radius due to diffusion dissolution into the environment, Fig. 2a, b, c. When a uniform magnetic field is applied, the photographs in Fig. 2d, e, f demonstrate an obvious violation of the axial symmetry of the droplet and its elongation along the field, which also corresponds to the above physical concepts of the diffusion and mechanical processes which take place in it.

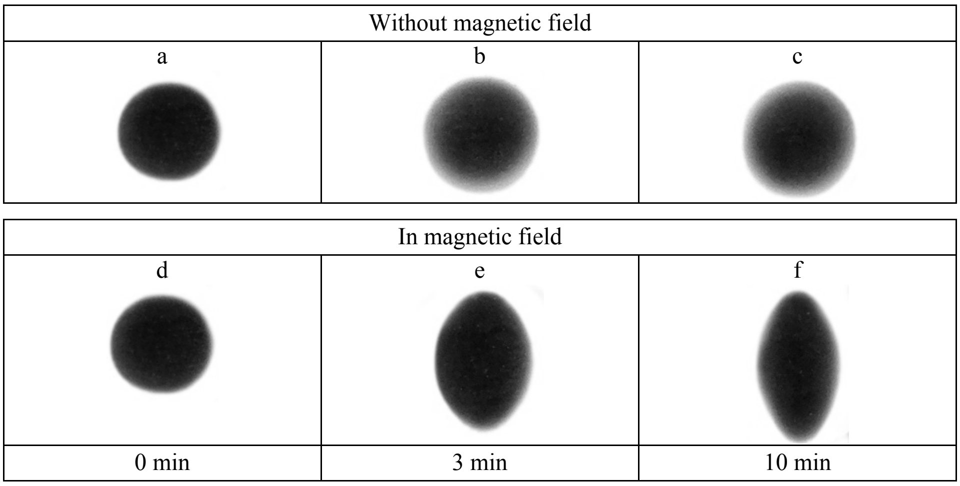

Fig. 2. Photos of droplets of magnetic fluid MMT-32 in a nonmagnetic solvent:
in the absence of magnetic field: a – the initial moment; b – after 3 min; c – after 10 min;
in a uniform magnetic field: d – the initial moment; e – after 3 min; f – after 10 min

Fig. 3 shows the results of processing images of droplets in the absence of a magnetic field from Fig. 2a, b, c at different moments of time with the help of Photoshop.

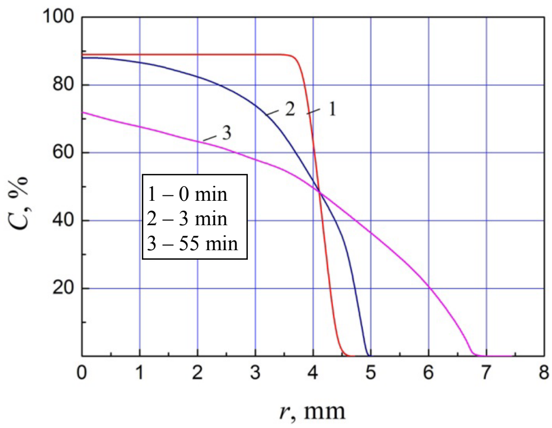

Fig. 3. Distribution of the darkness level of magnetic fluid droplet images at different moments of time during its diffusion dissolution in the absence of a magnetic field:
1 – initial moment of time; 2 – after 3 min; 3 – after 55 min

The distribution of the darkness level C of these images at different moments of time gives a clear picture of the distribution of the concentration of the magnetic particles in magnetic fluid at these moments and the dynamics of its change.

Since the magnetic fluid has a dark color and its environment is transparent, at the initial moment of time the boundary between them is quite clear. As the magnetic fluid dissolves, this boundary becomes fuzzy and is characterized by varying darkness levels in black and white images. Naturally, the darker areas correspond to a higher concentration of the magnetic fluid in the solution. The correspondence between the concentration of the magnetic fluid and the darkness level on the obtained photographic images in the first approximation can be established based on the Bouguer – Lambert – Beer law, although, due to the complex molecular composition of the magnetic fluid, its use cannot provide sufficient adequacy.

The boundaries of a magnetic fluid droplet at each moment of time were defined as the boundaries of the region in which the darkness level of the image differs by more than 1 % upwards from the darkness level of the environment. Since pure transformer oil is a transparent fluid, the darkness level corresponding to it in the presented photographs is 0. The results presented in this paper correspond to the condition that the dimensions of the magnetic fluid droplet are smaller than the longitudinal dimensions of the cavity, in which the studies were carried out, and its boundaries do not affect the process.

As can be seen from curve 1 in Fig. 3, at the initial moment of time, there is a sharp interface between the droplet of magnetic fluid and the surrounding solvent. Within the droplet, the concentration of the magnetic fluid is constant and sharply drops to zero at the boundary. With time, this interface becomes fuzzy and the thickness of the diffusion boundary layer increases. In the absence of a magnetic field, Fig. 2a, b, c, the droplet radius $r(t)$ increases only due to the diffusional dissolution of the droplet while maintaining its axial symmetry. The dimensions of the region with a nonzero concentration of the magnetic fluid are determined by the rate of movement of a diffusion front v_r which equals approximately 0.08 mm/min at the initial moment of time.

When a magnetic field is applied, the change in the size and shape of the droplet is provided by two mechanisms: diffusion dissolution and the above-described mechanical motion inside the drop. The droplet elongates along the field direction, taking a shape close to ellipsoidal with the major semi-axis $a(t)$ and the minor semi-axis $b(t)$. At the same time, knowledge of the behavior of a droplet of the same fluid and the same size in the absence of a magnetic field and its presence makes it possible to determine the characteristics of the mechanical deformation of the droplet.

Let us pay attention to the fact that the action of these mechanisms (diffusion and mechanical) can have a multidirectional character. Whereas diffusive dissolution triggers an increase in the size of the droplet in all directions, the mechanical motion triggers an increase in the longitudinal (along the field) and a decrease in the transverse size of the droplet.

As it can be seen from the graphs in Fig. 4 for a droplet of magnetic fluid MMT-32, the total action of these mechanisms over a 12-minute time interval ultimately triggers an increase in the relative longitudinal size a/r_0 by 60 % (curve 1) and a decrease in the relative transverse size b/r_0 (curve 3) size by 18 %. In this case, the relative increase in the droplet radius r/r_0 only due to diffusion dissolution in the absence of a magnetic field is about 10 % (curve 2).

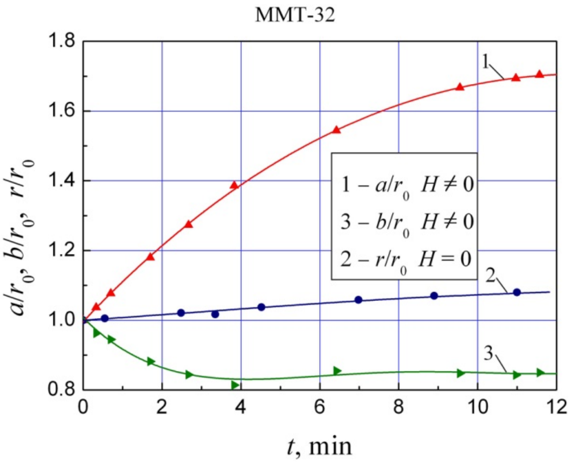

Fig. 4. Time dependence of the relative linear dimensions a/r_0, b/r_0, r/r_0 of the droplet of magnetic fluid MMT-32

The mechanical deformation of a magnetic fluid droplet in the processes under consideration is of the greatest interest, connected specifically with the magnetic properties of the fluid and the influence of a magnetic field. For a visual representation of the role of only the mechanical mechanism of droplet deformation, it is advisable to present the results of Fig. 4 without the diffusion expansion of the droplet $\Delta r = r - r_0$, namely $(a - \Delta r)/r_0$ and $(b - \Delta r)/r_0$ versus time. The results of this are shown in Fig. 5 and indicate elongation of the drop along the field direction and narrowing in the transverse direction. Moreover, in the concentrated fluid MMT-32, these processes occur more intensively than in the diluted one – MMT-8.

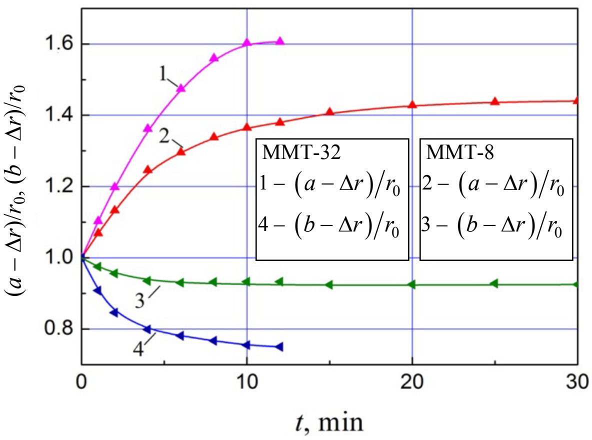

Fig. 5. Time dependence of relative linear dimensions $(a - \Delta r)/r_0$ and $(b - \Delta r)/r_0$ of droplets of concentrated MMT-32 and diluted MMT-8 magnetic fluids due to mechanical movement of its boundary

The change in the linear dimensions of the droplets of both fluids due to mechanical motion occurs most intensively in the initial time interval of about 12 min and practically stops after that.

Let us determine the rate of change in the linear dimensions of the drop as follows: $v_a = da/dt$ – the rate of change in the half-length of the drop (the rate of movement of point *A* in Fig. 1); $v_b = db/dt$ – the rate of change in the half-width of the drop (the rate of movement of point *B* in Fig. 1); $v_r = dr/dt$ – the rate of movement of the diffusion front. A positive value of the velocity indicates an increase in the corresponding sizes *a* and *r* of the drop, and a negative value indicates a decrease in the size *b*. Naturally, a total change in the linear dimensions of the drop in these directions occurs with a double value of these rates.

As follows from Fig. 6 at the initial moment of time, the rate of elongation of the drop v_a in a magnetic field is about 0.5 mm/min and exceeds the rate of its narrowing $v_b \approx 0.25$ mm/min, and the rate of the diffusion front $v_r \approx 0.08$ mm/min in the absence of a magnetic field.

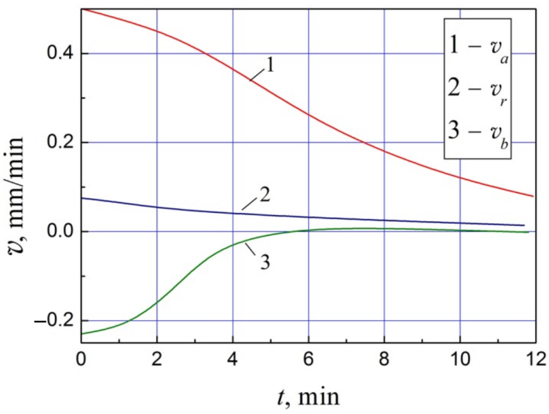

Fig. 6. Time dependence of the rate of change in the linear dimensions of a drop of magnetic fluid MMT-32 during diffusion and mechanical displacement of its boundary

For determining exclusively mechanical movement of the droplet boundaries, we present the results shown in Fig. 6, without the diffusion expansion of the droplet, namely: $v_{am} = v_a - v_r$, $v_{bm} = v_b - v_r$.

As can be seen from Fig. 7 at the initial moment of time, the rate of mechanical elongation of the droplet is approximately 0.5 mm/min for the MMT-32 fluid and 0.3 mm/min for the MMT-8 fluid, while the rates of narrowing of these droplets are 0.4 mm/min and 0.1 mm/min, respectively. Over time, the mechanical rates of the droplet boundaries drop to almost zero due to the action of viscous friction forces and a decrease in pressure gradients caused by magnetization and magnetic field intensity gradients as the diffusion boundary layer expands. The subsequent increase in the area occupied by the magnetic fluid is determined solely by its diffusion dissolution in the surrounding fluid.

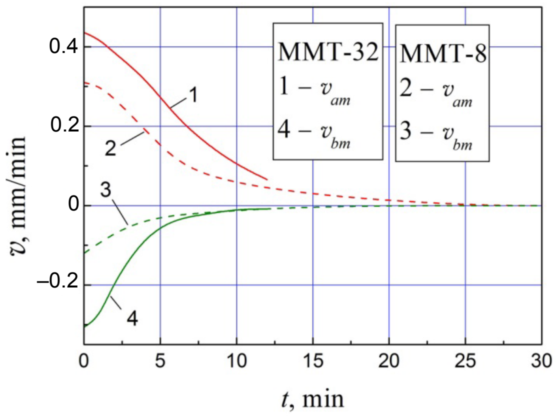

Fig. 7. Time dependence of the rates v_{am}, v_{bm} of the change in the linear dimensions of a magnetic fluid droplet due to the mechanical movement of its boundaries in a magnetic field

The results presented in Fig. 7 also indicate that large pressure gradients arising in a more concentrated magnetic fluid MMT-32 with a higher magnetization cause more intense movement than in a less concentrated fluid MMT-8 with a lower magnetization. On the other hand, the fluid MMT-32 with a higher magnetization has a higher viscosity. Therefore, the motion in the fluid MMT-32 monotonically decays faster (in about 12 min) than in the fluid MMT-8 (in about 30 min).

CONCLUSIONS

1. Thus, it has been experimentally established that a droplet of magnetic fluid surrounded by a nonmagnetic fluid-solvent that mixes with it in a uniform magnetic field changes its configuration and dimensions due to two mechanisms – diffusion dissolution and mechanical movement of the boundaries under the action of pressure differences inside it, caused by magnetic forces. The latter is due to magnetic pressure jumps at the boundaries, as well as gradients of the fluid magnetization and, accordingly, the magnetic field intensity associated with the inhomogeneous distribution of the concentration of magnetic particles in the fluid, which are a consequence of diffusion processes.

2. Magnetic forces cause the elongation of the droplet in the direction of the magnetic field. In this case, the greater the magnetization of the fluid, the greater the initial values – of the rates of the mechanical motion of the boundaries and the faster this motion monotonically decays.

REFERENCES

1. Rosensweig R. E. (1985) *Ferrohydrodynamics*. Cambridge, Cambridge University Press Publ. 344.
2. Blums E., Cebers A., Maiorov M. (1997) *Magnetic Fluids*. Berlin, Walter de Gruyter Publ. 416. https://doi.org/10.1515/9783110807356.

3. Bashtovoi V. G., Berkovsky B. M., Vislovich A. N. (1988) *Introduction to Thermomechanics Magnetic Fluids*. New York, Hemisphere Publ. Corp. 216.
4. Berkovsky B., Bashtovoi V. (ed.) (1996) *Magnetic Fluids and Applications Handbook*. New York, Begell House Inc. Publ. 851.
5. Magnet C., Kuzhir P., Bossis G., Meunier A., Nave S., Zubarev A., Lomenech C., Bashtovoi V. (2014) Behavior of Nanoparticle Clouds around a Magnetized Microsphere under Magnetic and Flow Fields. *Physical Review E*, 89 (3), 032310. https://doi.org/10.1103/PhysRevE.89.032310.
6. Rymasheuskaya K. D. (2017) The Improvement of Low-Waste Technologies of Working Body of Water Preparation at Thermal and Nuclear Power Plants. *Energetika. Izvestiya Vysshikh Uchebnykh Zavedenii i Energeticheskikh Ob'edinenii SNG = Energetika. Proceedings of CIS Higher Education Institutions and Power Engineering Associations,* 60 (4), 367–379. https://doi.org/10.21122/1029-7448-2017-60-4-367-379 (in Russian).
7. Tarapov I. E. (1974) Hydrodynamics of Magnetizable and Polarizable Media. *Fluid Dynamics,* 9 (5), 806–810. https://doi.org/10.1007/BF01017431.
8. Arkhipenko V. I., Barkov Iu. D., Bashtovoi V. G. (1979) Shape of a Drop of Magnetized Fluid in a Homogeneous Magnetic Field. *Magnetohydrodynamics*, 14 (3), 373–375.
9. Bacri J. C., Salin D. (1982) Instability of Ferrofluid Magnetic Drops under Magnetic Field. *Journal de Physique Lettres,* 43 (17), L649–L654. https://doi.org/10.1051/jphyslet:019820043017064900.
10. Langins A. A., Stikutsa A. P., Cebers A. (2022) A Three-Dimensional Boundary Element Method Algorithm for Simulations of Magnetic Fluid Droplet Dynamics. *Physics of Fluids,* 34 (61), 062105. https://doi.org/10.1063/5.0092532.
11. Gogosov V., Simonovskii A. Yu., Smolkin R. D. (1990) Quenching and Separation in Magnetic Fluids. *Journal of Magnetism and Magnetic Materials,* 85 (1–3), 227–232. https://doi.org/10.1016/0304-8853(90)90057-W.
12. Bashtovoi V. G, Challant G., Volkova O. Yu. (1993) Boiling Heat Transfer in Magnetic Fluids. *Journal of Magnetism and Magnetic Materials,* 122 (1–3), 305–308. https://doi.org/10.1016/0304-8853(93)91097-Q.
13. Bashtovoi V., Kovalev M., Reks A. (2005) Instabilities of Bubbles and Droplets Flows in Magnetic Fluids. *Journal of Magnetism and Magnetic Materials,* 289, 350–352. https://doi.org/10.1016/j.jmmm.2004.11.099.
14. Bashtovoi V., Kuzhir P., Reks A. (2002) Impact Between a Magnetic Fluid Drop and a Magnetic Fluid Surface. *Journal of Magnetism and Magnetic Materials,* 252, 280–282. https://doi.org/10.1016/S0304-8853(02)00601-7.
15. Labkovich O. N. (2017) Reduction of Friction Losses due to the Vortex Flow of the Magnetic Fluid Caused by the Additives of Carbon Nanotubes. *Energetika. Izvestiya Vysshikh Uchebnykh Zavedenii i Energeticheskikh Ob'edinenii SNG = Energetika. Proceedings of CIS Higher Education Institutions and Power Engineering Associations,* 60 (3), 265–275. https://doi.org/10.21122/1029-7448-2017-60-3-265-275 (in Russian).
16. Berkovsky B., Bashtovoi V. (1980) Instabilities of Magnetic Fluids Leading to a Rupture of Continuity. *IEEE Transections on Magnetic,* 16 (2), 288–297. https://doi.org/10.1109/TMAG.1980.1060613.
17. Bashtovoi V., Pogirnitskaya S., Reks A. (1999) Dynamics of Deformation of Magnetic Fluid Flat Drops in a Longitudinal Magnetic Field. *Journal of Magnetism and Magnetic Materials*, 201 (1–3), 300–302. https://doi.org/10.1016/S0304-8853(99)00144-4.
18. Derec C., Boltenhagen P., Neveu S., Bacri J.-C. (2008) Magnetic Instability between Miscible Fluids in a Hele-Shaw Cell. *Magnetohydrodynamics*, 44 (2), 135–142. https://doi.org/10.22364/mhd.44.2.6.
19. Huanhao Li, Chun-Yi Kao, Chih-Yung Wen. (2018) Labyrinthine and Secondary Wave Instabilities of a Miscible Magnetic Fluid Drop in a Hele-Shaw Cell. *Journal of Fluid Mechanics,* 836 (2), 374–396. https://doi.org/10.1017/jfm.2017.739.
20. Shyam S., Mondal P. K., Mehta B. (2021) Magnetofluidic Mixing of a Ferrofluid Droplet under the Influence of a Time-Dependent External Field. *Journal of Fluid Mechanics,* 917 (2), A15. https://doi.org/10.1017/jfm.2021.245.

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