Magnetic fluid phase separation in an electric field

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Abstract. The phase separation and structural organization of a thin layer of a magnetic fluid under the influence of a constant electric field are investigated. It is shown that the action of an electric field leads to the appearance of labyrinth structures in a thin layer of a magnetic fluid, which subsequently leads to the formation of a free charge at the boundary of this layer with the rest of the liquid volume. The results of the study of the current strength on the shear rate dependence made it possible to estimate the value of the surface charge density and the time of its formation in the near-electrode space. By artificially increasing the electrical conductivity of the initial magnetic fluid, it is shown that the formation of labyrinth structures in a magnetic fluid in an electric field occurs at a certain critical value of its electrical conductivity.

1. Introduction

Previous studies have shown the possibility of the periodic structural lattices formation in thin layers of MF in an electric field and their transformation with a change in external conditions [1, 2]. In [1], the formation of labyrinth structural lattices was observed when a certain critical value of the electric field strength was reached, the magnitude of which depended on the temperature, as well as on the strength of the additionally applied magnetic field. The analysis of the results of these studies allowed the authors of the work to conclude that under the influence of an electric field, a new, more concentrated phase is formed with its subsequent structural organization. The interpretation of the processes of structure formation in magnetic colloids as phase transitions was previously proposed in a number of works [3-5]. At the same time, our experimental studies have shown that stabilized MFs based on kerosene are quite stable and do not undergo phase separation due to magnetic dipole interaction in the temperature range corresponding to the existence of such systems, as well as under the influence of magnetic fields. This circumstance was also noted in [6].

2. Materials and methods

The object of the study was a kerosene-based MF with magnetite particles stabilized with oleic acid. An optical microscope equipped with a digital image recording unit was used to study the structural formations. The measuring cell consisted of two rectangular glass plates with a transparent conductive coating. A fluoroplastic film with a round hole was placed between the plates, which was filled with the studied MF. The thickness of the MF layer was 20 - 40 µm and was determined by the thickness of the fluoroplastic films. To create an electric field, a voltage was applied to the plates from a stabilized constant voltage source.
3. Results and discussion
The features of the behaviour of magnetic colloids in electric fields are largely determined by the interconnected process of formation of a free charge in the near-electrode space and a change in the structural state of the system. Indeed, in the case of the formation of a layer of a more concentrated magnetic fluid near the electrodes, a free charge should appear at the interface between strongly and weakly concentrated phases, which leads to a decrease in the electric field strength in the cell.

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An estimate of the magnitude of this charge can be made by representing the measuring cell in the form of a capacitor containing three layers of a weakly conducting dielectric. Suppose that the thickness of the layers of the highly concentrated phase at each of the electrodes is the same and equal to \( l_1 \), their specific conductivity and dielectric constant are equal to \( \rho_1 \) and \( \varepsilon_1 \) respectively, and the conductivity and dielectric constant of the layer of less concentrated liquid lying between them are equal to \( \rho_2 \) and \( \varepsilon_2 \). Then the surface density of free (external) charges at the interface between two layers \( \sigma = D_{2n} - D_{1n} = \varepsilon_0 \varepsilon_2 E_2 - \varepsilon_0 \varepsilon_1 E_1 \), where \( E_1 \) is the field strength in the near-electrode layers of the dielectric, \( E_2 \) is in the middle layer. According to the condition of current stationarity \( j_1 = j_2 \), i.e. \( E_1 \rho_1 = E_2 \rho_2 \). On the other hand, \( \int Edl = U \), or \( 2E_1 l_1 + E_2 l_2 = U \). From the last two equations it is easy to find \( E_1 \) and \( E_2 \), substitution of which into the equation for the surface charge density gives

\[
\sigma = \frac{\varepsilon_2 \rho_2 - \varepsilon_1 \rho_1}{2 \rho_1 l_1 + \rho_2 l_2} \varepsilon_0 U.
\]

An analysis of formula (1) shows that to estimate it is necessary to determine the thicknesses of the layers of highly and weakly concentrated phases, as well as their conductivity and dielectric permittivity. However, it is difficult to do this in real conditions. In addition, the layer of a highly concentrated phase concentrated in the near-electrode space, as follows from the results of experimental studies, is in fact not homogeneous, but represents a labyrinthine or stripe structural grid. Therefore, the field created by charges concentrated at the interphase boundaries of such a grid is not spatially uniform. Indeed, the field potential of a charged strip grid can be presented [7] in the form:

\[
\phi(x, z) = -\frac{\sigma|x|}{2\varepsilon_0} + \frac{1}{4\pi\varepsilon_0} \sum_{n=1}^{\infty} A_n A_n e^{-\frac{2\pi n z}{d}} \cos \frac{2\pi n x}{d}.
\]

It is obvious that the field strength, found according to the formula \( \mathbf{E} = \text{grad} \ \phi \) by substituting \( \phi \) in the form of expression (2), also changes both along the direction of the layer parallel to the plane \( (x) \), and perpendicular \( (z) \) to it. In this case, neglect of the inhomogeneous spatial distribution of the charged grid field is possible only at distances that significantly exceed the dimensions of the grid cells. It can be assumed that it is the lattice form of the free charge formed at the interface of a highly concentrated liquid that is the reason for the smooth, rather than abrupt, change in the field strength depending on the distance from the electrodes, established in [8]. The foregoing indicates the need to search for more accurate methods for determining the value of the free charge formed in the near-electrode space. In order to implement one of these methods, we carried out studies of the features of electrical conductivity when creating a flow in a magnetic fluid [9]. It turned out that the value of the current flowing through the cell with the magnetic fluid increases with an increase in the shear rate, reaching a maximum value at a certain velocity gradient. It was assumed that the observed phenomenon is associated with the complete erosion of the near-electrode charge. The latter made it possible to calculate the surface density...
of this charge, which turned out to be $\sigma=0.4\, \mu\text{C}/\text{m}^2$, which agrees in order of magnitude with that given in [8], where it was estimated using another (indirect) method.

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{figure1.png}
\caption{Dependence of current strength on shear rate.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=0.4\textwidth]{figure2.png}
\caption{Dependence of the surface density of the near-electrode charge on the solid phase concentration.}
\end{figure}

In order to further study the features of the charge transfer process in a colloidal medium, and their connection with structuring processes, similar studies were carried out for magnetic fluid samples with different volumetric content of the dispersed phase (figure 1). As can be seen from the figure, the current value, as well as its change with an increase in the fluid flow rate, significantly depends on the concentration of the solid phase. The obtained dependences made it possible to calculate the values of the surface density of the near-electrode charge for the samples of the corresponding concentrations (figure 2).

It turned out that the maximum $\sigma=f(C)$ corresponds to a magnetic fluid with a solid phase concentration of $C = 6\%$. Additionally, studies of the concentration dependence of the electrical conductivity (which was calculated from the I–V characteristics of the samples) of the magnetic fluid revealed the presence of a maximum on it at a concentration corresponding to the maximum concentration dependence of the surface density of the near-electrode charge.

The results of studying the dependence of the current on the shear rate also make it possible to estimate the time of charge formation in the near-electrode space. Indeed, the cessation of the increase in current at a certain flow rate may indicate that the time of flow of the liquid between the electrodes is insufficient for the formation of a free charge in it. This makes it possible, with known cell sizes, to estimate the charge formation time. The corresponding calculations gave for this time a value of the order of a few seconds, which corresponds to the time of formation of a labyrinth structure from a highly concentrated phase near the electrode. It can be concluded that the formation of a layer of a highly concentrated phase (labyrinth structure) occurs initially, which subsequently leads to the formation of a charge at the boundary of this layer with the rest of the magnetic fluid volume.

In [2], when studying the dependence of the processes of formation of a labyrinth structure in a magnetic fluid in an electric field on the excess content of oleic acid, it was suggested that the appearance of the structure may be associated with an increase in the conductivity of the magnetic fluid upon the addition of oleic acid containing impurity ions to it. To check this, the processes of the formation of such lattices were investigated when the electrical conductivity of a magnetic fluid changes in another way [10] - by adding crystalline iodine to it.
Indeed, it turned out that the addition of iodine grains to the magnetic fluid purified from excess surfactant increases its electrical conductivity, while, when a thin layer of such a liquid is placed in an electric field, the formation of a labyrinth structure is observed at intensities of the order of 100-300 kV/m, which coincides in magnitude with tensions at which structure formation is observed, due to an excess of oleic acid. In appearance, these structures (figure 3) have no visible differences from the structures obtained earlier by creating an excess of surfactant (oleic acid) in the volume of a magnetic fluid.

4. Conclusion
Thus, it can be concluded that the formation of a labyrinth structure in a thin layer of a magnetic fluid occurs at a certain critical value of its electrical conductivity. Apparently, the action of the electric field leads to the formation of a charge near the electrodes, in which the phase separation of the magnetic fluid occurs. In this case, a free charge is also formed at the interface between the interphase surfaces, which leads to an inhomogeneity of the electric field.

References
[1] Dikansky Y and Nechaeva O 2003 Colloid Journal 65 305-9
[2] Dikansky Y, Vegera Zh, Zakinyan A, Gladkikh D and Nechaeva O 2005 Colloid Journal 67 134-9
[3] Chekanov V 1980 Hydrodynamics and Thermal Physics of Magnetic Fluids (Riga: Institute of Physics of Latvia)
[4] Yurasov A and Yashin M 2020 Russian Technological Journal 8 59-66
[5] Buevich Yu, Zubarev A and Ivanov A 1989 Magnetohydrodynamics 2 39-43
[6] Van Ewijk G, Vroege G, Kuipers B and Philipse A 2002 Journal of Magnetism and Magnetic Materials 252 32-4
[7] Akhiezer A 1981 Electrical and Magnetic Phenomena (Kiev: Naukova Dumka)
[8] Yerin K and Padalka V 2005 Journal of Magnetism and Magnetic Materials 289 105-7
[9] Veguera Zh and Dikansky Y 2005 Journal of Magnetism and Magnetic Materials 289 87-9
[10] Zhakin A 2003 Physics-Uspekhi 46 45-61