Interaction and orientation of non-magnetic particles in magnetic fluid in magnetic and electric fields

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Abstract. In this article, the processes of structuring non-magnetic microparticles of various shapes (spherical and cylindrical) placed in magnetic liquid are investigated. It was established that the equilibrium orientation of non-magnetic microparticles and structural formations from them in magnetic and electric fields is determined by the ratio of both field strengths and magnetic and electrical parameters of the carrier medium and material of non-magnetic inclusions. Analysis of mechanisms of interaction of non-magnetic filler particles and orientation of formed structures under the influence of magnetic and electric fields was carried out. It has been found that the action of a uniform magnetic field on a magnetic liquid with a dispersed non-magnetic filler leads to a significant anisotropy of the thermal conductivity coefficient - the difference in the thermal conductivity coefficient in the direction coinciding with the field strength vector and perpendicular to it can reach 25%. The analysis of the detected effect is made on the basis of ideas about the occurrence of structural anisotropy in such a medium due to the structural organization of non-magnetic filler particles in the magnetic field.

1. Introduction

Previous studies have shown that the effect of a magnetic field on non-magnetic particles in a magnetic liquid results the formation of structural lattices [1-3]. The appearance of structural lattices depends on the value of the magnetic field strength, its orientation relative to the plane of the liquid layer and the volume concentration of non-magnetic inclusions. The orientation of non-magnetic particles in the magnetic liquid is determined by the strength of magnetic and electric fields, which is undoubtedly of interest from the point of view of controllability in the structure of the ensemble of non-magnetic microparticles.

2. Materials and methods

The object of the study was a kerosene-based MF with magnetite particles stabilized with oleic acid filled with non-magnetic microparticles. Two samples of a composite magnetic liquid were prepared: the first sample consisted a micron-sized droplets of magnetic liquid in glycerol, the second had an ensemble of glycerol droplets of micron dimensions in a magnetic fluid. The choice of glycerin as the dispersed phase in the first case and the dispersion medium in the second was due to its high permittivity ($\varepsilon=43$) and immiscibility with the magnetic liquid. The study of structural and orientation effects observed in magnetic and electric fields with a measuring set (figure 1). To create an electric field, a voltage was applied to the plates from a stabilized constant voltage source, at the same time, due to...
difficulties in conducting observations in constant electric fields due to electrode polarization and electrophoretic migration of structural formations, studies were carried out in variable fields in the frequency range of 45-2000 Hz.

3. Results and discussion

It was found that glycerol droplets in the magnetic fluid combine into the chain structures stretched along the field strength lines by both the electric and magnetic field. In the case of crossed fields, the chains firstly formed in the previously included one of the fields, when the other field is turned on, the chains rotated by an angle, the value of which is determined by the field strength ratio.

Figure 2 (curve 1) shows a graph of the dependence $E^2 = f (H^2)$ corresponding to the stationary location of the chain glycerol droplets of in the crossed magnetic and electric fields at an angle 30° to the magnetic field strength vector. It should be noted, that in case of trying to increase this angle above 30° by increasing the electric field strength, the chain droplets merged into larger ones, up to the formation of the one large drop. It can be assumed, that this process corresponds to minimizing the total energy of the chain, which is the sum of its three components - magnetic, electrical and surface energy. As the angle between the direction of the electric field and the axis of the chain decreases, the field-induced electric moment of each drop and the chain as a whole increases, and the angle between the moment of the individual drop and the axis of the chain decreases. This leads to an increase in the dipole interaction of glycerol droplets with sufficiently high dielectric properties, and as a result, to their merging.
Droplets of magnetic liquid suspended in glycerin also combined the chains, both in electrical and magnetic fields. However, unlike chains formed from glycerol droplets, chains of magnetic liquid droplets could have any angle to the field strength directions without breaking the droplets. Thus, observation of the processes of aggregation of magnetic liquid droplets in glycerin showed that the chains previously formed and oriented in the magnetic field unfold at the subsequent action of the electric field up to full orientation along vector \( E \). This difference seems to be associated with a small value of the dielectric constant of the magnetic liquid compared to glycerin. For chains of magnetic liquid microdroplets, a graph of the relationship \( \varepsilon^2 = f (H^2) \) was also obtained, corresponding to the stationary position of the chain in the crossed magnetic and electric fields (for the angle between the axis of the chain and the intensity of the magnetic \( 30\)°), which is shown in figure 2 (curve 2). As shown in figure 2, both \( \varepsilon^2 = f (H^2) \) relationships are linear for both the glycerol microdroplet chain and the magnetic liquid microdroplet chain, but the inclination angles of these relationships are different.

To analyze the results of the studies, consider the moments of forces acting on a particle of anisotropic form (chain aggregate) in magnetic and electric fields. Let us first consider the chain of glycerol drops located in magnetic and electric fields. According to [4], the expression for the moment of forces acting on the dielectric ellipsoid can be represented as:

\[
K_e = \varepsilon_0 \varepsilon_f \frac{\left( \frac{e_f}{e_l} - 1 \right)^2}{2 \left( 1 + \frac{e_f}{e_l} - 1 \right) \left( 2 + \frac{e_f}{e_l} - 1 \right)},
\]

where \( \varepsilon_f \) and \( \varepsilon_e \) are the dielectric constants of the magnetic liquid and glycerin, respectively, \( \phi \) is the angle between the long half-axis of the ellipsoid and the electric field strength vector, \( n \) is the depolarization coefficient, \( V \) is a particle volume, \( E \) is a strength of an electric field.

For the moments of magnetic forces, take the expression for the rod-shaped non-magnetic particle placed in the magnetic liquid:

\[
K_m = \mu_0 \chi^2 \frac{(1-3N)H^2\sin2\alpha}{2(1+x-xN)(2+x-xN)}
\]

where \( \chi \) – magnetic susceptibility of magnetic fluid, \( \alpha \) is the angle between the long half-axis of the ellipsoid and the magnetic field strength vector, \( N \) – particle demagnetizing factor, \( H \) is a strength of an electric field.

In stationary state, the values of these moments are equal and it is allow deriving the tangent of inclination angle of condensation dependence:

\[
tg \delta = \frac{\varepsilon^2}{H^2} = \frac{\mu_0 \varepsilon^2(1-3N)}{\varepsilon_0 \varepsilon_f \left( \frac{e_f}{e_l} - 1 \right) \left( 1 + \frac{e_f}{e_l} - 1 \right) \left( 2 + \frac{e_f}{e_l} - 1 \right)} \frac{n}{(1-3n)(1+x-xN)(2+x-xN)},
\]

(1)

It is easy to notice that, as expected, the slope of the dependence \( \varepsilon^2 = f (H^2) \) depends on the ratio of parameters characterizing the magnetic and dielectric properties of the medium.

Similarly, we obtain the expression for the stationary arrangement of the chain formed from microdroplets of magnetic liquid suspended in glycerol:

\[
tg \delta = \frac{\varepsilon^2}{H^2} = \frac{\mu_0 \varepsilon^2(1-3N)}{\varepsilon_0 \varepsilon_f \left( \frac{e_f}{e_l} - 1 \right) \left( 1 + \frac{e_f}{e_l} - 1 \right) \left( 2 + \frac{e_f}{e_l} - 1 \right)} \frac{n}{(1-3n)(1+x-xN)(2+x-xN)},
\]

(2)

The difference between expressions (1) and (2) can explain the inequality of the slope angles of the dependencies \( \varepsilon^2 = f (H^2) \) obtained for the case of chains of glycerol microdroplets in magnetic liquid and microdroplets of magnetic liquid in glycerin (figure 2).

Structural anisotropy on magnetic fluid with non-magnetic particles in a magnetic field should lead to the occurrence of anisotropy of the physical properties, in particular thermal conductivity. In order to
verify this assumption, graphite particles with a size of 1-6 μm and a volume content of 6% were introduced into a magnetic fluid with a volume content of magnetite 7.2%.

![Graph](image)

Figure 3. Dependence of thermal conductivity coefficient of magnetic fluid with non-magnetic filler on strength magnetic field.

It turned out that the magnetic field leads to a significant anisotropy of the thermal conductivity coefficient (figure 3). This effect can be explained by aggregation of non-magnetic particles in magnetic field [5]. The value of strength of magnetic field H at which aggregation occurs is by order less than intensity of magnetic field corresponding to aggregation of magnetic particles.

In order to explain the observed effect, consider a model according to which the suspension is a system of axisymmetric elongated aggregates formed under the influence of a magnetic field from particles of fine filler oriented along an external magnetic field. If the direction of heat flux coincides with the direction of the external magnetic field, then the thermal conductivity of such a liquid is determined by the expression [6]:

\[
\frac{\lambda_z}{\lambda_f} = \frac{1 + \frac{\lambda_p}{\lambda_f + (\lambda_p - \lambda_f)N_z} \frac{2 \varphi_p}{3}}{1 - \frac{\lambda_p}{\lambda_f + (\lambda_p - \lambda_f)N_z} \frac{\varphi_p}{3}}. \tag{3}
\]

Here \(\lambda_z\) and \(\lambda_f\) are the thermal conductivity factors of particle and liquid, \(N_z\) – a demagnetizing factor, which is defined by:

\[
N_z = \frac{1}{r^2 - 1} \left\{ \frac{r}{(r^2 - 1)^{1/2}} \ln \left[ r + (r^2 - 1)^{1/2} \right] - 1 \right\},
\]

where \(r=a/b\) is ratio of length to diameter of aggregate.

An increase in magnetic field strength leads to an extension of the chain aggregates, and, as a result, a decrease in the demagnetizing factor. According to expression (3), this leads to an increase in the thermal conductivity of the magnetic liquid, which corresponds to the experimentally obtained dependence shown in figure 3.

4. Conclusion

In conclusion, the studies have shown the possibilities of effective control of the structural properties of the studied media by using constant magnetic and electric fields. Introduction of non-magnetic dispersed phase into magnetic liquid allows control of its thermophysical properties in sufficiently small magnetic fields, which can be used in areas using materials with specified controlled parameters.
References

[1] Dikansky Y, Bedzhanyan M, Kolesnikova A, Gora A and Chernushev A 2019 Technical Physics 64 337-41
[2] Dikanskii Y, Bedzhanyan M and Kiselev V 2002 Colloid Journal 64 29-32
[3] Korobov M, Bedzhanyan M, Borisenko O and Dikansky Y Experimental Thermal and Fluid Science 85 69-74
[4] Landau L and Lifshitz E 1984 Electrodynamics of Continuous Media (Oxford: Pergamon Press)
[5] Yurasov A and Yashin M 2020 Russian Technological Journal 8 59-66
[6] Demchul S, Zalegendler E, KordonskyV, Prokhorov I and Khusid B 1985 Magnetohydrodynamics 1 14-8