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# THE EFFECT OF EXTERNAL MAGNETIC FIELD ON DIELECTRIC PERMEABILITY OF MULTIPHASE FERROFLUIDS

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*Nowadays, ferrofluids are applied in various fields of science and technology, namely space, medicine, geology, biology, automobile production, etc. In order to investigate the feasibility of applying ferrofluids in magnetic field sensors, the paper presents research into the influence of the external magnetic field on dielectric permeability of ferrofluids comprising magnetite nanopowder, multiwall carbon nanotubes, propanetriol and deionized water. The real and imaginary parts of the dielectric permeability change respectively by 3.7 and 0.5% when applying the magnetic field parallel to the electric. The findings suggest that the considered ferrofluid can be used as a magnetic level gauge or in design of variable capacitors.*

**Keywords:** ferrofluid, dielectric permeability, magnetic field.

## INTRODUCTION

One of the first review works concerning ferrofluids is the report by Kaiser and Rosensweig [1] presented to NASA and published in 1969. In this report, they described methods for manufacturing ferrofluids and their magnetic, electrical and physical and mechanical properties. Since that time, researchers have been extremely active in studying ferrofluids [2–10]. The ferrofluid manufacturing utilizes iron powders and other ferromagnetic substances as filling materials. Unlike other magnetic systems, ferrofluids are known to provide a free translational motion for particles of magnetic filler, thus inducing structural modifications, which in turn, are associated with changes in the magnetic ordering and spatial arrangement of particles in a carrier fluid. Magnetomechanical, magnetooptical and electrophysical phenomena observed in ferrofluids are largely determined by the properties of small particles of filling materials, their interaction in external fields and the structural state of the system. The interaction between macro- and microscopic parameters of the substance is one of the major concerns of physics of liquid dispersion systems.

Ferrofluids are multiphase, stable colloidal liquids made of nanoscale ferromagnetic particles suspended in a carrier fluid. Their properties are determined by parameters of components within (solid phase, carrier fluid, stabilizer). Modification of these parameters allows varying more widely physical and mechanical properties of ferrofluids with a view to solve many scientific and engineering problems. Frrofluids have a wide range of applications in various fields of science and technology, namely: space, medicine, ore separation, non-destructive testing, sealing, production of magnetic absorbers, *etc*. [6–10].

At early development stages of the science dealing with ferrofluids, researchers expected that it would be a medium with electric and magnetic properties controlled by external electromagnetic fields. To date, there had been achieved a successful control for magnetic properties of ferrofluids [11], whereas changes in electrical properties due to external impacts are not visible enough. Creation of a ferrofluid-based composite medium with controlled electrical properties will provide control over the ferrofluid electrical properties. Having studied the effect of the external

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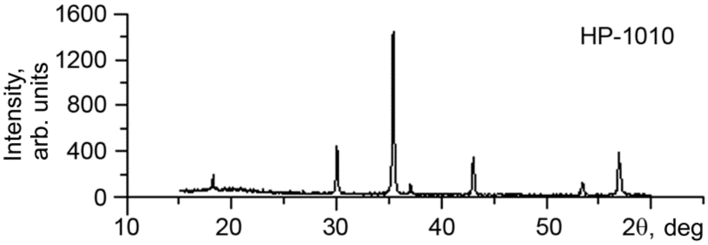

Fig. 1. X-ray diffraction pattern for HP-1010 toner powder.

magnetic field on a ferrofluid with graphite filler, Mkrtchyan *et al.* [12] showed that a measuring cell changes its capacity and conductivity.

The purpose of this work is to study the influence of magnetic field on electrophysical characteristics of ferrofluid comprising carbon nanotubes. More precisely, the aim is to explore the capability of controlling the ferrofluid dielectric permeability by the external magnetic field.

## MATERIALS AND METHODS

Ferrofluid manufacturing is still a complex matter as it is necessary to combine the size/weight ratio for filler particles and viscosity of a carrier fluid so that the magnetic particles would not precipitate. The addition of multiwall carbon nanotubes (CNT) in a small amount allows the viscosity to be increased.

In our experiment we use a multicomponent composite medium comprising HP-1010 toner powder from the Hewlett Packard Taiwan Company, Ltd., multiwall CNT-2 from the Boreskov Institute of Catalysis SB RAS, Novosibirsk, Russia; propanetriol from Galenofarm Company, Saint-Petersburg, Russia; and deionized water from Mikrogen Company, Tomsk, Russia.

The type HP-1010 toner powder was used as a magnetic filling material to prepare ferrofluid samples. According to the X-ray diffraction pattern presented in Fig. 1, the maximum peak position was observed at $2\theta$ = 35.38 degrees. This corresponded to $Fe_3O_4$ composition or magnetite powder covered with an amorphous carbon layer represented in Fig. 1 as low-intensity peaks. The particle size was 200 nm. If the ferrofluid is synthesized in the laboratory conditions, the carbon layer on the surface prevents magnetite particles from aggregation.

Measurements of the initial curve for specific magnetization showed that the saturation magnetization and residual magnetization of the powder were respectively 42.45 and 2.08 $\mathrm{Gs \cdot cm^3/g}$.

Multiwall CNTs with approximately 9.4 nm diameter were obtained in the Boreskov Institute of Catalysis SB RAS using the ethylene vapor deposition in the presence of a catalyst [13].

Phase composition of the magnetic filling material was investigated on a XRD-6000 X-ray Diffractometer from Shimadzu.

A bridge method was used to measure spectra of the dielectric permeability within the frequency band ranging from 20 kHz to 2 MHz. Measurements were carried out by means of an Agilent E4980A Precision LCR Meter. A disk capacitor with copper electrodes was used as a measuring cell. Its diameter and distance between plates were respectively 15 and 1.9 mm. The obtained values of capacitance and resistance were recalculated in accordance with the dielectric permeability using equations $\varepsilon' = C/C_0$, $\varepsilon'' = 1/\omega C_0 R$, where $\varepsilon'$, $\varepsilon''$ are real and imaginary parts of the dielectric constant; $C_0$ is the capacitance of capacitor without a dielectric; $C$ is the capacitance of capacitor filled with a dielectric; $R$ is the sample resistance.

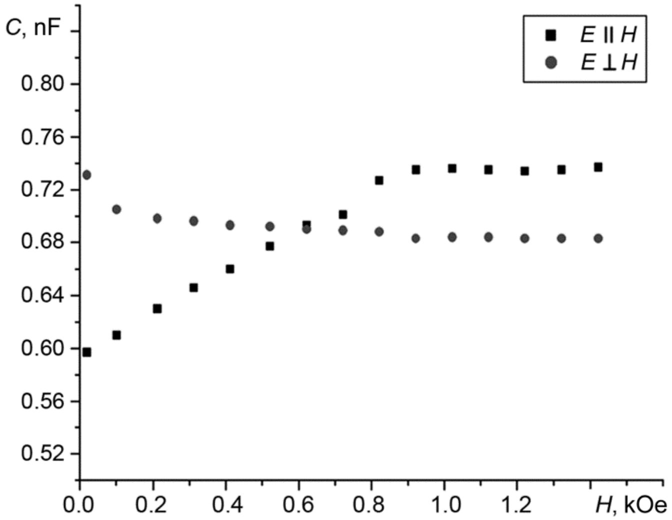

Fig. 2. Dependence between capacitance of the instrument capacitor and magnetic field.

## PREPARATION OF SAMPLES

The main requirement for the experiment is the preparation of a stable ferrofluid sample. The ferrofluid solution should retain its colloidal properties for at least one hour, because measurements of electromagnetic parameters take from 5 to 10 min, and that for the sample preparation take about 20 min. The carrier fluid, surface active agent and magnetic filling material are weighted on Shimadzu AUX-320 Analytical Balances with ±5 mg accuracy. Next, the filling material is added to and mixed with the surface active agent. The resulted suspension is diluted with a carrier fluid (deionized water) and mechanically mixed until a colloidal solution is obtained. The mass percentage mixture content of propanetriol/deionized water and toner is 70 : 30, whereas that of propanetriol/deionized water is 50 : 50. Multiwall carbon nanotubes are added to the prepared ferrofluid sample. The CNT content does not exceed 1 wt.%. The addition of CNTs to the ferrofluid increases its viscosity. The obtained sample is stable for 5 h allowing to provide a series of measurements just stirring it before use.

## RESULTS AND DISCUSSION

A study of the magnetic field effect on the capacitance of the instrument capacitor with a dielectric shows that this dependence presented in Fig. 2, is non-linear both in parallel and normal arrangement of magnetic field and electric field strength lines inside the capacitor. When the magnetic field strength $H$ is 0.9 kOe and higher, the capacitance is stable and its saturation occurs due to the following. In the absence of the magnetic field, the particles inside the ferrofluid sample are in chaotic state. When strength lines of the magnetic and electric fields are parallel ($\boldsymbol{H} \parallel \boldsymbol{E}$), the particles arrange along strength lines of the magnetic field from one electrode to another, thereby forming chains which interlock electrodes. And conductivity bridges appear in the measuring cell. Once all the powder particles will be involved in this state, saturation of capacitance occurs. This explanation is in a good agreement with results achieved in the work of Bhavsar *et al*. [14]. When $\boldsymbol{H} \perp \boldsymbol{E}$, magnetic particles arrange parallel to electrodes and form parallel-connected capacitors that ultimately reduces the capacitance. Its should be taken into account that when applying the external magnetic field, the ferrofluid viscosity reduces in the direction normal to the applied field.

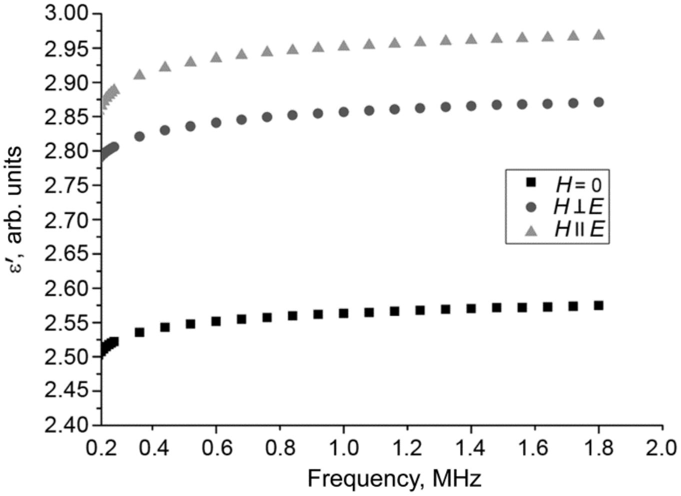

Fig. 3. The frequency dependence of the real part of the dielectric constant.

The addition of multiwall CNTs to the ferrofluid in the amount of not over 1 wt.% results in the linear growth of the dielectric permeability. This growth matches results obtained for solid composites made of polymers and CNTs and is caused by the formation of conducting channels connecting the capacitor plates. A further growth in the CNT concentration results in a strong increase in viscosity, and the sample is not longer categorized as a fluid.

Investigations also include the magnetic field effect on electrophysical parameters of the ferrofluid with CNTs. The magnetic field is applied in the amount of 1 kOe. Figure 3 contains the plot of the frequency dependence of the real part of the dielectric constant obtained using a bridge method. After each change in the magnetic field, there is a 15-minute wait for minimization of the transient process effect on the result obtained.

At a given amount of carbon nanotubes, the highest dielectric permeability is observed at $\boldsymbol{H} \parallel \boldsymbol{E}$. This is because the filamentary formations of magnetic particles arranging normal to the capacitor plates, enable carbon nanotubes to arrange also in this direction. When $\boldsymbol{H} \parallel \boldsymbol{E}$, the formation of conducting channels is the most probable and leads to the increase in the dielectric permeability. As can be seen from Fig. 3, it also grows when the magnetic field is applied in both directions. However, when strength lines of the magnetic and electric fields are parallel, the real part of the dielectric constant becomes larger than in the case when strength lines of both fields are normal. This effect exceeds a 2% measurement error of the dielectric permeability.

When $\boldsymbol{H} \perp \boldsymbol{E}$, carbon nanotubes form an ordered structure parallel to the capacitor plates, and the probability for the formation of conducting channels from plate to plate lowers. The difference between $\varepsilon'$ values is not very high that indicates merely to the formation of preferred direction rather than to a partial ordering of CNT arrangement in the ferrofluid. The formation of conducting channels occurs in both cases, but the probability for their formation increases at parallel strength lines. This is also promoted by both the CNT inertia and the ferrofluid viscosity which varies due to the orientation of strength lines.

For illustration purposes, we refer to Fig. 4 which plots dependences between the real and imaginary parts of the dielectric permeability to estimate the magnetic field effect. According to this figure, the ferrofluid Sample 1 is not provided with carbon nanotubes as against Sample 2.

As follows from this figure, the real part of the dielectric permeability grows with the application of the magnetic field, strength lines of which are parallel to that of the electric field.

The addition of carbon tubes to the ferrofluid evokes a 3.7% increase in the real part of the dielectric constant when applying the magnetic field parallel to the electric field. When the magnetic field is applied normal to the electric field, the real part of the dielectric constant increases by 0.5%. The magnetic field effect is stronger for the imaginary part of the dielectric constant. The CNT addition enables the metallic conductivity, when the imaginary part reduces

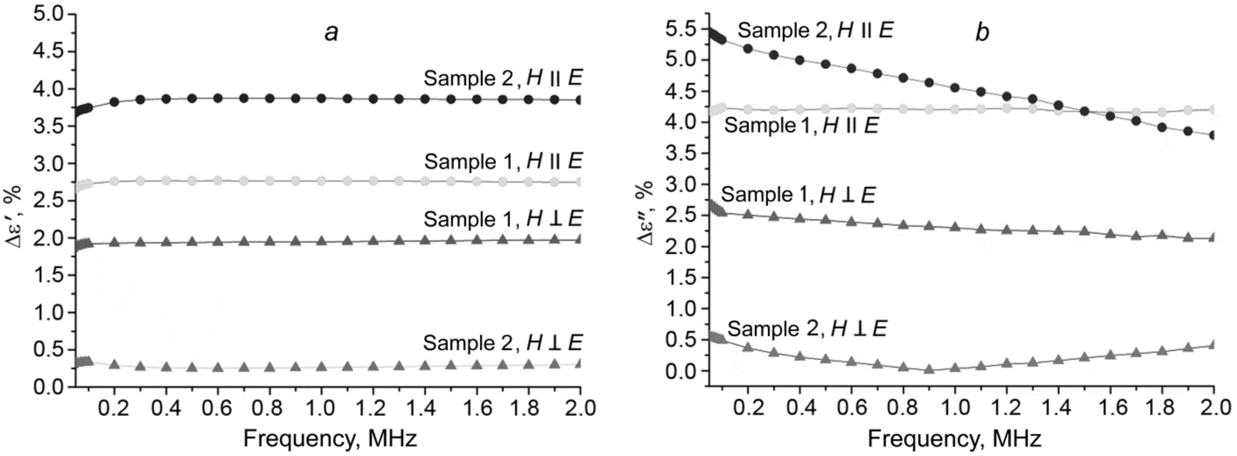

Fig. 4. Frequency dependences between the real (*a*) and imaginary (*b*) parts of ferrofluid dielectric constant.

with increasing frequency of the electromagnetic field. This behavior of the imaginary part confirms our assumption that in ferrofluid with CNT, conducting channels grow when applying the magnetic field parallel to the electric field.

## CONCLUSIONS

As a result of our investigation, we obtained the samples of stable ferrofluid and measured their electrophysical parameters. It was found that the capacitance of the capacitor, between the plates of which there was a ferrofluid with carbon nanotubes, changed depending on the direction of the magnetic field applied. This was explained by a strong probability of formation of conducting channels between the capacitor plates and, as a consequence, by the growth in the dielectric permeability, when strength lines of the magnetic and electric fields are parallel.

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