

DIELECTRIC PROPERTIES OF MAGNETIC FLUIDS BASED ON TRANSFORMER OIL ITO 100 IN A HIGH FREQUENCY ELECTRIC FIELD

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We have studied dielectric properties (complex permittivity and dielectric loss factor) of a transformer oil ITO 100 based magnetic fluid with various concentrations of magnetic Fe₃O₄ nanoparticles covered with oleic acid as a surfactant. The experiments were carried out at different volume concentrations of magnetite nanoparticles up to 4% at room temperature and in a frequency range from 100 Hz up to 2 MHz, with and without external magnetic field up to 30 mT. The linear increase of the dielectric constant with volume concentration has been confirmed. The presence of magnetic field causes the increase of the real part of complex permittivity and the decrease of both the imaginary part of complex permittivity and the dielectric loss factor.

1. Introduction. Magnetic fluids (MFs) are new technological materials, which are of great interest for applications. The physical properties of these fluids allow many applications in different fields such as sealing and grinding technologies, heat transfer and hydrodynamic flow applications. It is known that impedance measurement techniques experience some serious disadvantages, such as electrode effects, parasitic impedances, skin depth and accuracy related problems. Very recently, Yusuf *et al.* [1] have determined the magnetodielectric effect from magneto-optical measurements, where the disadvantages typical of conventional impedance measurement techniques are avoided. When the MF is exposed to a magnetic field, the processes in macroscopic surroundings of the electrode system and in microscopic surroundings between magnetic particles give rise to the formation of needle-shaped aggregations (clusters) of magnetite particles. In many works, authors dedicated their research to the influence of external magnetic and electric field on the dielectric properties of MFs at lower frequencies.

The goals of this work are to observe the dependences of complex relative permittivity on the concentration of magnetite particles in MFs based on transformer oil ITO 100 and to give a proof about course of frequency dependences of both the imaginary and the real part of complex relative permittivity in the measured frequency range up to 2 MHz. The influence of a uniform magnetic field on both the complex relative permittivity and the loss factor ($\text{tg } \delta$) will be studied too.

2. Theory. The capacitance of the electrode system was calculated according to the well-known equation $C = \varepsilon_0 S/d$ [2], where ε_0 is the vacuum permittivity, S is the area of the electrode with a circular shape, and d is the distance between the used electrodes. The relative permittivity of the measured liquid was derived

using the Maxwell equation for vacuum

$$\oint_A (\varepsilon_0 \mathbf{E}) \cdot d\mathbf{S} = \int_V \rho_V dV, \quad (1)$$

where ρ_V is the volume electric-charge density and V is the volume region. From Eq. (1) we can derive the differential form

$$\text{div} (\varepsilon_0 \mathbf{E}) = \rho_V. \quad (2)$$

In the presence of both free charges ρ_V and bound charge ρ_P excess the right side of Eq. (2) contains the sum of all charges and $\nabla \cdot (\varepsilon_0 \mathbf{E} + \mathbf{P}) = \rho_V$ corresponds to a divergence expression for \mathbf{E} in a material region. The average electric dipole moment per unit volume denoted as \mathbf{P} is called the electric polarization field. A more compact version is obtained using the abbreviation $\mathbf{D} \equiv (\varepsilon_0 \mathbf{E} + \mathbf{P})$. The experiments have revealed that many dielectric substances are linear (\mathbf{P} is proportional to \mathbf{E}). For such materials, $\mathbf{P} = \chi_e \varepsilon_0 \mathbf{E}$, where χ_e is the electric susceptibility of the dielectric, and we can write

$$\mathbf{D} = (1 + \chi_e) \varepsilon_0 \mathbf{E}, \quad (3)$$

where $1 + \chi_e \equiv \varepsilon_r$ is the relative permittivity of the region. Choosing the symbol ε for the permittivity of the material, we can express it as

$$\varepsilon = \varepsilon_r \varepsilon_0, \quad (4)$$

and then Eq. (3) as

$$\mathbf{D} = \varepsilon_r \varepsilon_0 \mathbf{E} = \varepsilon \mathbf{E}.$$

From Eq. (4), the relative permittivity derived is $\varepsilon_r = \varepsilon/\varepsilon_0$. The calculated electrode system capacitance C in vacuum and the measured electrode system capacitance with tested liquid C_1 as a dielectric material are expressed as a relation

$$\frac{C_1}{C} = \varepsilon_r, \quad (5)$$

and thus the relative permittivity of the measured fluid was calculated. Conductive materials can be classified with reference to the magnitude of the conduction current density term $\sigma \mathbf{E}$ relative to the displacement current density term $j\omega \varepsilon \mathbf{E}$. Denoting the complex permittivity by the symbol $\hat{\varepsilon}$ yields

$$\hat{\varepsilon} = \varepsilon - j \frac{\sigma}{\omega} = \varepsilon' - j\varepsilon'', \quad (6)$$

where σ is the specific conductivity. The angle δ is called the dissipation angle. Its tangent defined by $\text{tg} |\delta| = \sigma/(\omega \varepsilon)$ is called the dielectric loss factor, or the dissipation factor of material. The loss tangent can be written in various forms [2]

$$\text{tg} |\delta| = \frac{\sigma}{\omega \varepsilon} = \frac{1}{\omega RC} = \frac{\varepsilon''}{\varepsilon'} = \frac{1}{\omega \tau} = \frac{G}{\omega C} = \frac{X_C}{R}, \quad (7)$$

where $X_C = 1/(\omega C)$. When alternating voltage acts at steady state, a time-varying electric field has to be taken into consideration at stress of a liquid medium. It means that the characteristic electric quantities are dependent on the frequency. The specific electric conductivity is not dependent on the frequency in steady state if electric charge carriers during half-period do not trace a trajectory comparable with their mean free trajectory in the observed medium. If this requirement is fulfilled, the specific electric conductivity decreases with the increase of frequency and the conductivity mechanism converts to the state of relaxation mechanism. The relaxation processes are frequency dependent. This influence will manifest itself strong if the relaxation time constant is comparable with the period of alternating voltage.

3. Experimental. The used MF based on transformer oil ITO 100 and magnetite (Fe_3O_4) nanoparticles covered with oleic acid as a surfactant was prepared according the well-known procedure [3]. The MF with a magnetite nanoparticle concentration up to 4% was used in our experiment. Their magnetization curves were measured by SQUID magnetometer.

The measuring plan-parallel cupreous electrodes were placed into a Faraday cage to measure the dielectric parameters of magnetic fluids. The electrodes were 1 cm in diameter and the distance between the electrodes was 0.1 mm. The device for measurement was connected to both a microcomputer and a generator of signal with varying frequency (100 Hz – 2 MHz) that the output voltage was 2 V. The measurements made at a temperature of 20°C. The measurement of the relative permittivity was made with help of Shering bridge Tettex 2818. The experimental error of capacity measurements was 0.05%. The real part of the relative permittivity of magnetic fluids was determined from the capacity measurements as $\varepsilon_r = C/C_0$, where C is the capacity of the capacitor with a magnetic fluid as a dielectric, and C_0 is the capacity of the same capacitor filled with the air. The imaginary part of the complex permittivity is derived from Eq. (7) assuming that the calculated relative permittivity ε_r from Eq. (5) is related to ε' and $\varepsilon'' = \varepsilon' \text{tg} |\delta|$, with the dielectric loss factor measured by a LCR meter.

4. Results and discussion. The saturation magnetization curves for a MF with the concentration of magnetite 0.25, 0.5, 1.5 and 4% are shown in Fig. 1. The dependence of the relative permittivity on the concentration of magnetic nanoparticles in magnetic fluids is illustrated in Fig. 2. The observed dependence is linear with the correlation coefficient 0.98. The increase of the real part of relative permittivity is caused by the presence of magnetite nanoparticles covered with oleic acid in transformer oil. For MF applications, it is very important to observe their dielectric properties determined by the applied electric field frequency. These materials belong to the group of weak polar fluids dictated by the concentration of magnetic particles. It is known that the relative permittivity in magnetic fluids is dependent on a lot of factors, such as the type of surfactant around the particles, concentration, zeta potential, pH value and so on [4], and to generalize the description of the obtained results is not at all easy. In the literature, the ideal dependence of the relative permittivity and loss factor on the frequency was described. However, MFs are more complex colloidal systems. That is why the

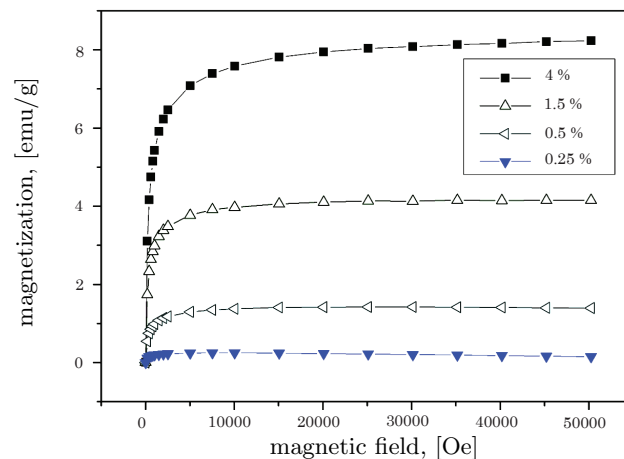


Fig. 1. Dependences of MF saturation magnetization on the magnetic field intensity.

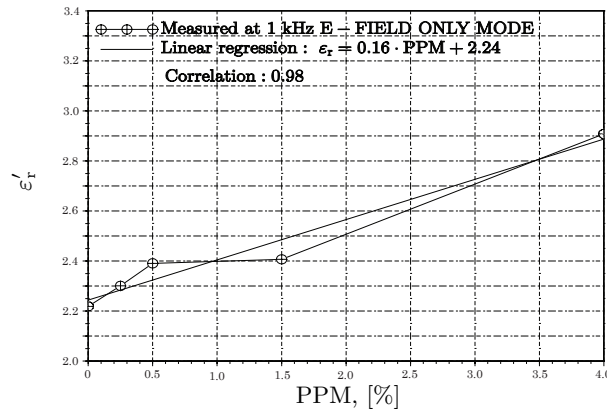


Fig. 2. Dependences of the real part of permittivity on the concentration of magnetic particles in MF.

behaviour of the real part of relative permittivity at low values of MF saturation magnetization does not correspond to its theoretical assumption completely (Fig. 3a). The crossing point was reached at a frequency of 100 Hz. When the frequency of electric voltage exceeds 100 Hz, the behaviour is almost monotonic. It means that a weak orientation polarization appearing at higher values of frequency causes a low and nearly constant relative permittivity.

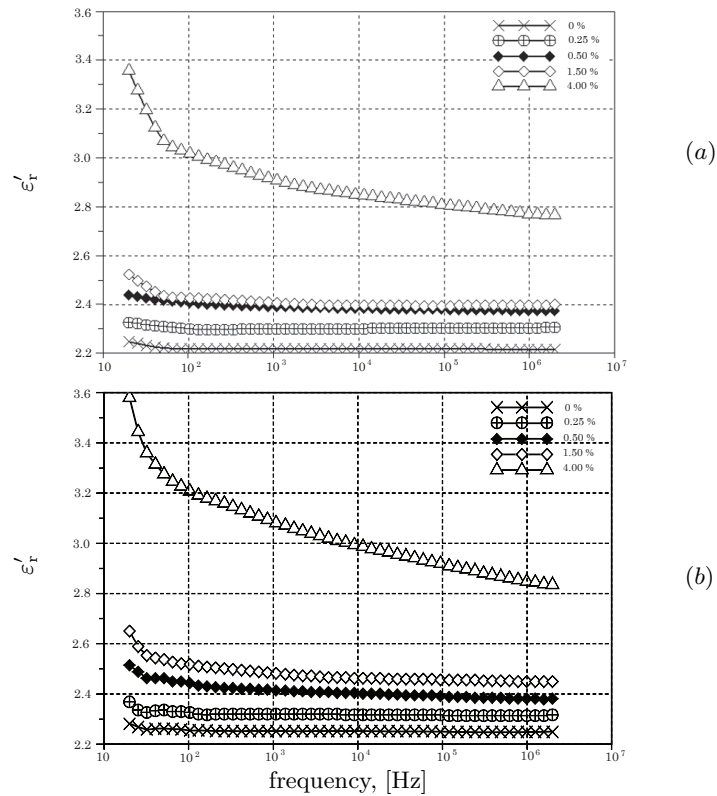


Fig. 3. The real part of relative permittivity vs. the MF frequency for pure oil ITO 100 and for MF for all concentration of magnetite (with $E = 0$ and $\mathbf{E} \parallel \mathbf{B}$, $B = 30$ mT).

The simultaneous action of the uniform magnetic field parallel to the electric field causes the increase of the real part of relative permittivity (Fig. 3) and the decrease of both the imaginary part of relative permittivity (not shown there) and the loss factor, as a consequence of Eq. (7).

5. Conclusions. In this work, we have described the obtained experimental results on the complex relative permittivity and loss factor of transformer oil ITO 100 based MFs with nearly spherical magnetite nanoparticles with the magnetite volume fraction up to 4% measured in the frequency range up to 2 MHz. The value of the real part of complex permittivity increases almost linearly with the volume concentration of magnetite nanoparticles as a consequence of higher specific conductivity. The variation of the real part of dielectric permittivity with the frequency has revealed that the dispersion exhibited by the samples is due to the Maxwell–Wagner type of interfacial polarization. The increase of the real part of dielectric permittivity at low frequencies can be explained by the existence of an electric double layer on the surface of a particle with reference to the Schwartz model [5], in which the polarization process, when an electric field is applied, is correlated to the corresponding relaxation process.

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