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Structure of transformer oil-based magnetic fluids studied using acoustic spectroscopy

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ABSTRACT

The structural changes in transformer oil-based magnetic fluids upon the effect of an external magnetic field and temperature were studied by acoustic spectroscopy. The attenuation of acoustic wave was measured as a function of the magnetic field in the range of 0–300 mT and in the temperature range of 15–35 °C for various magnetic nanoparticles concentrations. The effect of anisotropy of the acoustic attenuation was determined, too. The both strong influence of the magnetic field on the acoustic attenuation and its hysteresis were observed. When a magnetic field is increased, the interaction between the external magnetic field and the magnetic moments of the nanoparticles occurs, leading to the aggregation of magnetic nanoparticles and following clusters formation. However, the temperature of magnetic fluids also has very important influence on the structural changes because of the mechanism of thermal motion that acts against the cluster creation. The observed influences of both magnetic field and temperature on the investigated magnetic fluid structure are discussed.

1. Introduction

Magnetic fluids (MF) have attracted remarkable physical properties that have recently found wide application in technology [1–4] and medicine [5,6]. The transformer oil-based MF prepared by adding magnetic nanoparticle suspension to transformer oil with the purpose to improve some of the oil's insulating and thermal properties is an innovating example of the development in power electronic technology. The transformer oil usually used both for high voltage insulation and power electronics cooling is subjected to extensive research to enhance its characteristics. The dielectric breakdown strength of transformer oil, however, is strongly influenced by the aggregation effects of magnetic particles and can induce electric breakdown [7–9].

A MF is a colloidal suspension of nano-sized magnetic particles covered with a surfactant layer in a carries liquid [1,3,9,10]. Particles (usually ferrites) due to their small core diameters (4–20 nm) are generally monodomain and to prevent the interaction among them that may lead to their agglomeration and subsequent sedimentation they are coated by surfactants that produce entropic repulsion. The macroscopic magnetic properties of the MF are determined by the orientation of magnetic moments of nano-particles in the external magnetic field. An externally applied magnetic field induces ordering of the magnetic moments of the particles giving rise to magnetization of the sample as a whole and can cause certain amount of colloidal particles to join into quasispherical formations and clusters as long as hundreds of nanometers or more [11]. There are also computer simulations investigating an aggregation phenomena in a polydisperse colloidal dispersion of ferromagnetic nanoparticles [12–14]. After these simulations the cluster formation is strongly dependent on the magnetic particle–particle and particle–field interactions as well as on the ratio of these interactions. The shape of cluster is also dependent on the parameters of magnetic nanoparticles: radius, standard deviation and viscosity of magnetic fluid. In the dependence of these parameters there are three regimes of the formation: (1) short chain-like clusters, (2) long thin chain-like clusters and (3) long thick chain-like clusters [12].

For the making improvements in the transformer oil-based ferrofluids, it is important to find the methods the results of which enable to describe the physical behavior of these liquids, and in particular, the magnetic field induced structure changes of magnetic nanoparticles. One of the useful tool to study changes in the MF structure is based on the measurements of changes in acoustic wave attenuation $\Delta\alpha$ of MF under the influence of an external magnetic field and temperature. The structural changes (the process of clusters formation) in MF induce also additional changes in acoustic attenuation, so that the interaction between the acoustic wave and the aggregated magnetic particles or clusters produced in the presence of external magnetic field leads to the additional absorption of acoustic wave [15–19].

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The dependence of the attenuation of acoustic wave on the angle ϕ between the direction of propagation and that of the magnetic field (anisotropy) provides also important information on the ferrofluid structure in a magnetic field. The comparison of the experimental results with the theoretical predictions [18,21] allows the distinguishing of two motions of the clusters of the ferrous colloidal particles in the fluid (the rotation and translation motions) and the determination of the clusters radius, the density and other parameters of the colloidal particles. Also the proportion of the acoustic wave used for the excitation of translational and rotational degrees of freedom can be observed.

In the present study the changes of the acoustic attenuation as a function of external magnetic field and temperature in the transformer oils TECHNOL and ITO 100 based MF are investigated. The observed results are analyzed and discussed.

2. Experimental

Two kinds of transformer oil were used for the preparation of MF for the investigation by acoustic methods. The former MF used in experiments consisted of magnetite particles ($FeO \cdot Fe_2O_3$) with the mean diameter $D = 11.1$ nm, coated with oleic acid as a surfactant that were dispersed in transformer oil TECHNOL. The basic properties of this MF, such as the density, saturation magnetization and volume fraction were equal to 0.882 g/cm^3, 0.917 g/cm^3, 0.976 g/cm^3, and 4.7 mT, 9.5 mT, 14.1 mT for 1.0, 2.5 and 5.0% MF, respectively. The latter MF contained the same magnetic nanoparticles but with the mean diameter $D = 10.6$ nm, coated also with oleic acid as a surfactant, that were dispersed in inhibited transformer oil ITO 100. The basic properties of this MF, the density, saturation magnetization and volume fraction were equal to 1.071 g/cm^3 and 8.81 mT for 10% MF.

The block diagram of the experimental arrangement is shown in Fig. 1. The measurements of the attenuation of the acoustic wave of frequency 5 MHz and 13.3 MHz were carried out by a pulse method using the MATEC Pulse Modulator and Attenuation Recorder, Model 7700. An acoustic wave generated by *LiNbO*$_3$ or quartz transducer, propagated through the MF placed in the thermostated closed measuring cell ($1.5 \times 0.9 \times 1$ cm^3, the temperature stabilized with an accuracy ± 0.2 °C) inserted in an electromagnet underwent a multiple reflection between transducers. The first two selected adjacent echoes representing different paths after reflection and reaching a receiving transducer were received by the MATEC. The processed signals from the MATEC, the ratio of which represented the acoustic attenuation in MF, were displayed by the oscilloscope and evaluated and recorded by a computer. Computer also controlled current source for electromagnet.

3. Results and discussion

The dependence of the acoustic wave attenuation on external magnetic field at constant rate of its increase or decrease (2.2 mT per minute) and constant temperature of MF is shown in Fig. 2. This figure presents the attenuation changes for magnetic field **B** parallel to **k**, for 2.5% MF based on transformer oil TECHNOL (a) and for 1.25% MF based on transformer oil ITO 100 (b) where magnetic field linearly increased to maximum value 100 mT, 200 mT and 300 mT, respectively. The magnetic field after reach the maximum value and 1-minute pause decreased at the same rate to zero.

Similar behavior as in Fig. 2a was observed also for concentrations 0.5%, 1.0% and 5.0% of MF based on TECHNOL and result obtained in the case of MF based on ITO 100 for 2.5% and 5.0% concentrations were similar to those of Fig. 3b.

The observed results definitely show a strong influence of the magnetic field on the acoustic attenuation of investigated MF based on transformer oils. With increasing magnetic field, the acoustic attenuation from the beginning increases, because the interactions between the magnetic field and the magnetic moment of the nanoparticles leads to aggregation of particles and clusters formation (structures as long as hundreds of nanometers [1,11,14]). The behavior for higher magnetic fields (>120 mT) depends on the kind of MF (carrier liquid), concentration of nanoparticles and temperature. At the MF based on TECHNOL for all investigated concentrations of nanoparticles the acoustic attenuation increased about the same way for different values of achieved magnetic field. However, the character of acoustic attenuation changes with decreasing magnetic field depends on the achieved value of magnetic field (100, 200 or 300 mT) when after the achieved structural changes the process can even continue at decreasing magnetic field or at least achieved state remains unvaried. This is the reason that the changes of the acoustic attenuation show a hysteresis [15–18]. This effect can be explained by both the existence of clusters in TECHNOL, which lifetimes after their formation are longer than time of decrease of

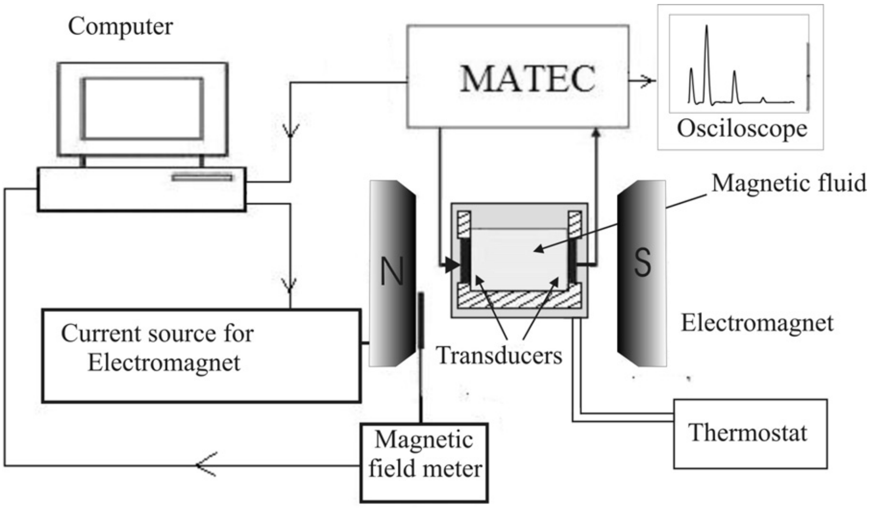

Fig. 1. Experimental setup.