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Research articles

Electrical conduction in a transformer oil-based magnetic nanofluid under a DC electric field

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A B S T R A C T

In this paper, we report on the experimental study of the direct current electrical conduction in a magnetic nanofluid based on transformer oil and iron oxide nanoparticles stabilized with oleic acid. We present the current–voltage characteristics of the pure transformer oil and the magnetic nanofluid with various particle volume fractions. From the Ohmic region, we calculate the electrical conductivity values and confirm the effect of increasing conductivity with increasing particle volume fraction. A few sources of space charge have been taken into account, among which the ion impurities play the key role. It was found that the current–voltage characteristics exhibit the inverse hysteresis-like behavior. Then, we focus on the magnetic field influence on the hysteresis behavior of a selected sample. The external magnetic field was applied in both, parallel and perpendicular configuration in regard to the electric field direction. It is shown that the magnetic field acting on the magnetic nanofluid in the perpendicular configuration results in the remarkable thinning of the current–voltage inverse hysteresis loop.

1. Introduction

Recent progress in high voltage engineering and power transmission industry has stimulated development of alternative cooling and electrical insulating nanofluids [1,2]. Among the various types of novel nanofluids, the magnetic nanofluids (ferrofluids) are of special interest due to their remarkably enhanced heat transfer properties and resulting cooling effectiveness [3]. It is well known that an external magnetic field is a vital factor affecting the convective heat transfer performances of the magnetic nanofluids and the control of heat transfer processes of a magnetic nanofluid flow can be possible by applying an external magnetic field [4]. It was shown [5] that the enhancement of the ferrofluids' heat transfer coefficient is caused due to remarkable changes in thermophysical properties of ferrofluids under the influence of the applied magnetic field. Moreover, under strong magnetic field and temperature gradients inherently present around electrical devices like power transformers, the magnetic nanofluid could undergo the thermomagnetic convection [6–9]. Thus, the magnetic nanofluid based on transformer oils have a potential to provide more effective cooling of the transformer core and windings as compared to pure transformer oils.

Besides the investigation of heat transfer properties of transformer oil-based magnetic nanofluids, much effort has been put into studying their dielectric and insulating properties, too. The increased dielectric permittivity due to the presence of nanoparticles was demonstrated in several papers [10,11]. Furthermore, from broad dielectric spectra, polarization and relaxation processes, as electric double layer and Maxwell-Wagner polarization, or space charge migration were deduced and analyzed [12–15]. Recently, electrode polarization and unusual magneto-dielectric effect in a magnetic nanofluid exposed to a magnetic field were reported in [16]. From electrical insulation point of view, the most intriguing phenomenon experimentally confirmed on various magnetic nanofluids is the increased electrical breakdown field strength as compared to pure oils [17,18]. A theoretical model explaining the phenomenon suggests that the dispersed nanoparticles act as electron scavengers, which slow down the streamer propagation leading to the electrical breakdown in the oil [19,20]. However, less attention has been paid to conduction currents in this type of magnetic nanofluids.

In general, suspensions containing nanoparticles in nonpolar liquids may exhibit the intrinsic σ_i and extrinsic conductivity σ_e

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[21]. The intrinsic conductivity usually originates in thermal excitation of charge carriers in the bulk liquid, or the charge carriers can be injected at the electrodes. On the other hand, extrinsic conductivity of nonpolar liquids may refer to electrolytic conduction associated with the dissociation of impurities in the liquid. The other contribution to the extrinsic conductivity is the injection of charge carriers from tips or edges connected with the induction of liquid motion. It can be suggested that in magnetic nanofluids, the nanoparticles also contribute to the conduction as they can be charged at one electrode and discharged at the other. Recently, it was shown that electrical conductivity measurements can provide a deeper understanding of suspensions structure, stability and rheology with implications in colloidal manipulation and consolidation methods [22]. In [23] the electrical conduction currents of purified transformer oil with and without surface-modified MgO nanoparticles were investigated. It was found that in the injection region of the current-voltage characteristics, the nanoparticles increase the charge production in the fluid. The electrical conductivity of transformer oil-based AlN nanofluid was studied in [24] as dependent on temperature and volumetric fraction. The study revealed that the nanofluid electrical conductivity has little relationship to the electrical conductivity of the dispersing nanoparticles but is sensitive to the electric double layer and aggregation of the nanoparticles. Therefore, it is obvious that investigation of electrical conduction mechanisms and pre-breakdown currents in insulating liquids can shed light on the understanding of the peculiar breakdown behavior, as discussed in [25].

The presented paper is focused on the current-voltage (I-V) characteristics measured on a transformer oil-based magnetic nanofluid with various concentrations of iron oxide nanoparticles. We analyze the conduction mechanisms and from the low voltage region we estimate the nanofluid's conductivity. Further attention is paid to the apparently saturated currents region and an observed inverse hysteresis-like behavior. It is shown how an external magnetic field affects the observed I-V hysteresis.

2. Materials and methods

The most widely used method to analyze the electrical conductivity of low-conducting liquids is to obtain a current-voltage characteristic and estimate the conductivity from the linear part of the curve [26]. The experimental setup used in our study is depicted in Fig. 1. The sample vessel of cubic shape (dimension 5 × 5 × 5 cm) is constructed from Teflon material because of its outstanding insulating properties. Two copper (Rogowski shape) electrodes with a diameter of 20 mm were inserted in the vessel in parallel each to other. The electrode separation distance was set to 0.6 mm. To apply and control DC voltage on the electrodes and to measure the current flowing through the investigated samples, the model 6517B electrometer/high-resistance test and measurement system (Keithley, USA) was employed. The voltage was continuously changed with 5 V steps within the range from −300 V to 300 V following the measurement sequence controlled by a computer. Each particular voltage value was held for a period of 1 s, during which the current was measured. In order to expose the vessel and the studied samples to an external magnetic field, two block permanent ferrite magnets (square shape, 5 × 5 cm) were attached to the vessel opposite side walls. In this way, the sample was exposed to a non-homogenous magnetic field in parallel (Fig. 1a) or perpendicular (Fig. 1b) configuration in regard to the electric field. In order to quantify the magnetic field distribution between the two permanents magnets, a numerical simulation has been performed by means of Newton's method solver implemented in the Agros2d software [27]. The calculated magnetic field intensity values distributed in the center between the two magnets are presented in Fig. 1c. The mean field intensity value between the magnets was found to be 45.3 kA/m.

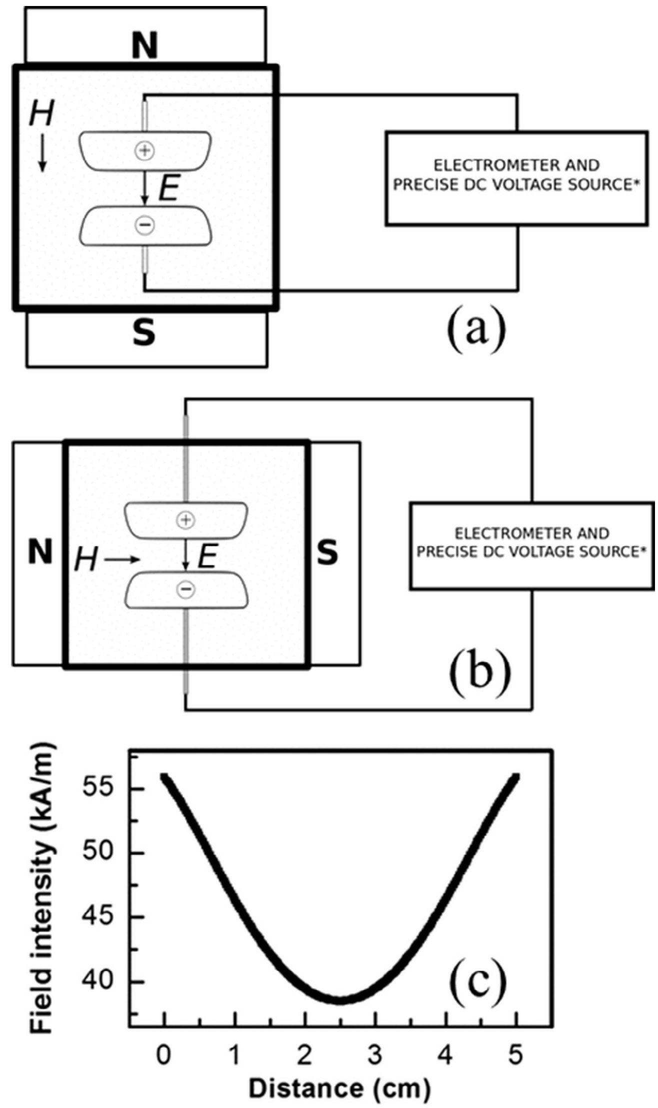

Fig. 1. The schematic of the experimental setup used to measure the I-V characteristics of the transformer oil and the magnetic nanofluid. (a) and (b) represent the measurement setup configuration where the magnetic field intensity *H* is parallel and perpendicular to the electric field intensity *E*, respectively. N and S denote the North and the South pole of the permanent magnets attached to the vessel. (c) represents the simulated magnetic field intensity distribution in the center between the two permanent magnets.

The investigated magnetic nanofluid was based on inhibited transformer oil ITO 100. The dispersed phase was composed of co-precipitated iron oxide nanoparticles stabilized with oleic acid in a well proven way [28,29]. The average diameter of the nanoparticles is 10 nm. Further information on the studied magnetic nanofluid have been published in a previous work [30]. For the purpose of the presented study, we have investigated four nanofluid samples with particle volume fraction of 0.25%, 0.5%, 1.5%, and 4%.

3. Theoretical consideration

Before presenting the experimental results, it is valuable to consider some processes and phenomena expected to appear in the studied nanofluid. Generally, with a parallel plate measurement cell, three regions can be distinguished in I-V characteristics. First,

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