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Magnetic fluid droplet deformation in electrostatic field

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ABSTRACT

The stability of the ferrofluid (FF) subjected to the electric field is crucial for the application in high voltage (HV) technology. There are several cases where the fluid interacts with solid interfaces. We examined experimentally FF drop on a glass surface. The drop was exposed to the steady electric field. During tests the suspended particles started to aggregate. Changing drop's shape was recorded during a time period. It was observed that the further deformation development depends on aggregates shape and location. The results are compared with the behaviour of pure carrier fluid. Understanding the phenomenon associated with FF drop deformation can help more reliable HV component design.

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1. Introduction

Ferrofluids (FFs) are known as colloidal suspensions composed of solid, single-domain magnetic nanoparticles (MNPs) coated with surfactant and suspended in a liquid carrier [1]. For decades the engineering surprises with FFs unprecedented innovation possibilities. The feasibility of FFs as cooling and insulating medium in power transformers is of great interest till today. Such fluids are usually based on the transformer oil carrier. Numerous experimental studies deal with magneto-dielectric effect in FFs. Less often the FFs interactions with electric field have been reported. However, one can see the raising efforts to unleash the NPs behaviour in colloids subjected to external electric fields [2–4].

Generally, external electric field causes the electrohydrodynamic flow in a colloidal system [5]. It has been observed that in the FF under DC electric field the nanoparticles (NPs) of Fe_3O_4 form themselves into the cloud patterns with the time depended shape development [6], moreover, the other physical properties of the FFs are moderated by external electric field, too [7,8]. External electric and magnetic fields cause structural-phase transitions in the FF that support a particle aggregation process in the FFs. It was proven experimentally by optical methods. The phase separation in the FF and large aggregate formation in the electric field was observed by Yerin and Padalka [9].

The FF droplet dynamics and the equilibrium shapes of free fluid bodies are important issues with outcomes to many practical applications. A number of the previous researches were carried out on the observation and analysis the fluid drops under specific conditions [10–14]. To describe a drop deformation due to the weak external electric field, Zholkovskij et al. proposed the electrokinetic model, where the charge carriers take part in the migration, diffusion and convection transport [15]. Recently, the transient response of drop deformation under steady electric field and the relation between electric capillary number dimensionless deformation time is reported by He et al. [16].

Here, we would like to bring to the attention specifics offered by the interaction of the FF leaky-dielectric drop and steady electric field. Our approach is based on the investigation of the FF drop on dielectric solid base. We show that in an external electric field the MNPs are carried by electro-hydrodynamic convective flow. During observation, MNPs were concentrating themselves close to the location of an ‘electrical equator’. MNPs started to aggregate there, creating the shape like a chain. Once the colloidal chain was assembled, it caused unexpected drop shape deformation. To our knowledge such phenomenon observed in magnetic fluids has not yet been reported. We optically observed the deformation process

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and quantized the concurrent variations of droplet shape for the FF and pure insulating oil. We propose the lacunarity estimation as a method for exhibition of scale-dependent changes in drop shape outline. The space charge distribution in the FF under steady electric field is different as the one in the transformer oil. Insulating liquid-dielectric barrier interface is known by the triboelectric effect that is coupled just with the space charge problem. There are many power system apparatus where this type of interface is possible, e.g. the power transformers, HV capacitors etc. Our experimental findings can suggest the consequences to be considered in the design of HV applications where FFs can be involved.

2. Material and methods

The investigation was done on the FF consisting of the transformer oil, iron oxide nanoparticles covered with a hydrophobic ligand of the oleic acid as a surfactant. The paraffin inhibited oil (Mogul Trafo CZ-A) was of power losses 0.001 at 90 °C and kinematic viscosity of 10 $mm^2 s^{-1}$ at 40 °C (values have been taken from the product list). The oil is often used as an insulating and cooling fluid in electrical power apparatus. The Fe_3O_4 NPs were synthesized by chemical co-precipitation of Fe^{3+} and Fe^{2+} from the aqueous solution of $H_{12}Cl_3FeO_6$ (Ferric chloride hexahydrate) [17]. The median of particle size distribution was 7.9 nm. The FF was diluted to reach the volume fraction of NPs 0.95%. The volume concentration was calculated as follows: $\Phi_V = M_s/M_d$, where M_s is the saturation magnetization of the FF sample, M_d is the domain magnetization of the bulk magnetic particle. For magnetite particles $M_d = 446$ kA m^{-1}. The saturation magnetization of as-prepared sample was 26.6 A m^2 kg^{-1}. The observations were conducted at ambient conditions: a temperature of 23 °C, a relative humidity of 48%. In following text the MFM indicates as-prepared sample of FF and OIL indicates pure oil.

To facilitate the observation, the 2-electrode test cell has been developed. Two needle-shaped electrodes have been employed as working electrodes. Their main dimensions follow: length of 30 mm and thickness 0.5 mm. The radius of the tip was 0.1 mm. The tips were placed in touch with a surface of the rectangular microscope glass slide. It was of 75 mm long, 25 mm wide and approx. 1 mm thick. During experiments the inter-electrode distance was set to 2 mm. Steady electric field of 2 kV/mm was created between the electrodes. The drop of investigated fluid was placed at the midpoint between the electrode tips. The diameter of the drop spreading on the glass was 700 μm approximately. The setup configuration is depicted in Fig. 1.

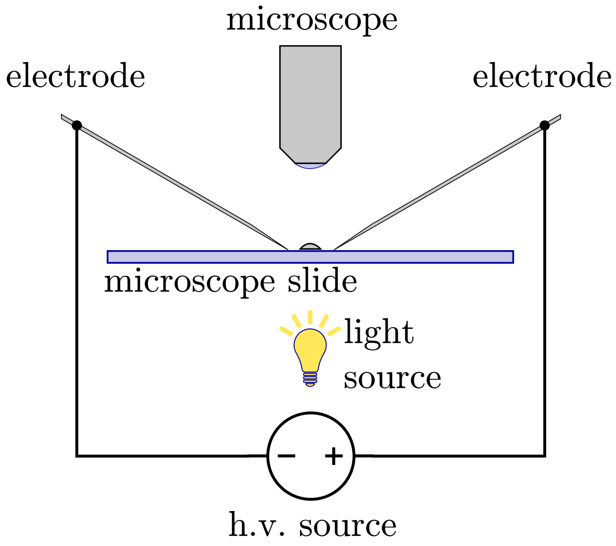

Fig. 1. Two-electrode test cell and experimental setup.

During experimental investigations, the drop deformation development has been visualized by integrated into the microscope the charge-coupled device (CCD) camera. Up-to 454 images with the resolution of 3264 × 2448 pixels in RGB working colour-space were acquired, grabbed and stored in the computer memory to be analysed later. The camera allowed streaming at 30 frames per second. The ferrofluid and the base carrier oil drops were tested in the experiment.

3. Theory and feature extraction

3.1. Lacunarity estimation

In the natural and technical sciences the quantification of spatial patterns is an important analysing approach. Fractal analysis is widely used as a morphometric measuring tool. Quantities such as the fractal dimension or lacunarity was originally developed to describe a property of fractals. However, it has been shown that i.e. lacunarity quantification can be suitable for the description of spatial distribution various types of real data sets, not only those with fractal and multifractal distributions [18]. Today, any irregular set can be modelled in these properties regarding texture analysis and image processing. Fractal dimension analysis can measure structural detail change with increasing magnification, scale or resolution of the object under test. It allows to quantify the complexity of the structure. With real objects, the lacunarity (λ) can quantify the distribution of gap sizes. It supplements fractal dimension, giving the characterization of patterns extracted from digital images.

Two sets of image records have been collected, each for both fluids observed. We decide to analyse the outline of each drop by estimating the lacunarity. To obtain the outline of the drop shape, we have applied a set of digital image processing procedures: the image colour-space was changed to 255 grey levels with enhancing the black and white colour threshold and finally, followed by the edge detect algorithm. The outline of each image represents the drop shape fingerprint. It was analysed by estimating the lacunarity where the box-counting algorithm were applied. Let us briefly recall the method of the lacunarity estimation.

The principle of the box-counting method is the step by step partitioning the pattern into square boxes and the counting the number of outline pixels inside the boxes. Boxes are of equal size at some scale ε. Not all, but the number of only outline pixels that fall within the box overlay the pattern is counted. At each step the size of boxes is decreased, see Fig. 2. Let p be the probability that box of given size B contains m black pixels. The mean μ of the pixels in the box is:

$$\mu_\varepsilon = \sum_{i=1}^{B} m_{i,\varepsilon} p_{i,\varepsilon} \tag{1}$$

The standard deviation σ of number of outline pixels in a box of the size ε follows:

$$\sigma_\varepsilon = \sum_{i=1}^{B} m_{i,\varepsilon}^2 p_{i,\varepsilon} - \mu_\varepsilon^2 \tag{2}$$

Finally, the lacunarity can be calculated as

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