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Numerical simulation of particle concentration in dielectrophoretic flow for high voltage applications

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ABSTRACT

A numerical simulation of magnetic nanoparticles in a liquid dielectric was developed to model dielectrophoretic flows for high voltage applications, e.g. transformers, capacitors, high voltage cables, and switchgears. From previous research, we found that the dielectric breakdown voltage of a transformer oil-based magnetic fluid was affected positively or negatively according to the amount of magnetic nanoparticles under the official testing condition of dielectric fluids. In order to understand these phenomena for enhancing the dielectric characteristics of the fluid, the magnetic particles were finally visualized experimentally and numerically in a fluidic chip consisting of a microchannel and electrodes. In this study, we calculated the dielectrophoretic flow and the particle concentration in the microfluidic system with different applied voltage and investigated the virtual images of magnetic nanoparticles for explaining the dielectric characteristics changes of a liquid dielectric with adding the particles.

1. Introduction

As a dielectric material in liquid state for high voltage applications, e.g. transformers, capacitors, high voltage cables, and switchgears, the main purpose of a liquid dielectric is to endure electric fields as high as possible or to quench electric discharges as fast as possible [1]. The dielectric breakdown voltage (DBV) is a measure of a liquid dielectric ability to withstand a high electric field stress without breaking down [2].

Magnetic fluid is a stable colloidal mixture containing magnetic nanoparticles (MNPs) coated with a surfactant [3]. It was found recently that the addition of magnetic nanoparticles could increase the dielectric breakdown voltage of the fluid if the condition of the added particles in the fluid was in balance with that of keeping down the initiation and propagation of electrical streamers [4–6].

In order to explain the phenomenon for increasing DBV with adding MNPs, which was in direct conflict with conventional wisdom regarding the breakdown of dielectric liquids, Hwang et al. with MIT [7] tried to explain the reason of the phenomena with the concept of electron scavengers of magnetic nanoparticles by computations. But they showed only the trend of initiation and propagation of electrical streamers only with a spherical particle for computations [8].

We have tried to verify the phenomena with the integration of dielectrophoresis (DEP) and microfluidic system for the characterization of micro/nano particles experimentally [9] and numerically [10]. Particle movement towards regions of high electric field intensities is called positive DEP (p-DEP) and occurs when the interior of the particle is more permissive to the field [11]. Positive DEP force traps particles in regions with strong electric field gradients, while negative DEP (n-DEP) force repels them from such regions [12]. However, it was very difficult to visualize the particles motion in situ using the microfluidic system, which was made up of a microchannel and electrodes. Therefore, we have been developing a simplified unified model for estimating the dielectrophoretic activity of magnetic nanoparticles using a commercial multiphysics program, COMSOL Multiphysics [13].

In this study, we numerically simulate the dielectrophoretic flow and the particle concentration in the microfluidic system with the different applied voltage. Furthermore, the virtual images of MNPs under the different DEP force are investigated for explaining the electrical breakdown characteristics of a liquid dielectric with adding MNPs.

2. Methodology

The computational domain, which is modeled according to a fabricated chip (50×20mm) used for visualizing magnetic nanoparticles in [9], consists of two cylindrical electrodes, a 2 mm-long microchannel filled with magnetic fluids and PDMS

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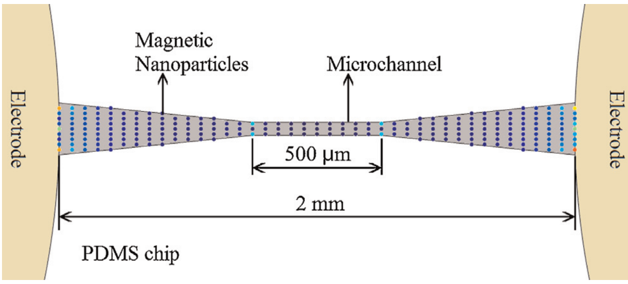

Fig. 1. Schematic diagram of the microfluidic system for computations with magnetic nanoparticles.

(polydimethylsiloxane) around a channel as shown in Fig. 1. The width and the height of a 500 μm – long microchannel located in the middle of the channel are 50 μm and 5 μm, respectively.

In order to compute MNP's trajectory in the microfluidic system under an electric potential, we have to calculate the electrostatic field and the flow field, sequentially. The electric field distribution in the system described by the Laplace equation with appropriate boundary conditions will provide the potential distribution in the computational domain. This potential distribution is used to calculate the DEP force acting on particles as shown in Eq. (1).

Table 1
Material properties for the computations of electric and flow fields.

	Magnetic fluid (0.065%)	Transformer oil	Magnetic nanoparticle (Fe_3O_4, 20 nm)	Electrode	PDMS
Density (ρ) [kg/m^3]	–	837	4800	–	–
Relative			permittivity (ε)	2.208	2.2
	1	12.1			
14.5					

$$F_{DEP} = 2\pi r_p{}^3 \varepsilon_m \mathrm{Re}[K(\omega)] \nabla |E|^2 \quad (1)$$

where ε_m is the permittivity of the base fluid and $K(\omega)$ the Clausius–Mossotti factor at frequency ω given by

$$K(\omega) = \frac{\varepsilon_p{}^* - \varepsilon_m{}^*}{\varepsilon_p{}^* + 2\varepsilon_m{}^*} \quad (2)$$

where $\varepsilon_p{}^*$ and $\varepsilon_m{}^*$ are the complex permittivities ($\varepsilon^* = \varepsilon - j\sigma/\omega$) of the particle and fluid, respectively. The magnetic nanoparticles with high polarizability compared to the base fluid ($\mathrm{Re}[K(\omega)] > 0$)

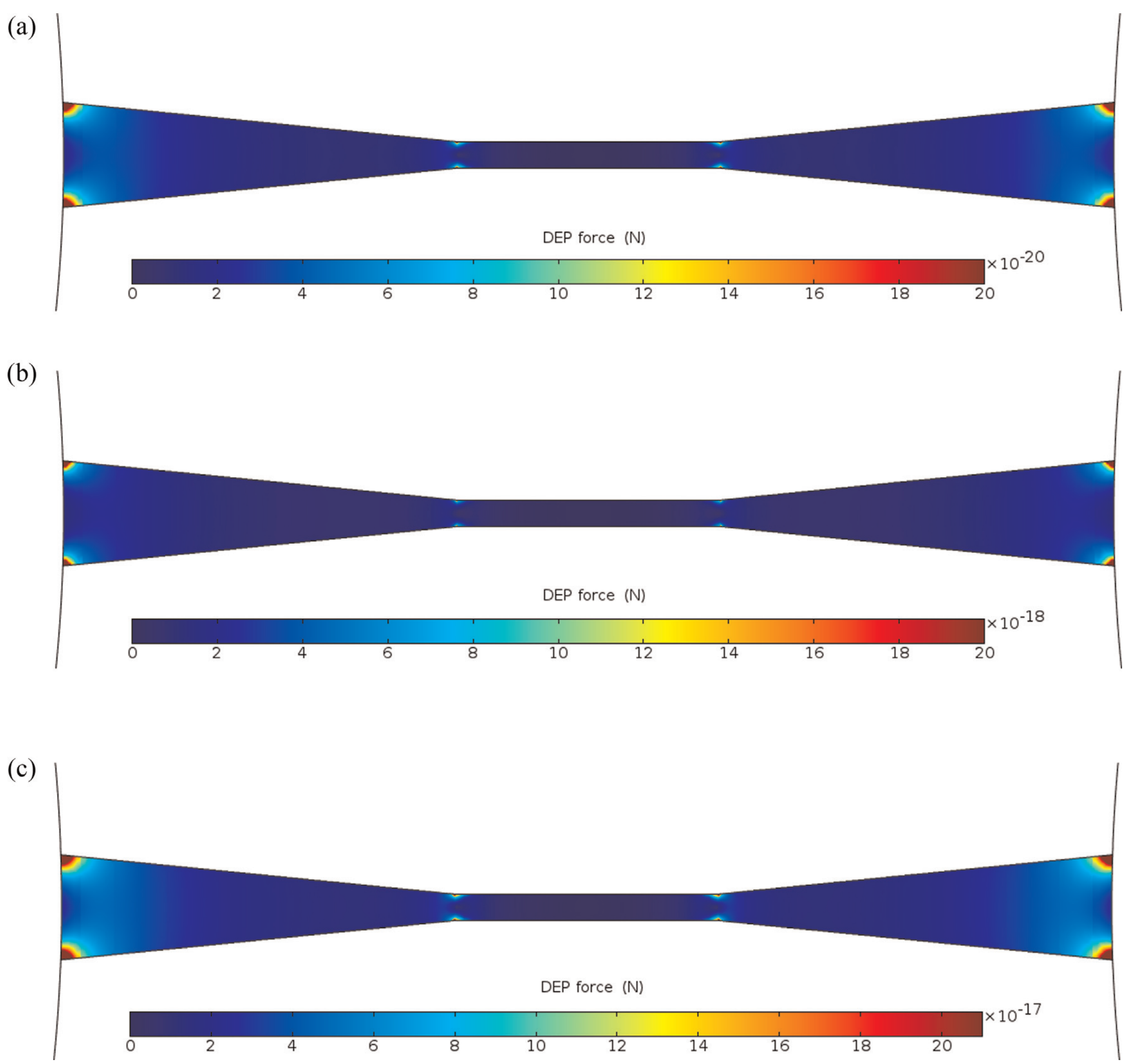

Fig. 2. The computational results of dielectrophoretic force [N] for three different voltages. (a) 2.5 kV, (b) 20 kV, (c) 90 kV.