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Visualization on the behavior of nanoparticles in magnetic fluids under the electric field

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Abstract. The dielectric breakdown characteristics of magnetic fluids can be influenced by the magnetic nanoparticles included because their properties should be affected by the applied electric field. Based on measuring the dielectric breakdown voltage of magnetic fluids, we found that it is higher than that of the pure transformer oil in the case of the specific volume concentrations of magnetic nanoparticles. It is known from a numerical simulation that the conductive nanoparticles might behavior as electron scavengers in the electrically stressed magnetic fluids and change fast electrons into slowly negative charged nanoparticles for the electrical breakdown. In this study, we focus on the motion of magnetic nanoparticles in the fluids under the electric field applied by the visualization using a microchannel and an optical microscope.

1. Introduction
Magnetic fluid is a colloidal suspension consisting of carrier liquid (water or oil) and magnetic nanoparticles with the size of 10 nm. It is used for the magnetic drug delivery, cooling of electrical system and the rotary shaft seal of a computer disk drive etc. in various fields [1]. Recently, it was found that transformer oil based magnetic fluids are possible to improve the heat transfer property and dielectric performance in electrical power systems such as a high-voltage transformer [2, 3].

Based on measuring the dielectric breakdown voltage of magnetic fluids by Lee et al. [4], it is higher than that of the pure transformer oil in the case of the specific volume concentrations of magnetic nanoparticles as shown in Figure 1. It was shown that dielectric breakdown voltage of the pure transformer oil is about 12 kV and the magnetic fluid dielectric breakdown voltage is around 37 kV in the case of the magnetic nanoparticles volume concentrations between 0.08% and 0.6%. This result is accord with true that conductive nanoparticles act as electron scavengers in the electrically stressed transformer oil-based magnetic fluids converting fast electrons to slow charged particles [5]. Also, the magnetic nanoparticles experience an electrical force directed towards the region of maximum electric field strength [5]. This phenomenon is consistent with the dielectrophoresis. It is a phenomenon in which a force is exerted on a dielectric particle when it is affected by a non-uniform electric field. All particles exhibit dielectrophoretic activity in the presence of electric field. If particles are in a non-uniform field, the electric field polarizes the particle and polarizable particles experience a
force along the electric field gradient [6]. And the aggregated magnetic nanoparticles like chain by external field affect the dielectric breakdown characteristics [7, 8]. In order to analyze the effect by electric field between the movement of magnetic nanoparticles and dielectric breakdown voltage, the movements of magnetic nanoparticles were observed by microscope and camera.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Dielectric breakdown voltage with different magnetic nanoparticles volume concentrations.}
\end{figure}

2. Experimental method

In this study, the movements of magnetic nanoparticles to applied electric field in a microchannel by an optical microscope were visualized. In order to observe the magnetic nanoparticles, a microchannel with 4 holes for fluid injection and electrode insertion as show in Figure 2(a) was made. In Figure 2(a), No.1 and 4 are holes for fluid injection and No.2 and 3 are holes for electrode insertion. In order to make a microchannel, 50 mL of silicon elastomer base liquid with 5 mL of curing agent were mixed and heated to harden for 3 h at 60°C. After, 4 holes were punched with 6 mm diameter on microchannel for fluid injection and electrode insertion. As shown in Figure 2(b), it has a passage between No. 1 and 4 holes with a length of a 500 µm, a width of 50 µm and a height of a 5 µm.

10 µL of a magnetic fluid (EFH-1, FerroTec, USA) can be diluted, which includes the magnetic nanoparticles, Fe₃O₄, with the size of about 10 nm reported, and 990 µL of transformer oil (OT-4, Michang, Korea) for experiments. The volume concentration of magnetic nanoparticles is 0.065%. A microscope was used (Eclipse Ti-E model) with a camera (HQ2 Monochrome camera) for the observation of magnetic nanoparticles movement. The position of observed photograph is about a height of 2.5 µm near the electrode in a microchannel passage. The applied DC voltage between the electrodes is 2.5 kV. The magnification of a microscope can be controlled into 100 times. The captured photographs have 696x520 pixels where the length of 1 pixel is 900 nm.
3. Results

In this study, the magnetic nanoparticle movement according to applied electric field was observed. And the effect by the field between the movement of magnetic nanoparticles in the fluid and the dielectric breakdown voltage of the fluid was analyzed.

In the case of non-applied electric field, the magnetic nanoparticles are uniformly dispersed in the microchannel as shown in Figure 3. In order to measure the size of magnetic nanoparticles in the fluid, NIS Element software to photographs was used. Although the size of particles just above 200 nm by this software can be measured, which is much larger than the original particle size 10 nm, however, the particles can be found to the photographs because it is the shadow of magnetic nanoparticles in the fluid as well as the aggregation of the particles in the initial magnetic fluid. Therefore, the number of magnetic particles visualized in Figure 3(a) should be much less than the real number of magnetic particles in the fluid.

In order to analyze the movement of magnetic particles by electric field, the DC voltage is applied between electrodes up to 2.5 kV. More and bigger particles in Figure 4(a) than the previous in Figure 3(a) can be seen. It is because the magnetic nanoparticles are attracted by the dielectrophoretic force and migrated toward the region of the maximum electric field near electrodes. The particles can be agglomerated by the attraction, the size of particles is 2~3 times larger as shown in Figure 4(a). If consider the particles not visualized in the photograph are considered, the magnetic nanoparticles in the fluid should be attracted near electrode as shown in Figure 4(b).
Unfortunately, we have captured pictures in the different positions due to the reflection of light from the electrode, however, we can deduce that what the change of dielectric breakdown voltage of transformer oil based magnetic fluids is primary due to the movement of magnetic nanoparticles by the applied electric field. It is known that the conductive magnetic nanoparticles in the fluids can act as electron scavengers, the dielectric breakdown voltage of the fluid can be changed positively or negatively according to the distribution of magnetic particles near electrodes. The further research on this point will be followed to control the movement of magnetic nanoparticles by dielectrophoretic and magnetophoretic forces.

4. Conclusion
In this study, the movement of magnetic nanoparticles influenced by the applied electric field was observed. From the photographs of magnetic nanoparticles in the fluid with and without the applied electric field, it was found that the magnetic nanoparticles are attracted by the dielectrophoretic force and migrated toward the region of the maximum electric field near electrode. And the particles can be agglomerated by the attraction; the size of particles visualized is 2–3 times larger when the electric field is applied. It can be deduced that what the change of dielectric breakdown voltage of transformer oil based magnetic fluids is primary due to the movement of magnetic nanoparticles by the applied electric field. The further research on this point will be followed to control the movement of magnetic nanoparticles by dielectrophoretic and magnetophoretic forces.

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