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Research Article

Investigation on the Electrical Conductivity of Transformer Oil-Based AlN Nanofluid

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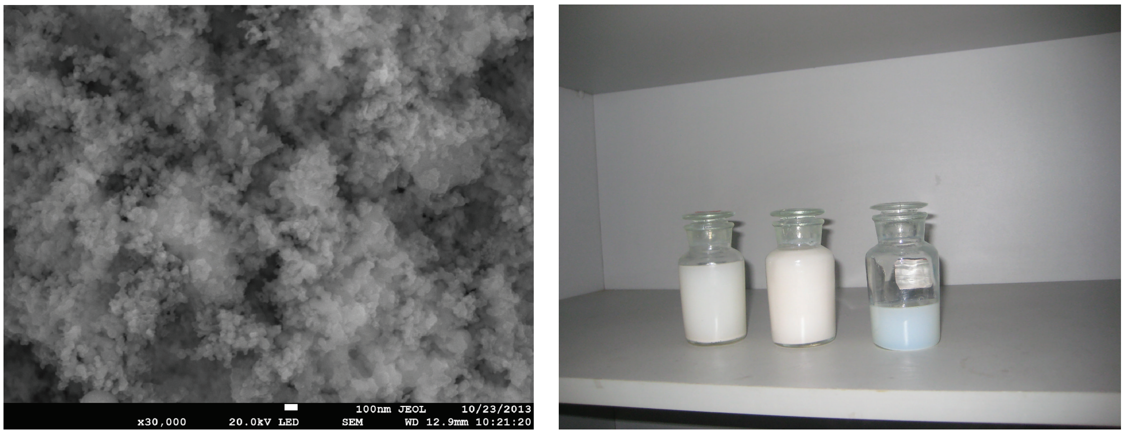
Aluminum-nitride-(AlN)-transformer oil-based nanofluid was prepared by dispersing AlN nanoparticles in transformer oil. The composition-dependent electrical conductivity of AlN-transformer oil nanofluid was investigated at different ambient temperatures. The results indicate the nonlinear dependences of the electrical conductivity on volumetric fraction and temperature. In comparison to the pure transformer oil, the electrical conductivity of nanofluid containing 0.5% AlN nanoparticles has increased by 1057 times at 60°C. By considering the electrophoresis of the AlN nanoparticles, a straightforward electrical conductivity model is established to modulate and understand the experiment results.

1. Introduction

Recent studies have shown that the thermal conductivity of the suspension which contains suspended metallic or non-metallic nanoparticles can be much higher than that of the base fluid, and it was called as "nanofluid" by Chio and Eastman [1]. On this basis, adding certain kinds of nanomaterials into base fluid is considered to be a novel approach to enhance the thermal conductivity in heat transfer medium. Accordingly, the mechanism for thermal conductivity enhancement of the nanofluid has attracted much attention. However, the research on electrical properties of the nanofluid is very limited.

On special occasions, the electrical properties of the nanofluid are as important as the heat transfer properties, such as electrical properties of the insulated oil-based nanofluid. However, only a few investigations have been carried out on the electrical properties of the insulated oil-based nanofluids. Miao et al. [2] measured the permittivity of the transformer oil-based ZnO nanofluid and revealed a higher relative permittivity than that of the pure transformer oil. Meanwhile, the relative permittivity of ZnO nanofluid presented a linear increase with nanoparticle volumetric concentration and a linear decrease with ambient temperature. Hwang et al. [3] developed an electrodynamic analysis of the processes which took place in electrically stressed transformer oil-based nanofluids and presented a model for streamer propagation. Lee et al. [4] measured the dielectric breakdown voltage of transformer oil-based nanofluids and investigated the dielectric breakdown performance. It was found that the dielectric breakdown voltage was three times larger than that of the pure transformer oil. When the external magnetic field was applied the breakdown voltage was 30% higher than that without external magnetic field. Du et al. [5] measured the charge trap and transportation characteristics of pure oils and nanofluids by using thermally simulated current method and pulse electroacoustic technique. It was found that electron shallow trap density and charge decay rate were greatly increased which would result in improved breakdown performance compared with that of the pure transformer oil. In our previous study, stable ZnO-insulating oil nanofluids were prepared and the electrical conductivity of the nanofluid was investigated [6]. Measurement of electrical conductivity of ZnO nanofluids showed that the electrical conductivity increased significantly for the insulated oil containing various fractions of ZnO nanoparticles.



(a) (b)

Figure 1: The characteristic of the AlN nanoparticles: (a) SEM image of the AlN nanoparticles dispersed in organic solvent. (b) theoptical image of the AlN-transformer oil-based nanofluid.

Among various electrical transport properties of the particulate suspension, the electrical conductivity not only reflects the insulation performance but also brings information on the degree of dispersion and stability of the nanofluid. However, only a few studies concerned the issue of the mechanisms for the electrical conductivity of nanofluid [7, 8] or suspension [9, 10]. Our previous work showed that the electrical conductivity of transformer oil increased significantly by adding semiconductive ZnO nanoparticles. However, it is not clear to what extent the electrical conductivity of nanoparticles affects the total electrical conductivity of the nanofluid. In this work, we choose insulated AlN nanoparticles as additives in transform oil which possess much higher thermal conductivity (140~180 $\mathrm{Wm^{-1}K^{-1}}$) and smaller electrical conductivity (<0.01 pS/cm in theory) than those of ZnO. The electrical conductivity with different volume fraction of AlN nanoparticles was measured under various temperatures. Based on the experiments, a new model was proposed by considering the dynamic electrical conductivity aroused by electrophoretic transactions of the AlN nanoparticles. Since the aggregated AlN nanoparticles in the base fluid have an average size of several hundred nanometers, the Brownian motion of the nanoparticles is isotropic and faint, and the electrical conductivity aroused by Brownian motion therefore can be neglected in our models. Accordingly, the enhancement of the electrical conductivity is mainly owing to the electrical double layers (EDL).

2. Experimental

AlN nanofluids were prepared by dispersing commercially available AlN nanoparticles in transformer oil. The nanoparticles were purchased from Aladdin Reagent Inc., China. The purity of the AlN nanoparticles was higher than 99.5%, with an average particle size of 50 nm. In order to prepare stable nanofluids, the solid AlN particles were mixed into ethanol and were deagglomerated by milling and intensive ultrasonic vibration. After centrifugating and drying, the AlN nanoparticles were successfully dispersed into the transformer oil by stirring and ultrasonic vibration and no any surfactant was added into the nanofluids to avoid reunion.

Material Characterization. Detailed morphology and microstructure of the samples were characterized using scanning electron microscopy (SEM, JEOL7100F, JSM). Electrical conductivity of the AlN nanofluid was measured as functions of temperature and volumetric fraction by electrical conductivity meter. In detail, the electrical conductivities of the nanofluids were measured by using two coaxial electrodes, which are the inner electrode and outer electrode. In the measurement, 100 mL nanofluid was injected between the two electrodes. When the voltage (V) was applied on the two electrodes, there would be a current (I) flowing through the nanofluid and thus to produce a $I\sim V$ curve. The electrical conductivity of the nanofluid can be calculated according to the formula

$$\sigma = \frac{I}{V} \cdot \frac{L}{S}, \quad (1)$$

where L is the spacing between the electrodes and S is the effective area of the electrodes. The typical response time for measurements was about 60 s, and our experimental results revealed that after 60 s the presence of polarization effects can be neglected. The data were obtained by taking the average of four or five measurements.

3. Experiment Results

Figure 1(a) shows a SEM image of the AlN nanoparticles. The average diameter of these particles is about 50 nm. Figure 1(b) shows the optical image of the AlN nanofluid using transformer oil as the base fluid after 30 days. As revealed in Figure 1(b), the AlN nanoparticles disperse homogeneously in the transformer oil, which indicates that the nanoparticles are quite stable in the base fluid. Simultaneously, the ivory color depth of the nanofluid varies with the volume fraction of the AlN nanoparticles.

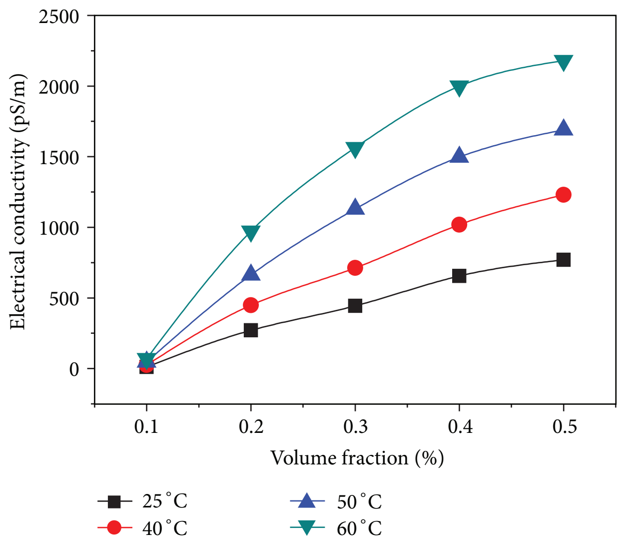


FIGURE 2: The electrical conductivity of nanofluid versus volumetric fraction of AlN measured at different temperatures.

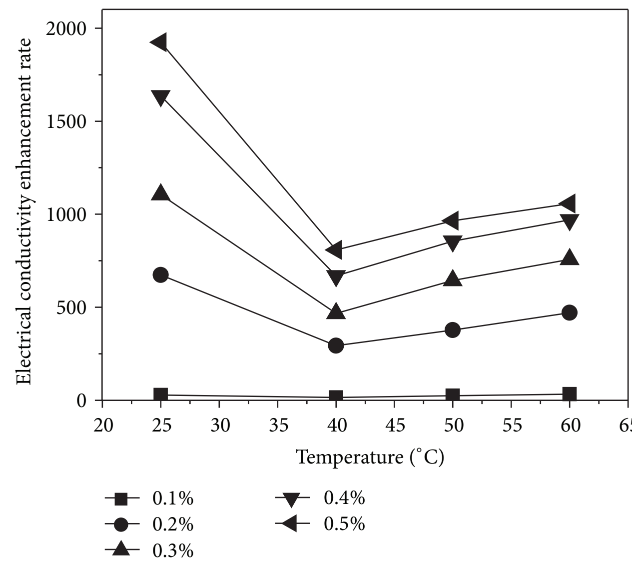


FIGURE 3: The variation of electrical conductivity enhancement $((\sigma_{\text{eff}} - \delta_0)/\delta_0)$ as a function of temperature for the AlN nanofluids with volumetric fraction of 0.1%, 0.2%, 0.3%, 0.4% and 0.5%, respectively.

Figure 2 presents the electrical conductivity of nanofluid versus volumetric fraction of AlN measured at different ambient temperature. As plotted in Figure 2, a nonlinear dependence of the electrical conductivity on volumetric fraction was presented, which is different from the reported linear dependence of electrical conductivities on volume fraction of nanoparticles in ZnO-insulated oil [6] and aluminum oxide-water [8] nanofluids. The electrical conductivity of pure transformer oil is measured to be $\sigma_0 = 1.52$ pS/m at 40°C. The electrical conductivity of the AlN material σ_p is reported as $\sigma_p = 1$ pS/m [11]. In the present study, the aggregation of the nanoparticles is neglected, so the theoretic value $\sigma_p = 1$ pS/m was used in further discussion and calculation. As the volume fraction of the AlN nanoparticles increased to 0.5%, the value of electrical conductivity was measured to be $\sigma = 1.23$ nS/m at 40°C, which is 809 times larger than that of the base fluid at the same temperature. Though the electrical conductivity of the nanoparticles and the base fluid are in the same order, the electrical conductivity of the nanofluids is much higher than that of the base fluid. This reveals that the electrical conductivity of the nanofluid is not only related to the physical properties of the base fluid and nanoparticles but is also strongly affected by other factors such as the electrochemical properties, electrical double layers (EDL), particle size, and aggregation. As also plotted in Figure 2, weakly nonlinear dependence of the electrical conductivity on temperature is depicted, which is similar with the existing experimental results [12]. The higher the temperature is, the greater the electrical conductivity will be.

The variation of electrical conductivity enhancement rate $((e_{\text{eff}} - \delta_0)/\delta_0)$ as a function of temperature for the AlN nanofluids with volume fraction of 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% was plotted in Figure 3, respectively, where the σ_{eff} is the effective electrical conductivity of nano-modified transformer oil. It is shown that when the temperature is lower than 40°C, the enhancement rate of the electrical conductivity gradually falls with temperature. As the temperature becomes higher, the enhancement rate of electrical conductivity is stable. The trend of temperature-dependent electrical conductivity at higher temperature is similar to that reported by Minea and luciu [12] for the water-based Al_2O_3 nanofluids.

The electrical conductivity enhancement rate $((\delta_j - \delta_i)/\Delta V)$ of nanofluid versus volumetric fraction of AlN measured at different temperature was plotted in Figure 4. It is shown that with the increase of volume fraction of AlN, the enhancement rate of electrical conductivity increases firstly and then decreases. The variation of the electrical conductivity can be explained as follows: when the AlN nanofluid is diluted, the distance between the nanoparticles is long and the nanofluid can be treated as monodisperse system. Therefore, the Zeta potential together with the mobility of the Brownian motion increases when the distance of the particles becomes larger. As a result, the dynamical electrical conductivity of the nanofluid is increased. When the volume fraction of AlN nanofluid increases, the aggregation of the particles cannot be neglected which leads to the enlargement of the particle size. This factor has negative impacts on both the Brownian motion and electrophoresis of the nanoparticles, which decreases the electrical conductivity of the AlN nanofluid.

4. Electrical Conductivity Modeling

Previous studies [6, 8, 12, 13] elucidated that the Maxwell model underestimated the electrical conductivity enhancement in nanofluid. This is due to the fact that the electrical conductivity is not only associated with the physical properties of nanofluid but also relates to some other physicochemical properties such as the shape and size of the nanoparticles, agglomeration, the EDL, the electrophoresis, and the Brownian motion of nanoparticles. In this paper, we assume

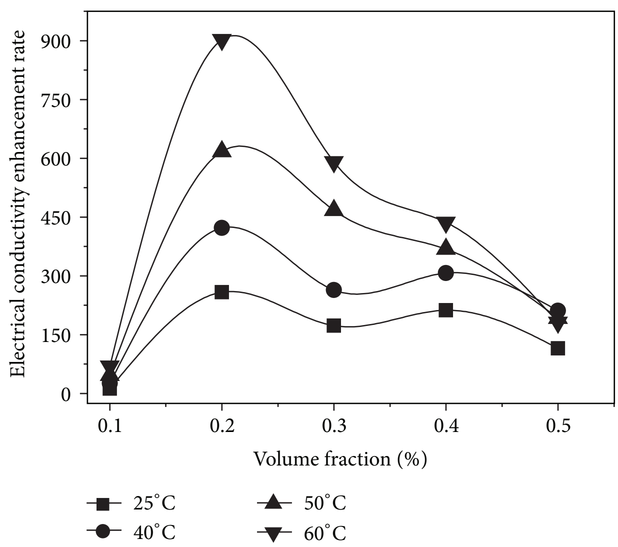


Figure 4: The electrical conductivity enhancement $((\sigma_j - \delta_i)/\Delta V)$ of nanofluid versus volumetric fraction of AlN measured at different temperature. δ_j is the electrical conductivity at the current AlN volume fraction, δ_i is the electrical conductivity at the former AlN volume fraction, and ΔV is difference between the adjacent volume fraction.

the AlN nanoparticles are spherical and monodisperse, the Brownian motion of the nanoparticles are isotropic; thus the enhancement of the electrical conductivity is mainly owing to the EDL.

According to the theory of colloid and surface chemistry, there is an electrical double layer (EDL) around each particle surface. The surface charge of the particles, together with ion cloud that constitutes the EDL, would contribute to the enhancement in conduction through the electrophoretic transactions. Generally, the particles are positively charged when their dielectric constant is larger than that of the base fluid. And in turn, the particles will be negatively charged. The nanoparticle has a Zeta potential U_0 relative to the base liquid. When an electrical field is applied, the charged particles will move towards the electrode and thus form the electrophoretic conductivity. That is to say that the nanoparticles are electric current carriers in the fluid.

The electron attachment on the particle can be expressed as [14]

$$q = 4\pi\varepsilon_r\varepsilon_0 r U_0. \tag{2}$$

Considering that the particle has a uniform velocity under the joint function of electric force and viscous force, the electrophoretic conductivity can be expressed as

$$\sigma_E = \frac{8\pi n_0 \varepsilon_r^2 \varepsilon_0^2 U_0^2}{3\eta}, \tag{3}$$

where n_0 is the number of particles per unit volume, η is the dynamic viscosity of the liquid, ε_0 is the dielectric constant of the vacuum, and ε_r is the relatively dielectric constant of the nanoparticles. If the n_0, ε_r, U_0, and r remain unchanged, the value of $\sigma_E\eta$ is a constant. The relationship reflects that though the electrical conductivity and viscosity of the base fluid change with the temperature, the product of σ_E and η will remain constant in the nanofluids. This relationship is called Walden law [15]. Hence, n_0 can be expressed as

$$n_0 = \frac{1 \cdot \varphi}{(4/3)\pi r^3} = \frac{3\varphi}{4\pi r^3}. \tag{4}$$

Substituting this result into (4) leads to

$$\sigma_E = \frac{2\varphi\varepsilon_r^2\varepsilon_0^2 U_0^2}{\eta r^2}. \tag{5}$$

On the other hand, the relationship of dynamic viscosity and kinematic viscosity in fluid is

$$\eta = \rho\upsilon. \tag{6}$$

Here υ is the kinematic viscosity of the fluid and ρ is the density of the fluid.

In nanofluid, both the dynamic viscosity and Zeta potential will be affected by the fluctuation of the volumetric fraction of nanofluid. For example, the dynamic viscosity will increase with the increase of the volumetric fraction, while the Zeta potential will decrease with the volume fraction because the electric double-layer is suppressed at higher volumetric fraction. The variation of dynamic viscosity with respect to the volumetric fraction of the nanofluid is given by (7) when considering the interaction of the particles. When the volume concentration of the nanofluid is lower than 10%, η can be described as [16]

$$\eta = \eta_f\left(1 + 25\varphi + 625\varphi^2\right), \tag{7}$$

where η_f is the dynamic viscosity of the pure base fluid.

In fluid mechanics, the viscosity varies with the pressure and the temperature. Since the pressure has a very small influence on the viscosity, we can only consider the effect of temperature. The relationship between the viscosity and temperature can be expressed as [17]

$$\eta = \eta_0 e^{-\lambda(T-T_0)}, \tag{8}$$

where η_0 is the dynamic viscosity of the nanofluid at temperature T_0 and λ is the decreasing rate of the viscosity when the temperature is increasing, namely, the viscosity index of the fluid.

The electrophoresis conductivity of the nanofluid is obtained by substituting (6), (7), (8) into (5)

$$\sigma_E = \frac{2\varphi\varepsilon_r^2\varepsilon_0^2 U_0^2}{\rho\upsilon\left(1 + 25\varphi + 625\varphi^2\right) r^2} e^{\lambda(T-T_0)}. \tag{9}$$

Finally, the total electric conductivity is the sum of the Maxwell conductivity and dynamic electrical conductivity caused by the electrophoresis of the nanoparticles. Consequently, the electric conductivity model is defined as

$$\sigma = \sigma_M + \sigma_E = \frac{\sigma_p + 2\sigma_f - 2\varphi\left(\sigma_f - \sigma_p\right)}{\sigma_p + 2\sigma_f + \varphi\left(\sigma_f - \sigma_p\right)} + \frac{2\varphi\varepsilon_r^2\varepsilon_0^2 U_0^2}{\rho\upsilon\left(1 + 25\varphi + 625\varphi^2\right) r^2} e^{\lambda(T-T_0)}, \tag{10}$$

where σ_f and σ_p are the electrical conductivity of the base fluid and solid AlN material, respectively.

5. Electrical Conductivity Model Applied to Transformer Oil-Based AlN Nanofluid

Figure 5 presents the dependence of electrical conductivity on volumetric fraction at room temperature based on the experiment measurements, the Maxwell model, and electrophoresis of nanoparticles, respectively. No matter the Maxwell model or the electrophoresis model is solely considered, there is large deviation between the experimental data and the models. Maxwell model underestimates the electrical conductivity of the nanofluid while the electrophoresis model neglects the static electrical conductivity. It can be seen that the electrical conductivity values obtained from our new model as (10) agree better with the measured values, in an order of magnitude sense.

Figure 6 shows the calculated and measured electrical conductivity as a function of volumetric fraction at different temperature. Though (10) predicts a nonlinear dependent of σ on φ, due to the small value of φ, the equation yields a quasi-linear dependence of σ on φ. It is found that the experimental data agree well with the theoretical value when the volume fraction is between 0.2% and 0.4%. Nevertheless, the experimental data are systematically underestimated at smaller volume fraction and overestimated at lager volume fraction. When the volume fraction of AlN is small, as reported in the literature [18], the electrophoretic motion of the nanoparticles should surmount percolation threshold, but the present model takes no account of this factor. When the volume fraction of AlN becomes larger, the main deviation of the present model does not consider the agglomeration of AlN nanoparticles. According to EDL theory, since the charged nanoparticles are electrically conducting material, the electrical conductivity may still increase due to establishment of short conducting paths by aggregate contact of the solid materials. It is noteworthy that Debye length λ is inversely proportional to the root square of the electrical conductivity, and typically, the Debye length in a low conducting fluid is very large, for example, 20 μm (see, Washabaugh et al., dielectric measurements of semi-insulation liquids and solids [19]). According to this assumption, the EDL effects are very small and insignificant, and, therefore, the electrophoretic effects may be also unimportant. On the contrary in this study, it is interesting to observe that the EDL not only enhances the electrical conductivity of the nanofluid but also play important role in the electrical conducting process. This may be due to the fact that in high concentration and nanoscale solid-fluid suspension, the EDLs' distribution and interaction have changed.

In Figure 7, the experimental changes of σ as a function of temperature for AlN nanofluids are compared with the established model. Both the experimental and theoretical conductivity curves follow a nonlinear relationship. As revealed in Figure 7, the electrical conductivity values obtained from the new model are in the same order of magnitude to the measured results. With increasing temperature, deviation

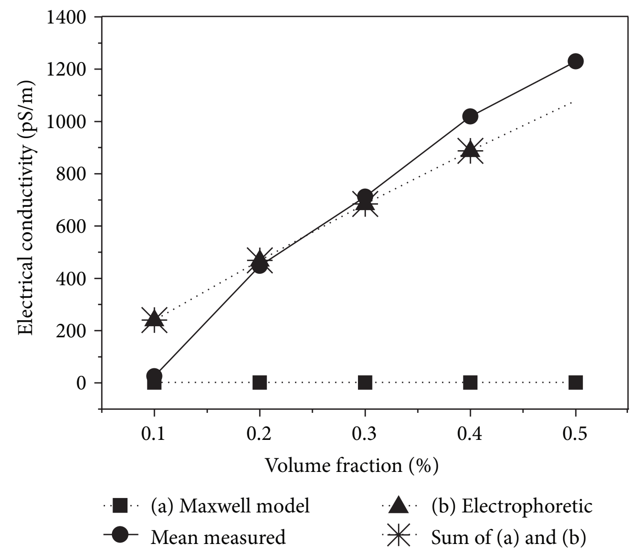


Figure 5: The experimental and theoretical electrical conductivity of the nanofluids as a function of AlN volumetric fraction at room temperature. The theoretical values were estimated by (a) Maxwell model, (b) electrophoresis model and sum of (a) and (b), respectively.

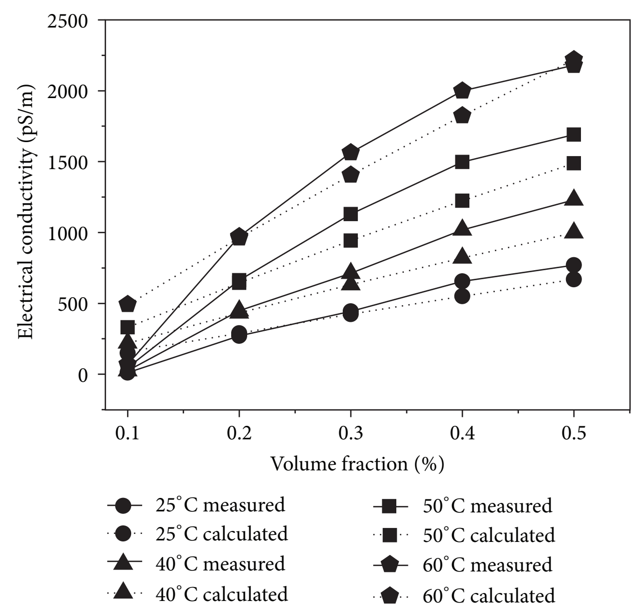


Figure 6: The theoretical and experimental electrical conductivity as a function of AlN volumetric fraction at different temperatures.

between the calculated and measured becomes larger at lower volume fraction, whereas it becomes smaller at higher volume fraction. One possible reason is that the present model does not take account of the Brownian motion of the AlN nanoparticles. When the volume fraction is low, the aggregation of AlN nanoparticles is not serious; the nanofluid can be treated as monodisperse system. The mobility of the charged nanoparticles caused by the Brownian motion increases with the increasing of temperature; thus the electrical conductivity of the nanofluid is enlarged. On the contrary, up to a certain

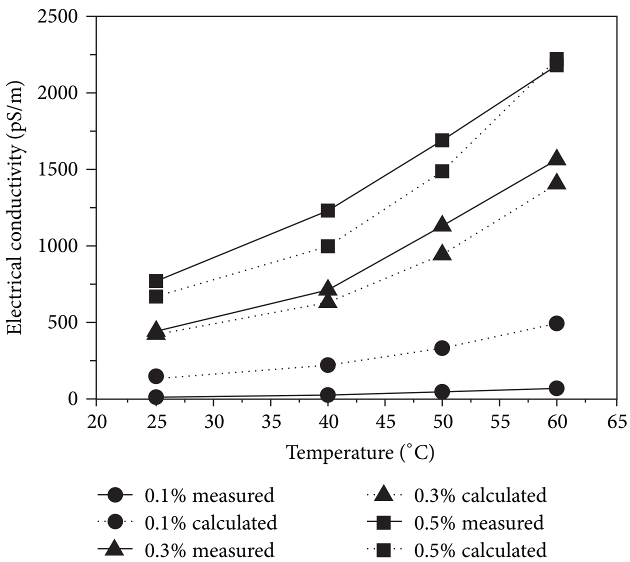


Figure 7: The theoretical and experimental electrical conductivity of the AlN nanofluids as a function of temperature.

volume fraction, the aggregation of AlN nanoparticles may become serious. The increased mass and the enlarged particle size will decrease the mobility of the individual nanoparticles caused by the Brownian motion, and in turn the enhancement rate of the electrical conductivity will slow down.

6. Conclusion

In summary, the electrical conductivity of AlN-transformer oil nanofluid was systematically studied versus volumetric fraction and versus temperature. Though the electrical conductivity of the nanoparticles and the base fluid are of the same order, the measured electrical conductivity of the nanofluids is much higher than that of the base fluid. The peculiar variation of electrical conductivity does not follow the traditional Maxwell model and other reported models. In this study, by considering the electrophoresis of the AlN nanoparticles, a straight forward electrical conductivity model is established. The electrical conductivity of the AlN-transformer oil-based nanofluids calculated by the new model is in good agreement with the experimental data. The study reveals that the effective electrical conductivity of transformer oil-based nanofluid has little relationship to the electrical conductivity of the dispersing nanoparticles but is sensitive to the EDL and aggregation of the nanoparticles. The present work takes a further effective step towards understanding the electrical transport properties in insulated oil-based nanofluid.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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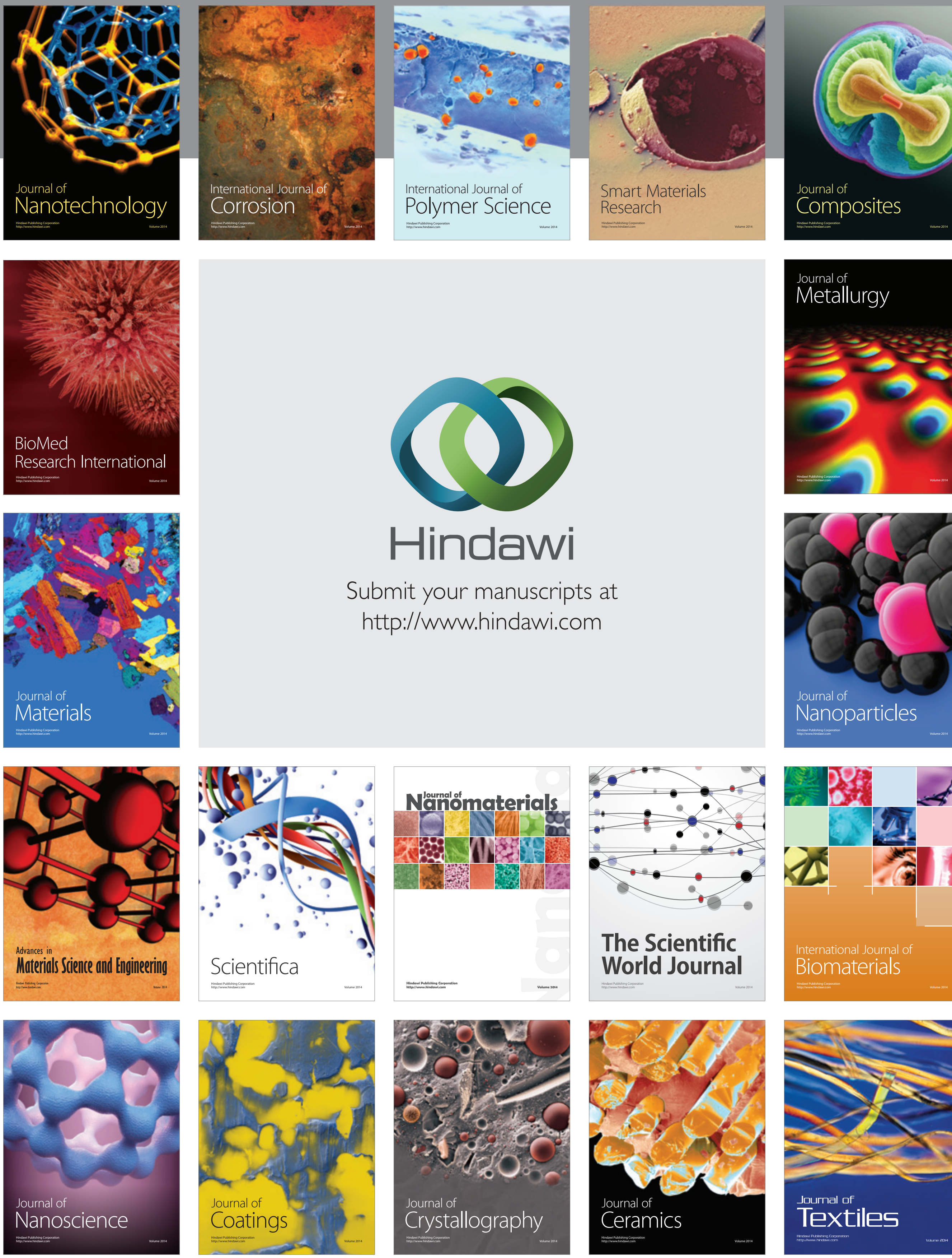

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