Thermal Conductivity of Nanofluid with Magnetic Nanoparticles

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Abstract — The thermal conductivities of Fe\(_3\)O\(_4\) and Al\(_2\)O\(_3\) nanofluids with the viscous base fluid composed by various fluids are investigated in this study. In order to change the viscosity of mixed fluid, the volumetric fractions between two fluids in the mixed fluid are varied. Measured values of thermal conductivity of nanofluids gradually approach the values predicted by Maxwell equation with increasing the viscosity. Our measured results demonstrate that Brownian motion of suspended magnetic particles could be an important factor that enhances the thermal conductivity of nanofluids, but it has little effect for suspended Al\(_2\)O\(_3\) nanoparticles. It also indicates that the conduction part of prediction model can be obtained from Maxwell prediction.

1. INTRODUCTION

Due the applications of suspended nanoparticles in a base fluid, the thermal properties of nanofluids have been continually studied in the last decade. Various nanoparticles and base fluids are applied to fabricate different kind of nanofluids. Former experimental data have shown that nanofluids have higher thermal conductivity than that predicted by the conventional models like Maxwell model \([1–11]\). However, the conventional models did not consider the effects associated with Brownian motion. This may cause the underestimation to the thermal conductivity of nanofluids. New models included the effects associated with Brownian motion are hotly investigated in the recent years \([11–23]\).

Some prior studies have indicated that the enhancement of thermal conductivity which directly results from collisions between nanoparticles is not obvious, and the dominant factor of the enhancement in thermal conductivity is the convection-like behavior which indirectly results from Brownian motion \([12, 14, 16, 22]\).

Most new models divide the effective thermal conductivity, \(k_{\text{eff}}\), into the conduction part, \(k_{\text{conduction}}\), which stands for the thermal conductivity due to differences of composition of nanofluids and convection part, \(k_{\text{convection}}\), which stand for the thermal conductivity due to the effects associated with Brownian motion.

\[
k_{\text{eff}} = k_{\text{conduction}} + k_{\text{convection}}
\]

However, for the conduction part, some models are based on parallel path of conduction heat transfer \([22, 23]\) and other models are based on Maxwell prediction \([13, 20]\). They do not provide a consistent and convincing predict model for the conduction part of all nanofluids.

This study tries to clarify the model of conduction part on the enhancement of thermal conductivity with nanoparticles in a base fluid at different values of viscosity. According to the Einstein-Stokes’s equation, the Brownian diffusion coefficient, \(D_B\), is the function of temperature, diameter of nanoparticle and viscosity of fluid:

\[
D_B = \frac{k_B T}{3\pi \mu d_p}
\]

where \(k_B\) is Boltzmann constant, \(T\) is temperature, \(\mu\) is viscosity of nanofluids, and \(d_p\) is diameter of nanoparticles. The Brownian diffusion coefficient will decrease with increasing the viscosity of nanofluids, and the effect of Brownian motion or convection-like behavior will be weakened. Then the thermal conductivity of convection part should decrease and the thermal conductivity of conduction part will be measured solely in the experiment.

2. EXPERIMENTAL SECTION

In this study, Al\(_2\)O\(_3\) water-based nanofluid and Fe\(_3\)O\(_4\) oil-based nanofluid are investigated. For the Al\(_2\)O\(_3\) water-based nanofluid, two kinds of viscous base fluids, the compound of water and EG and
the compound of EG and Glycerol, are used. The measured viscosities of water, EG and glycerol are 1cP, 16.8cP and 937cP, respectively. Figure 1(a) shows the viscosity of the water-EG base fluid as a function of volume fraction of EG at 25°C. Figure 1(b) shows the viscosity of the EG-glycerol base fluid as a function of volume fraction of glycerol at 25°C. The viscosities of both base fluids grow exponentially when the volume fraction of EG or glycerol increases. Al$_2$O$_3$ of average diameter of 13 nm is used as nanoparticles dispersed in water-EG or EG-glycerol base fluid. Al$_2$O$_3$ nanoparticles are purchased from the Yong-Zhen technomaterial CO., LTD.

For the Fe$_3$O$_4$ oil-based nanofluid, diesel oil and PDMS are used to form viscous base fluid. The viscosity of diesel oil and PDMS are 4.188cP and 5500cP, respectively. Figure 1(c) shows the viscosity of the base fluid as a function of volume fraction of PDMS at 25°C. The viscosity of the base fluid grows exponentially when the volume fraction of PDMS increases. Fe$_3$O$_4$ of average diameter of 10 nm used in this study is fabricated by co-precipitation method. The chemical reaction formula is expressed as:

$$Fe^{2+} + 2Fe^{3+} + 8OH^- \rightarrow Fe_3O_4 + 4H_2O$$

The thermal conductivity of such nanofluids is measured by the thermal hot wire method at 25°C.

![Figure 1: Measured values of viscosity of the mixed base fluid versus volume fraction of (a) EG (b) glycerol (c) PDMS at 25°C.](image)

3. RESULTS AND DISCUSSION

Figure 2 shows the thermal conductivity ratio of Al$_2$O$_3$ nanofluid versus the viscosity of base fluid with 2% volume fraction of Al$_2$O$_3$ nanoparticles. The experimental results do not have regularities in thermal conductivity. It may result from that the commercial nanoparticles are dry powder and cannot be dispersed in the base fluid well. The aggregation causes the unstable thermal conductivity ratio of nanofluid.

![Figure 2: Thermal conductivity ratio of Al$_2$O$_3$ nanofluids versus viscosity of base fluid: (a) water-EG base fluid, (b) EG-glycerol base fluid.](image)

Figure 3 shows the effect of viscosity of base fluid on the thermal conductivity ratio, $k_{nano}/k_{bf}$ and $k_{Maxwell}/k_{bf}$, of nanofluids with 1% and 2% volume fraction of Fe$_3$O$_4$ nanoparticles. The parameters, $k_{nano}$ and $k_{bf}$, denote the thermal conductivity of nanofluids and base fluid, respectively.
The predicted thermal conductivity of nanofluid, $k_{\text{Maxwell}}$, is determined by the Maxwell equation, given by

$$k_{\text{eff}} = \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})\phi}{k_p + 2k_{bf} - (k_p - k_{bf})\phi}$$  \hspace{1cm} (3)

where $k_p$ is thermal conductivity of nanoparticles, $k_{bf}$ is thermal conductivity of base fluid, and $\phi$ is volume fraction of nanoparticles.

**Figure 3:** Effect of viscosity of base fluid on thermal conductivity ratio of nanofluids: (a) $k_{\text{nano}}/k_{bf}$, (b) $k_{\text{nano}}/k_{\text{Maxwell}}$.

With the low viscous base fluid (4.188cP), the thermal conductivity ratio ($k_{\text{nano}}/k_{bf}$) of nanofluids is higher than that predicted by the Maxwell equation. The highest enhancement of thermal conductivity is 8.75% at 2.24% volume fraction of Fe$_3$O$_4$ nanoparticles. And $k_{\text{nano}}/k_{\text{Maxwell}}$ are 1.007 and 1.021 at 1.12% and 2.24% volume fraction of Fe$_3$O$_4$ nanoparticles, respectively. The experimental results indicate that Brownian motion and the convection-like behavior are much active and cause the observable enhancement of thermal conductivity in the low viscous base fluid.

With the high viscous base fluid (140.4cP), the thermal conductivity ratio ($k_{\text{nano}}/k_{bf}$) of nanofluids becomes the same as that predicted by the Maxwell equation. Measured values of $k_{\text{nano}}/k_{\text{Maxwell}}$ in the high viscous fluid are 1 at 1.12% and 2.24% volume fraction of Fe$_3$O$_4$ nanoparticles. At this situation, high viscosity of nanofluids makes Brownian motion and the convection-like behavior disappear. The measured thermal conductivity of nanofluids only presents the conduction part which Maxwell equation predicts.

The experimental results with the extra high viscous base fluid (648cP) are almost identical to those in the high viscous base fluid (140.4cP).

**4. CONCLUSIONS**

For the Al$_2$O$_3$ nanofluid, the unstable thermal conductivity may result from the aggregation. For the Fe$_3$O$_4$ nanofluid, high viscosity of base fluid weakens Brownian motion of suspended nanoparticles. Our experimental results with various viscosities of base fluids indicate that Brownian motion of suspended nanoparticles is one of important factors to enhance the thermal conductivity of nanofluids. In such a highly viscous fluid, Maxwell equation gives a good prediction on the thermal conductivity of nanofluids without Brownian motion of suspended nanoparticles, and the conduction part of prediction model can be obtained from Maxwell prediction, i.e., $k_{\text{conduction}} = k_{\text{Maxwell}}$.

**REFERENCES**