Effect of Nanoconvection due to Brownian Motion on Thermal Conductivity of Nanofluids

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Abstract: - A nanofluid is a new class of heat transfer fluids that contain a base fluid and nanoparticles. The use of additives is a technique applied to enhance the heat transfer performance of base fluids. The thermal conductivity of the ordinary heat transfer fluids is not adequate to meet today’s cooling rate requirements. Nanofluids have been shown to increase the thermal conductivity and convective heat transfer performance of the base liquids. One of the possible mechanisms for anomalous increase in the thermal conductivity of nanofluids is the Brownian motions of the nanoparticles inside the base fluids. It is shown in this study that the heat diffusion assumption that has been used in the macro- and micro- composite systems is not valid in the nanofluid systems. Apart from heat diffusion the nanoconvection diffusion that it due to the indirect effect of Brownian motion is responsible of enhancement in thermal conductivity of nanofluid systems.

Key-Words: - Heat Transfer, Thermal Conductivity, Nanofluids, Nanoconvection, Brownian Motion

1 Introduction

The thermal conductivity of ordinary heat transfer fluids is not adequate to meet today’s industrial requirements. They are about two orders of magnitude less efficient in conducting heat compared to metals. Therefore the use of solid particles as an additive suspended into the base fluid is a technique for increasing the heat transfer rate. Enhancement of the thermal conductivity is the main idea for improving the heat transfer characteristics of ordinary fluids [1].

Dispersing solid particles in liquids to improve the physical properties of liquids is hardly new as it has been well known for 100 years. The idea can be traced back to James Clerk Maxwell’s theoretical work (Maxwell, 1873) [2]. In conventional cases, the suspended particles are of micrometer or even mm dimension. Such large particles may cause such severe problems as abrasion and clogging. Therefore, fluids with suspended large particles have little application in heat transfer enhancement [3].

Nanofluids have a potential to reduce such problems. Nanofluids, a name conceived by Choi [4], in Argonne National Laboratory, to describe a fluid consisting of solid nanoparticles of size less than 100nm suspended on it with solid volume fractions typically less than 4%. Nanofluids consisting of such particles have been shown to increase the thermal conductivity and convective heat transfer performance of the base liquids. Because of the higher thermal conductivity of particle materials, even at low volume concentrations, a significant increase occurs in thermal performance. Research results from nanofluid research groups all around the world show that nanofluids have thermal properties that are very different from those of ordinary heat transfer fluids [5].

The apparent thermal conductivity is the most important parameter demonstrating the enhancement potential of heat transfer in nanofluids.

Understanding of the effective thermal conductivity of mixtures originates from continuum models where it is assumed that diffusive heat transfer occurs in both fluid and solid phases. The models with this assumption give good results for the large particles suspended in base fluid systems [6]. Nevertheless, they could not predict the anomalous heat transfer characteristics of nanofluids. In addition, the important disadvantage of the macroscopic approach based on the diffusive heat transport is that the particle size does not affect the thermal conductivity. On the other hand, the experimental data for the thermal conductivity of different types of nanofluids show that in the same volume fraction the effective thermal conductivity is greater for suspensions of smaller particles. Indicating that there exist some other parameters affecting the thermal characteristics of nanofluids.

Four possible explanations for the cause of an anomalous increase in the thermal conductivity are the effects of interfacial layer, Brownian motion, nanoparticles clustering, and the nature of heat transport...
This study focuses on the Brownian motion effect of the nanoparticles on the thermal conductivity of the nanofluids.

### Nomenclature

- $d$: Diameter ($m$)
- $D$: Diffusion constant ($m^2/s$)
- $f$: Drag coefficient ($kg/s$)
- $k$: Thermal conductivity ($W/m.K$)
- $r$: Radius ($m$)
- $T$: Temperature ($K$)
- $V$: Drift velocity ($m/s$)
- $v$: Kinematic viscosity ($m^2/s$)
- $c_p$: Specific heat ($kJ/kg.K$)
- $k_B$: Boltzmann constant ($J/K$)

### Greek Symbols

- $\mu$: Dynamic viscosity ($kg/m.s$)
- $\rho$: Density ($kg/m^3$)
- $\alpha$: Thermal diffusivity ($m^2/s$)
- $\tau$: Time scale ($s$)

### Subscripts

- $f$: Fluid
- $BD$: Brownian motion diffusion
- $CD$: Convection diffusion
- $HD$: Heat diffusion

### 2 Brownian Motion Effect

In nanofluid systems, due to the size of the nanoparticles, Brownian motion takes place which can affect the heat transfer properties. In a conventional approach for calculating thermal conductivity of nanofluids such as Maxwell [7] and Hamilton-Crosser model [8], the effect of the particle Brownian motion is neglected due to the large particle size. As the particle size scale approaches to the nano-meter scale, the particle Brownian motion and its effect on the surrounding liquids play an important role in heat transfer. Jang and Choi in 2004 [9] conducted a study that takes into account the Brownian motion behavior of nanoparticles. Their model consists of the four modes of energy transport in nanofluids. The first mode is collision of the base fluid molecules showing the heat conductivity at micro-scale, the second mode is the thermal diffusion in nanoparticles inside the base fluids, the third one is the collision between nanoparticles due to Brownian motion, and the last one is the thermal interactions of dynamic or dancing nanoparticles with the base fluid molecules due to the Brownian motion. Therefore, they postulate that Brownian motion of nanoparticles in a nanofluid produces convection like effects at the nanoscale (nanoconvection).

The last two modes are related to the Brownian motion effect that is being considered in this work.

### 3 Comparing the Time Scales

The Brownian motion of nanoparticles could contribute to the thermal conduction enhancement through two ways: a direct contribution due to the motion of the nanoparticles that transport heat i.e. solid-solid transport of heat from one to another, and an indirect contribution due to nanoconvection of the fluid surrounding individual nanoparticles.

In order to prove the inadequacy of the heat diffusion approach in nanofluid systems, the time scales involved in the two Brownian motion effects, and in heat diffusion approach are compared in this section.

#### 3.1 Particle Collisions

The first mechanism that is expected to increase the thermal conductivity is the nanoparticle collisions inside the base fluid that could increase the solid-solid heat transport from one particle to another one [10]. For calculating this effect, a single sphere nanoparticle was considered that moves slowly through the continuum of the base fluid. In this case the net velocity of the particle is proportional to the force acting on it

$$\text{force} \propto fV$$

where $f$ is the drag coefficient and according to the Stokes’ law it is equal to $6\pi\mu r$, and $V$ is the drift velocity.

After simplifications and according to the Stokes-Einstein formula particle diffusion constant takes the form [10]

$$D = \frac{k_B T}{6\pi\mu r}$$  \hspace{1cm} (2)

where $k_B$ is the Boltzmann constant ($1.3805 \times 10^{-23} J/K$), $\mu$ is the fluid viscosity, and $r$ is the particle radius.

Equation 2 shows that the effect of particle collisions on thermal conductivity could be estimated by calculating the time scale of the particle motion. Time required for a particle to move by the distance equal to its size $\tau_{BD}$, is given by [10]

$$\tau_{BD} = \frac{d^2}{6D} = \frac{24\pi\mu r^3}{6k_B T}$$

(3)
3.2 Nanoconvection
The energy transport due to the convection of the nanoparticles caused by the Brownian motion is called nanoconvection. Nanoconvection is the second mechanism that could be responsible of the energy transport in nanofluid systems. The rate of heat transfer due to convection could be calculated by convection diffusivity. Convection diffusivity is the kinematic diffusivity ($v$) of the liquid, which is also known as the momentum diffusivity [11].

$$v = \frac{\mu}{\rho_f} \tag{4}$$

where $\mu$ is the viscosity of the base liquid, and $\rho_f$ is the liquid density.

Hence, the time required for the transfer of the heat due to the convection effect at a distance equal to the nanoparticle size is given by [11]

$$\tau_{CD} = \frac{d^2}{v} = \frac{4r^2}{v} \tag{5}$$

3.2 Heat Diffusion
Diffusion of heat occurs by the net transport of heat from a higher temperature region to a lower temperature one by random molecular motion. The result of diffusion is a progressive equilibrium temperature. Conduction is the transfer of heat by direct contact of molecules. Heat is transferred by conduction when adjacent atoms vibrates against each other. Heat conduction in a stationary fluid could be simulated as the diffusion of particles into a fluid.

Normally one can estimate the rate of heat diffusion in a solid or stationary fluid by the thermal diffusivity as

$$\alpha = \frac{k}{\rho c_p} \tag{6}$$

Where $k$ is the thermal conductivity of the medium, and $\rho c_p$ is a volumetric heat capacity.

Based on the thermal diffusivity the time required for the heat to diffuse into a liquid by a distance equal to the size of the particle is

$$\tau_{HD} = \frac{d^2}{6\alpha} = \frac{4r^2 c_p \rho}{6k_f} \tag{7}$$

4 Result and Discussion
Three time scales for different mechanism of heat transfer in nanofluids are evaluated by comparing them for a nanofluid system with a base fluid of water and nanoparticles of a 5nm diameter. For water at 300K, specifications are as follows: $k_f = 0.613$ W/m.K, $c_p = 4.179$ kJ/kg.K, $\mu = 0.798 \times 10^{-3}$ kg/m.s, $\rho = 995.7$ kg/m$^3$. This comparison has shown in Table 1.

<table>
<thead>
<tr>
<th>Diffusion time scale</th>
<th>Formula</th>
<th>Value (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brownian motion Diffusion</td>
<td>$\tau_{BD} = \frac{24\pi\mu r^3}{6k_b T}$</td>
<td>$3.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>Nanoconvection Diffusion</td>
<td>$\tau_{CD} = \frac{4r^2}{v}$</td>
<td>$3.11 \times 10^{-11}$</td>
</tr>
<tr>
<td>Heat Diffusion</td>
<td>$\tau_{HD} = \frac{4r^2 c_p \rho}{6k_f}$</td>
<td>$2.83 \times 10^{-11}$</td>
</tr>
</tbody>
</table>

Keblinski et al. [10] in 2002, showed that the movement of nanoparticles due to the Brownian motion is too slow compared to heat diffusion which is apparent from Table 1 as well. However, another effect that is not considered in their study is the nanoconvection diffusion due to indirect effect of Brownian motion.

Comparing the time scales of the different diffusion mechanism, it can be concluded that the effect of nanoconvection diffusion is comparable to that of heat diffusion. This simple comparison shows why the effect of Brownian motion is too slow compared to heat diffusion which is apparent from Table 1 as well. However, another effect that is not considered in their study is the nanoconvection diffusion due to indirect effect of Brownian motion.

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