

Effects of Nanolayer Structure and Brownian Motion of Particles in Thermal Conductivity Enhancement of Nanofluids

M. Izadi, S. Hossainpour, and D. Jalali-Vahid

Abstract—Nanofluids are novel fluids that are going to have an important role in future industrial thermal device designs. Studies are being predominantly conducted on the mechanism of these heat transfers. The key to this attraction is in the increase in thermal conductivity brought about by the Nanofluids compared with the base fluid. Different models have been proposed for calculation of effective thermal conduction that has been gradually modified. In this investigation effect of nanolayer structure and Brownian motion of particles are studied and a new modified thermal conductivity model is proposed. Temperature, concentration, nanolayer thickness and particle size are taken as variables and their effect are studied simultaneously on the thermal conductivity of the fluids, showing the concentration of the nanoparticles to affect the nanolayer thickness which also affects the Brownian motion.

Keywords—Relative thermal conductivity, Brownian motion, Nanolayer structure.

I. INTRODUCTION

DOWNCALING or miniaturization has been a recent major trend in modern science and technology. The advances in nanotechnology have resulted in the development of a class of fluids termed nanofluids, first used by a group at the Argonne National Laboratory in 1995 (Choi 1995). Nanofluids are suspensions containing particles that are significantly smaller than 100 nm (Wen and Ding 2004), and have a bulk solids thermal conductivity of orders of magnitudes higher than the base liquids. Microscale devices have been recently developed as microchannel heat exchangers that are the size of dust specks. Further major advances is thought to be brought about if the coolant flowing in the microchannels were to contain nanoscale particles resulting in an enhancement in heat transfer, making Nanofluid technology an emerging and exciting technology for the 21st century. Mechanism of any increase in the thermal conductivity of the fluid is not fully understood and studies are currently being predominantly conducted to clarify this matter. As the number of these variables are not yet fully

confined, different literatures have investigated this matter from there own prospective. Experimental studies conducted have shown (Wang et.al., 1999, Lee et.al 1999, Keblinski et.al 2002) that the effective thermal conductivity increases under macroscopically stationary conditions. Lee and Choi (1996), under laminar flow conditions, Nanofluids in microchannels have shown a two fold reduction in thermal resistance and dissipate heat power three times more than that of pure water. Studies conducted using water-Cu Nanofluids (Xuan and Li, 2003) of concentrations approximately 2% by volume was shown to have a heat transfer coefficient 60% higher than when pure water was used.

Early experimental studies on the thermal transport properties of Nanofluids focused on changes in properties created by high concentrations of metal oxides nanoparticles [1][2][3][4][5][6][7][8]. Masuda et al. [9] reported a 30% increase in the thermal conductivity of water with the addition of 4.3 vol. % Al_2O_3 nanoparticles. Subsequent study by Lee et al [10] also examined the behavior of Al_2O_3 nanoparticles in water, but observed only a 15% enhancement in thermal conductivity at the same nanoparticle concentration. These differences in behavior were attributed to differences in average particles size in the two sets of samples. The Al_2O_3 nanoparticles used by Masuda et al had an average diameter of 13 nm, compared with 33 nm in the study by Lee et al. The purpose of this paper is determination of thermal conductivity of Nanofluids as fluids have fewer problems relative to suspensions with larger particles such as sedimentation, erosion, additional pressure drop and non-Newtonian behavior in low concentrations. This Study's focus has mainly been on different prediction models for enhanced thermal conductivity. We have accounted effect of movement of base fluid molecules and particles, diffusion in particles and nanolayer structure simultaneously, taking temperature, concentration, nanolayer thickness and particle size as variables, improving earlier studies conducted by Jang and Choi [11] and Yu and Choi [12].

II. MATHEMATICS

W. Yu and S.U.S. Choi [12] proposed a model for nanofluid that particles have a special structure and particles are surrounded by nanolayer. This nanolayer has the bulk material in nature but more compressed, making this

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assumption that this nanolayer and particle be thought as one equivalent particle. Equation (1) and (2) show the proposed model representing the concentration and heat conductivity of equivalent particle of the nanofluid, where the equivalent particle radius is taken as the sum of the r and h representing the diameter of particle and nanolayer thickness respectively.

$$\phi_e = \phi(1 + \beta)^3 \quad (1)$$

$$k_{pe} = \frac{[2(1-\gamma) + (1+\beta)^3(1+2\gamma)]}{-(1-\gamma) + (1+\beta)^3(1+2\gamma)} k_p \quad (2)$$

Where $\beta=h/r$ is the ratio of the nanolayer thickness to the original particle radius and $\gamma=k_{layer}/k_p$ is the ratio of nanolayer thermal conductivity to particle thermal conductivity. ϕ , ϕ_e and k_{pe} represent concentration particle, concentration equivalent particle and heat conductivity equivalent particle.

In a later study conducted by Jang and Choi [11] the Brownian motion behavior of nanoparticles had been taken into account. Fig. 1 demonstrates the model proposed forming the effective heat conductivity.

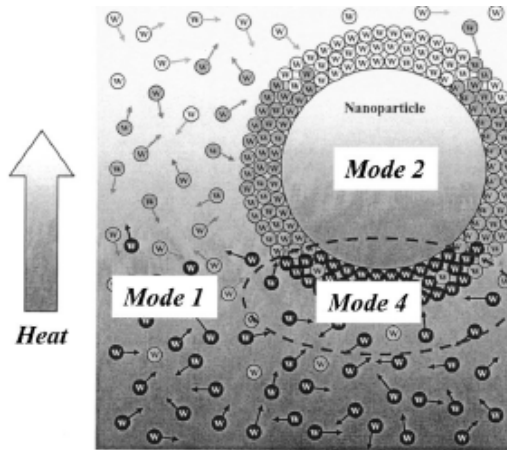


Fig. 1 Four factors as effective parameters on the heat conductivity of the nanofluid [11]

In this study they had identified four factors as effective parameters on the heat conductivity of the nanofluid as follows

A. Collision of the base fluid molecules showing the heat conductivity in the micro-scale. Collide, the net energy flux J_u , across a plane at z is given by:

$$J_u = -k_{bf} \frac{dT}{dz} (1 - \phi_e) \quad (3)$$

Where in above equation T represent temperature and k_{bf} heat conductivity of base fluid respectively.

B. Thermal diffusion in nanoparticle fluids, which is given by:

$$J_u = -k_{ep} \frac{dT}{dz} \phi_e \quad (4)$$

C. Collision between nanoparticles due to Brownian motion. Nanoparticle collision due to Brownian motion is a very slow process [13]. By an order-of-magnitude analysis

they have found that this mode is much smaller than the other modes and can be neglected.

D. Thermal interactions of dynamic or dancing nanoparticles with base fluid molecules. Even though the random motion of nanoparticles is zero when time averaged, the vigorous and relentless interactions between liquid molecules and nanoparticles at the molecular and nanoscale level translate into conduction at the macroscopic level, because there is no bulk flow. Therefore, they postulate that Brownian motion of nanoparticles in nanofluids produces convection like effects at the nanoscale. So, the last mode can be defined by:

$$J_u = -h \delta_T \phi_e \frac{dT}{dz} \quad (5)$$

Where h , δ_T represent the heat transfer coefficient for flow past nanoparticles and the thickness of the thermal boundary layer, respectively. Heat transfer coefficient for flow past nanoparticles are defined in the following form:

$$h \approx \frac{k_{bf}}{d_e} \text{Re}_{de}^2 \text{Pr}^2 \quad (6)$$

Where d_e and Re_{de} represent the equivalent diameter of nanoparticles and Reynolds number respectively. Reynolds number is defined in the following form:

$$\text{Re}_{de} = \frac{\bar{C}_{R.M} d_e}{\nu} \quad (7)$$

Where $\bar{C}_{R.M}$ and ν represent the random motion velocity of nanoparticles and dynamic viscosity of the base fluid, respectively. $\bar{C}_{R.M}$ is defined by:

$$\bar{C}_{R.M} = \frac{D_o}{l_{bf}} \quad (8)$$

Where l_{bf} and D_o represent the mean-free path of a base fluid molecule and nanoparticle diffusion coefficient, respectively. nanoparticle diffusion coefficient is given by Einstein [13].

$$D_o = k_b T / 3 \Pi \mu d_e \quad (9)$$

Where $k_b = 1.3807 \times 10^{-23} \text{ J/K}$ represents the Boltzmann constant and c the hydrodynamic boundary layer δ is defined as [14]:

$$\delta \approx 3 d_{bf}$$

Where d_{bf} represents diameter of base fluid molecule.

$$\delta_T \approx \frac{\delta}{\text{Pr}}$$

With adding all factors influence effective thermal conductivity using above relation, it derive the following expression for the thermal conductivity of Nanofluids.

$$k_{eff} = k_{BF} (1 - \phi_e) + k_e \phi_e + 3 C_1 \frac{d_{BF}}{d_e} k_{BF} \text{Re}_{de}^2 \text{Pr} \phi_e \quad (7)$$

Where C_1 is constant.

III. RESULTS

Validity of the above results had been separately approved for the heat conductivity of the nanofluids, and further studies are conducted using the validated models.

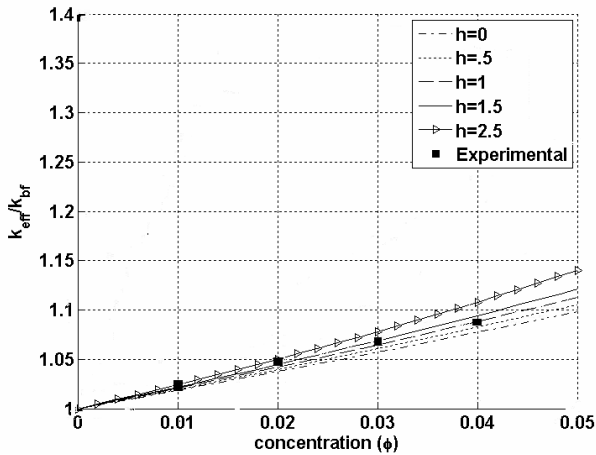


Fig. 2 Effect of nanoparticle concentration on the relative heat conductivity for different nanolayer thickness (38.4nm Alumina in water nanofluid) is compared with experimental data

Fig. 2 represents the effect of nanoparticle concentration on the relative heat conductivity (taking all other parameters as constant), showing that experimental results are in good agreement for the different nanolayer thickness with the plotted data using the suggested model (Equ.7) at different particle concentrations, Concluding that the nanolayer thickness changes with concentration of the particles.

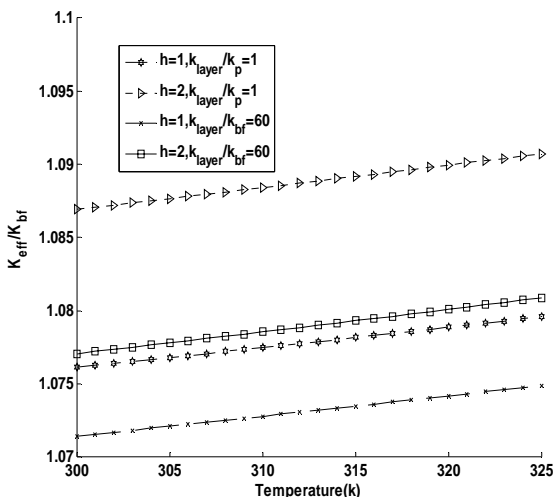


Fig. 3 The data correlated for 38.4nm water in alumina nanofluid, showing dependency of relative heat conductivity for different values of nanolayer thicknesses and nanolayer conductivities

Although the reason of these changes are not fully understood, at high concentrations the experimental results are convergent with the plotted data at $h = 1$ nm, as in low concentrations the difference between the results are not important. The steep of the lines representing the effective relative heat conductivity are much more when the concentrations of the nanoparticles are greater than when the concentrations are lower, which is thought to be due to the increase in the nanolayer thickness and Brownian motion of the equivalent particle. Fig. 3 demonstrates the data correlated for the water-alumina nanofluid, showing for different values of nanolayer thicknesses and nanolayer conductivities, the relative heat conductivity has a liner correlation with temperature. As the nanolayer thickness is increased the relative heat conductivity is astonishingly increased. Rate of this increase with temperature is independent of nanolayer thickness and nanolayer heat conductivity. This is thought to be due to independence of the nanolayer formation from temperature. As the nanolayer thickness is increased, the heat conductivity is increased. This is thought to be due to an increase in the Brownian motion of the particles. It has to be pointed out that the Brownian motion of the particle is decreased as the size of the particle is increased, suggesting that the nanolayer to have a different effect on the heat conductivity of the Nanofluids compared with the size of the particles.

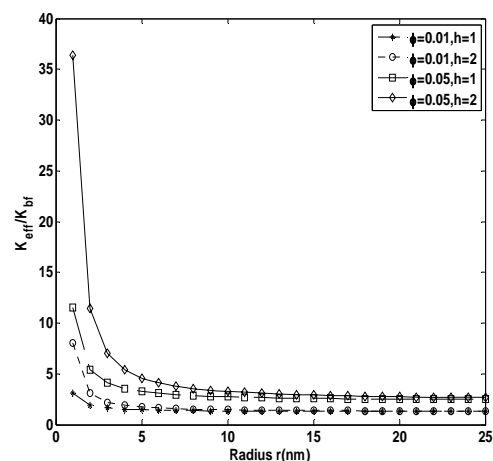


Fig. 4 Relative thermal conductivity enhancement ratio as a function of particle radius for water in alumina suspensions with different concentration and nanolayer thickness of particles

The proposed model shows that heat conductivity of nanofluid is greatly affected by the smaller sized particles as also demonstrated by Fig. 4. As is also expected as the size of the particles are increased the effect of nanolayer on the heat conductivity is diminished, suggesting this layer to be not formed when the size of the particles exceeds some limit around 15 nm.

In this model effect of particle concentration on the heat conductivity is also demonstrated. In smaller particles effect of both nanolayer thickness and particle concentration on the

effective heat conductivity is seen, where the former is more effective.

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