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Effect of Particle Size on Effective Thermal Conductivity of Nanofluids

[1]Aklilu Tesfamichael Baheta and [2]Abraham D. Woldeyohannes

[1]Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

[2]School of Engineering and Science, Curtin University Sarawak Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia

Corresponding Author: Aklilu Tesfamichael Baheta, Department of Mechanical Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

ABSTRACT

Experiments have demonstrated that when nanoparticles such Al_2O_3, Cu, TiO_2 are added to traditional heat exchanger working fluids their thermal fluid properties changes. Especially, the effective thermal conductivity of the nanofluids increases. Different empirical models were suggested to predict there effective thermal conductivity based on experimental data. Effective thermal conductivity varies with size, shape, volume fraction of the nanoparticles and thermal conductivities of the particle and base fluid. Hence, this study investigates the effect of nanoparticles size, volume fraction and type of nanoparticles in water based nanofluids. Using interfacial shell concept, the Hamilton and Crosser model was modified to study the nanoparticles size effect. The modified model was compared with literature data and found under predict the effective thermal conductivity but follow the same trend. The result shows that as the nanoparticles size increases the thermal conductivity decreases. Cu water nanofluid gives better thermal conductivity than Al_2O_3 water nanofluid at a given particle volume fraction.

Key words: Nanoparticles size, nanofluid, volume fraction, effective thermal conductivity

INTRODUCTION

The world energy demand is ever increasing as the energy consumption of nations increases because of economic growth. This higher energy usage has contributed to the global warming effect. On the other hand, the world raw energy resource is limited. In order to overcome the shortage of raw energy sources and the global warming effect improving the energy conversion efficiency is vital. With respect to this, heat exchangers play a great role in energy conversion systems. Heat exchangers are involved almost in all thermal systems such as in petrochemical, power plant, air conditioning, electronic devices. Various means have been proposed to improve the heat exchanger performance including introducing different shape and size of fins and different flow arrangements. Two phase mixture studies that were done with millimeter and micrometer suspended particles size indicated improvement of thermal properties of fluids but rapid settling of particles, increase of the pressure drop and clogging of pipes has caused problem (Hamilton and Crosser, 1962). On the other hand, with the advent of sophisticated technology the suspended particles are able to be produced with ultra fines (nano) sizes. Hence, this has created a new area of study in the field of thermal fluid including examining the thermal fluid properties and heat transfer mechanisms. The thermal fluid properties such as thermal conductivity and convective heat transfer coefficients of fluids are improved when ultra fine solid particles are mixed with fluids as a suspension (Hwang *et al*., 2009). The suspension of the solids can be metal, non-metal materials (Xuan and Roetzel, 2000). The mixture is called nanofluid. These suspended nanoparticles change the effective thermal conductivity and the convective heat transfer coefficient of the fluid which in turn enhance the heat transfer performance of the nanofluid. If the heat transfer capacity of the working fluids improved, then heat exchanger size decreases and also fuel consumption rate decreases which in turn reduce the CO_2 emission on the environment.

The effect of different nanoparticles, namely, TiO_2, Al_2O_3 Fe and WO_3 on thermal conductivity of nanofluids was studied experimentally by Yoo *et al*. (2007). They concluded that nanoparticle surface to volume ratio has effect on the thermal conductivity of the nanofluid in addition to its thermal conductivity. The heat transfer coefficient of Al_2O_3 nanofluid flow through 1.812 mm round pipe for laminar and fully developed flow was studied experimentally by Hwang *et al*. (2009). During the study Al_2O_3 volume fraction was varied in the range of 0.01 to 0.3% and they concluded that enhancement of the convective heat transfer coefficient is larger than thermal conductivity. Recently, Anandan and Rajan (2012) formulated CuO-water nanofluid and characterized it experimentally. Using existing nanofluids characteristics correlations and for uniform heat flux on a circular pipes Balla *et al*. (2012) examined the effect of nanoparticles volume fractions on the heat transfer coefficient and pressure drop of CuO, TiO_2 and Al_2O_3-water nanofluids. There are different models that can predict the effective thermal conductivity of nanofluids (Maxwell, 1873; Hamilton and Crosser, 1962; Davis, 1986; Lu and Lin, 1996). The aforementioned literatures show nanoparticles enhance the thermal transport behavior of heat exchanger fluids. However, the exact mechanism of thermal transport in nanofluids is not yet known at the moment (Yoo *et al*., 2007; Maiga *et al*., 2005) that clearly defines thermal conductivity for nanofluids. Hence, there is still a need to develop a model that can predict the effective thermal conductivity of nanofluids. This study focus on modifying the existing Hamilton and Crosser model to take into account the effect of nanoparticles size using the concept of interfacial shell. Furthermore, this study investigates the effect of particle type and volume fraction on the effective thermal conductivity of nanofluid. For the study Al_2O_3 and Cu water nanofluid were considered.

APPROACH AND METHODS

Effective thermal conductivity models: To predict the thermal conductivity of nanofluid, different formulae were developed. The well known analytical formula that has been used for long time to predict the thermal conductivity a mixture of micro particles and fluids is the classical effective thermal conductivity model, known as Maxwell model (Maxwell, 1873) is given in Eq. 1:

$$\frac{k_{eff}}{k_f} = 1 + \frac{3(\alpha - 1)\upsilon}{(\alpha + 2) - (\alpha - 1)\upsilon} \quad (1)$$

where, k_f is the thermal conductivity of the base fluid, $\alpha = k_p/k_f$ and volume fraction, $\upsilon = V_p/(V_p+Vf)$. One of the basic formula that has been used by researches as a bench mark whenever they do model improvement is the Hamilton and Crosser model that takes into account the shape effect (Hamilton and Crosser, 1962) is given in Eq. 2:

Table 1: Physical properties for liquid metals or traditional fluids

Physical property of basic fluid or nanoparticles	Thermal conductivity (W m^{-1} K^{-1})
Water	0.61
Cu	401
Al_2O_3	40
CuO	61

Eapen *et al*. (2010)

$$\frac{k_{eff}}{k_f} = \frac{\alpha + (n-1) - (n-1)(1-\alpha)\upsilon}{\alpha + (n-1) + \upsilon(1-\alpha)} \tag{2}$$

where, n is the empirical shape factor and given by:

$$n = \frac{3}{\psi} \tag{3}$$

where, Ψ is the sphericity, defined as the ratio of the surface area of sphere with volume equal to that of the particle to the surface area of the particle and n = 3 and 6 for spheres and cylinders, respectively.

Another formula that can be used to predict the effective thermal conductivity of nanofluids is the Davis model (Davis, 1986):

$$\frac{k_{eff}}{k_f} = \left(1 + \frac{3(\alpha-1)\upsilon}{(\alpha+2)-(\alpha-1)\upsilon}\right)\left(\upsilon + f(\alpha)\upsilon^2 + 0(\upsilon)^3\right) \tag{4}$$

High-order terms represent pair interaction of randomly dispersed spheres. Here, f (α) = 0.25 for α = 10, f (α) = 0.5 for α = 8.

Table 1 shows the physical properties for liquid metals.

Interfacial model to consider the effect of size on effective thermal conductivity of nanofluids: Interfacial shell layer is formed when nanoparticles are inside a base fluid. The prediction of the interfacial shell layer thickness that envelope the particle is given by Eapen *et al*. (2010):

$$t = \frac{1}{\sqrt{3}}\left(\frac{4M}{\rho_f N_A}\right)^{1/3} \tag{5}$$

where, M is the molecular weight of liquid, ρ_f is the density of the fluid and N_a is the Avogadro's constant (6.023×10^{23} M^{-1}).

The thermal conductivity of the fluid within the interfacial shell layer thickness t varies between the solid particles to the fluid thermal conductivities. Furthermore, the combined thermal conductivity of the enveloped particle is given by Wang *et al*. (2003):

$$k_{com} = k_s \frac{(k_p + 2k_s) + 2\lambda(k_p - k_s)}{(k_p + 2k_s) - \lambda(k_p - k_s)} \tag{6}$$

where, $\lambda = [d/(d+2t)]^3$ and k_s is the thermal conductivity of the solid-like shell enveloping the nanoparticles, d is the diameter of nanoparticles.

To take into account the effect of nanoparticle size on the effective thermal conductivity of nanofluids, existing models need to be modified. In the existing formula d+2t, $((d+2t)/d)^3$ and k_{com}, should be used in place of d, u and k_p, respectively. As the Hamilton and Crosser model takes into account the effect of shape this model was used with the aforementioned modifications to be substituted in their respective place. The modified Hamilton and Crosser model was used to predict effective thermal conductivity of nanofluids. This modified equation takes into account the effect of nanoparticle size in addition to the volume fraction, particle and fluid thermal conductivities and shape.

RESULTS AND DISCUSSION

The common heat transferring fluid water and Al_2O_3 and Cu nanoparticles were considered for this study. Their physical properties are shown in Table 1. The existing models were used to predict effective thermal conductivity for Al_2O_3 water nanofluid and were compared with the experimental data obtained from literature (Eastman *et al.*, 1996) for sphericity of 0.75. As shown in Fig. 1, all the models under predict the effective thermal conductivity of nanofluids. Especially, the Maxwell and Davis model give low prediction as they do not take the effect of particles shape. The effective thermal conductivity increases as the volume fraction increases. Furthermore, the data and Hamilton and Crosser model prediction show that the presence of 5% volume fraction Al_2O_3 nanoparticles in the water has enhanced the effective thermal conductivity of the nanofluid by 27 and 20%, respectively.

The effective thermal conductivity of nanoparticles depends on the particle size. To study the effect of size on effective thermal conductivity Al_2O_3 water nanofluid was considered where there thermal conductivities are given in Table 1. Before the model used for particle size effect it was validated with literature experimental data as indicated in Fig. 2. As it is shown in the figure, this model under predict the effective thermal conductivity of the nanofluids; however, it follows the trend of the experimental data.

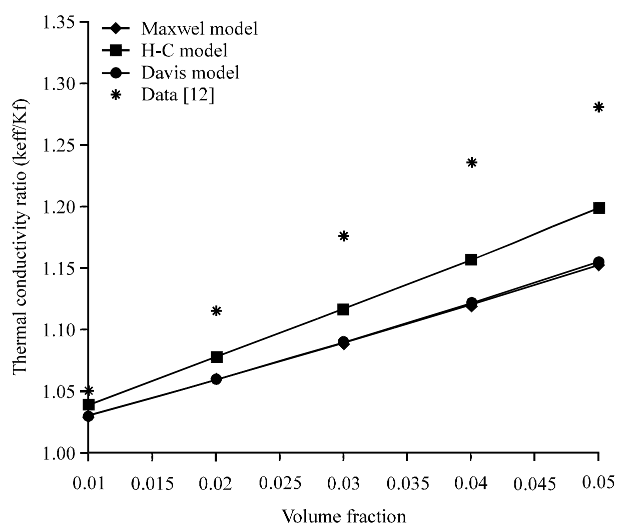

Fig. 1: Comparison of different thermal conductivity models

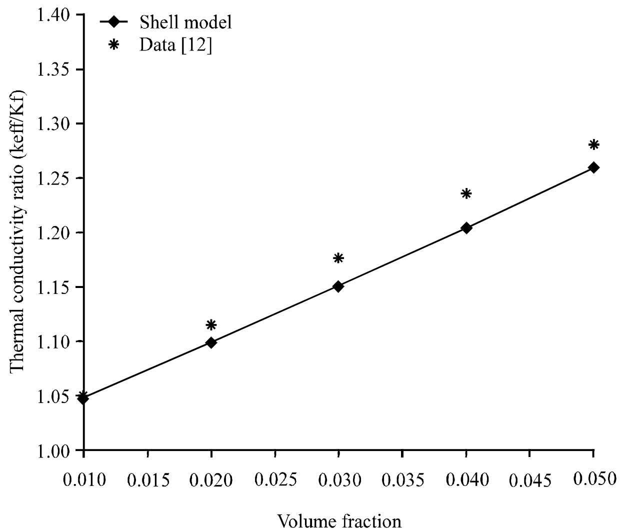

Fig. 2: Comparison of the Interfacial shell model with the literature experimental data

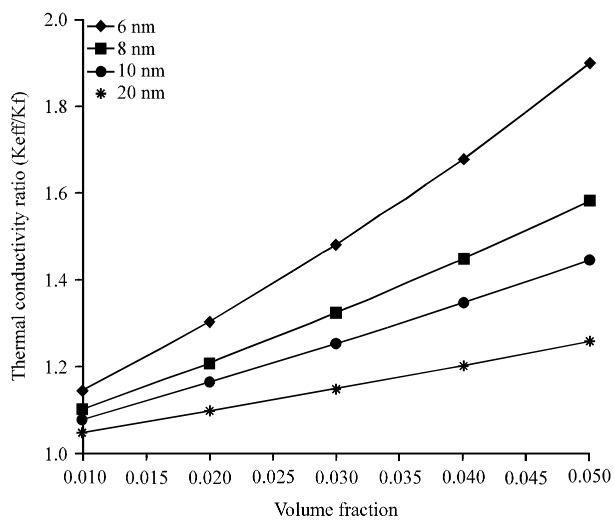

Fig. 3: Effect of nanoparticles size on the effective thermal conductivity for Al_2O_3 water nanofluid

The effective thermal conductivity was predicted at 6, 8, 10 and 20 nm sphere diameters for a wide range of volume fraction. Figure 3 shows the effect of particle sizes for 3 W m^{-1} K^{-1} thermal conductivity of the interfacial shell layer. The thermal conductivity enhancement ratio decreases when the size of nanoparticles increases and hence, the thermal conductivity enhancement reduces as the particle size increases.

Figure 4 shows the same base fluid water with different nanoparticles for cylindrical shape and 10 nm diameter nanoparticles. The figure shows the effective thermal conductivity of nanofluid with the Cu particles is higher than the nanofluid with Al_2O_3 at a given volume fraction. This is because the thermal conductivity of Cu is higher than Al_2O_3. Hence, the

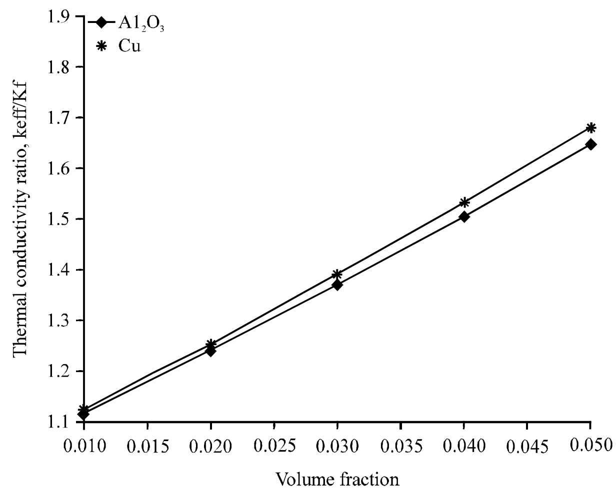

Fig. 4: Variation of the effective thermal conductivity for Al_2O_3 and Cu water nanofluids with respect to volume fraction

effective thermal conductivity depends not only on the volume fraction and shape but also on the thermal conductivity of the particles and the base fluid.

CONCLUSION

The effective thermal conductivity Al_2O_3 water nanofluid was predicted using different existing models. The comparison of the different models and literature experimental data shows that the effective thermal conductivity is under predicted by the models. This suggests that there is no clear formula that can predict the thermal conductivity of nanofluids. Hence, a model should be developed so that it will narrow the gap between the existing models and experimental data. The existing Hamilton and Crosser model was modified to take into account the effect of particle size using the concept of interfacial shell. The study shows that the smaller the size of nanoparticles the better was the effective thermal conductivity of the nanofluids. The developed model takes into account the effect of size, volume fraction, shape and nature of the nanoparticles that contribute to enhance the thermal conductivity. Other factors that contribute to thermal conductivity such as stability of the suspended particles, viscosity and specific heat of the base fluid should be taken into account. This requires further theoretical study to understand the thermal transport in nanofluids supported by experimental work.

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