International Journal of Advanced Mechanical Engineering.
ISSN 2250-3234 Volume 8, Number 1 (2018), pp. 9-16
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A non-linear model for interfacial layer's thermal conductivity of nanofluid

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Abstract

Traditional heat transfer fluids which are used in various applications such as chemical processes, refrigeration, heating and cooling processes, transportation, power generation and other micro-sized applications have poor heat transfer properties and impose limitation to heat transfer augmentation. Thermo-physical properties of conventional fluids play an important role in the development of energy efficient heat transfer equipment. The poor thermal conductivity limits their performance. Improving the thermal conductivity is the key idea to improve the heat transfer characteristics of conventional fluids. Since a solid matrix has a larger thermal conductivity relative to base fluid, suspending solid fine particles (millimeter or micrometer sized range) into the base fluid is expected to improve the thermal conductivity. A dilute suspension of nanometer-sized particles dispersed in a base fluid is known as Nanofluids. Nanofluids exhibit enhanced heat transfer properties and are expected to be a promising coolant candidate for thermal management systems of next generation. Thermal conductivity of an ordered liquid layer on nanoparticle-base fluid interface called as interfacial layer is an essential parameter for determining unusual high thermal conductivity compared of nanofluid. In present work, a non-linear model has been developed for interfacial layer's thermal conductivity Results using the correlations have been used to determine the effective thermal conductivity of nanofluid and compared with already established models. Effective thermal conductivity of nanofluid based on present model is found to be closer to the experimental data available in open literature.

Keywords - Interfacial layer, Nanofluid, Thermal conductivity

Nomenclature:

k_p	Particle thermal conductivity	k_{eff}	Effective thermal conductivity
k_m	Base fluid thermal conductivity	ϕ	Particle volume fraction
k_l	Interfacial layer thermal conductivity	r_p	Particle radius
k_{pe}	Equivalent particle thermal conductivity	t	Interfacial layer thickness
$k(r)$	Thermal conductivity variation across interfacial layer thickness		

I. Introduction

Nanofluids are essentially the dispersion of nano sized particles in a base fluid. These fluids are thought to be next generation “lubricants” due to their anomalously high thermal conductivity. Due to the small size of the nanoparticles ($O\sim10^{-9}$), these particles easily fluidize inside the base fluid and as a result, clogging of channels, pressure drop, pipeline erosion problems are no longer an issue [1]. Therefore, the study of nanofluids is of main concern. It was examined that around 20% enhancement in thermal conductivity was achieved with 4 vol.% CuO/ethylene glycol nanofluid and around 40% enhancement with 8 vol.% Al_2O_3/water nanofluid [2,3]. Madhesh [4] observed that for 1.0 vol % of dispersed nanoparticles in the base fluid, the convective heat transfer coefficient of the Ag-EG nanofluids was effectively increased by 54.3%.

The heat transfer enhancement can be well traced back to the theoretical work of Maxwell [5]. Hamilton Crosser [6] extended Maxwell’s work by considering the effect of particle shape. Both Maxwell and Hamilton Crosser derived equations for relatively larger solid particles typically of millimetres or micrometres order. However these models are frequently used in the study of nanofluids due to their simplicity to have a comparison between theoretical and experimental findings. Recently, many studies have been conducted and corresponding models have been developed to explain the main reason behind the enhanced thermal conductivity of nanofluids. These reasons mainly include Brownian Dynamics, nanoparticle aggregation and interfacial layer effect or liquid layering effect around a nanoparticle [7, 8 and 9].

The nanolayer around the nanoparticle attributes to the enhancement of heat transfer properties of nanofluids. The work by Yu and Choi [10] modified the Maxwell model to determine the effective thermal conductivity by taking the interfacial layer effect into consideration and found that the solid like liquid layer, acts as a thermal bridge between the solid particle and the bulk liquid. In this paper a non linear variation of thermal conductivity in the interfacial layer of Al_2O_3-Water and Al_2O_3-Ethylene Glycol nanofluids is modelled and parametric studies are conducted with the existing models. Henceforth, a novel non-linear model i.e. Hyperbolic has been proposed for the prediction of effective thermal conductivity. Results are found in close agreement with the experimental data as well as with other models.

II. Formulation of Associated Equations and Parametric Studies:

Existing Models used earlier to predict thermal properties

Various have been proposed for finding effective thermal conductivity of nanofluid with considering interfacial layer formed on particles. Maxwell [5] proposed model for determining effective thermal conductivity of suspension of solid particles in the based fluid for low volume fraction of spherical particles and given by:

$$k_{eff} = \frac{k_p + 2k_f + 2\phi\left(k_p - k_f\right)}{k_p + 2k_f - \phi\left(k_p - k_f\right)} k_f \tag{1}$$

Hamilton Crosser [6] proposed model for suspension of solid particles in based fluid with considering effect of the shape of the solid particles and given by:

$$k_{eff} = \frac{k_p + (n-1)k_f - (n-1)\phi\left(k_f - k_p\right)}{k_p + (n-1)k_f + \phi\left(k_f - k_p\right)}, \tag{2}$$

Where, empirical shape factor defined as $n = \frac{3}{\psi}$ and Ψ is the sphericity.

Yu and Choi [10] developed model by considering the effect of ordered liquid nano layer around the nanoparticles on the thermal conductivity of nanofluids by modifying the Maxwell’s model for the size of nanoparticles less than 10 nm.

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2k_f + 2(1+\gamma)^3 (k_p - k_f)\phi}{k_p + 2k_f - (1+\gamma)^3 (k_p - k_f)\phi} \tag{3}$$

Determination of thermal conductivity of interfacial nano-layer

In this model it has been assumed that in nanofluid, nano particles are suspended either in aggregated form or in separated form. Choi et al. [10] suggested that an ordered nano layer exist on the surface of individual particles. This ordered interfacial layer is having higher thermal conductivity than the bulk liquid.

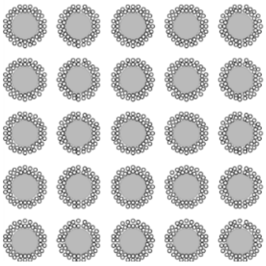

Fig. 1. Schematic cross section of nanofluid structure consisting of nano particle, bulk liquid and nano layer at solid/liquid interface [10].

The portion of interfacial layer just in contact with the particle has thermal conductivity (K_p) and the thermal conductivity goes on decreasing along the thickness of interfacial layer towards the base liquid and finally approaching the value equal to (K_m) just before it blends and behave as liquid.

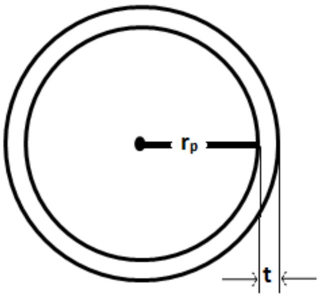

Fig. 2. Schematic model of nanoparticle with interfacial layer

III. Modelling for non-linear variation of thermal conductivity of interfacial layer:

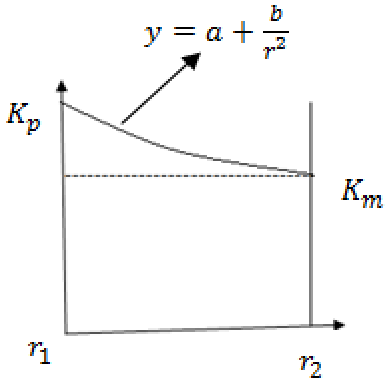

Fig. 3. Variation of thermal conductivity of interfacial layer along its thickness.

Where $r_1 = r_p$ & $r_2 = r_p + t$

The equation for finding the thermal conductivity at a distance 'r' within the interfacial layer expressed as:

$$k(r) = \frac{k_m (r_p + t)^2 - k_p r_p^2}{\left((r_p + t)^2 - r_p^2\right)} + \frac{(k_p - k_m) r_p^2 (r_p + t)^2}{\left((r_p + t)^2 - r_p^2\right) r^2} \tag{4}$$

Now considering the steady state heat transfer condition across the interfacial layer with heat flow rate being constant and equal to Q. The following equation in spherical coordinates can be written as:

$$Q = -k(r) A \frac{dT}{dr} \tag{5}$$

For an infinitesimally small interfacial layer at a distance r from the centre of particle the surface area A can be written as$A = 4\pi r^2$. Putting the value of A and k(r) in equation, rearranging and integrating it we obtain:

$$\frac{-4\pi\Delta T}{Q}=\int_{r_p}^{r_p+t}\frac{dr}{r^2\left[(k_p+\lambda r_p)-\lambda r\right]} \tag{6}$$

Now considering the interfacial layer as a whole having equivalent thermal conductivity k_l we can write similar heat transfer equation for hollow sphere as:

$$Q=-k_l\,4\pi r_p\left(r_p+t\right)\frac{\Delta T}{t} \tag{7}$$

This can be rearranged to give:

$$\frac{-4\pi\Delta T}{Q}=\frac{t}{r_p\,(r_p+t)k_l} \tag{8}$$

Equating the right hand side of above equations and we obtain the value of equivalent thermal conductivity k_l as:

$$k_l=\frac{t}{r_p\left(r_p+t\right)\int_{r_p}^{r_p+t}\frac{dr}{r^2k\left(r\right)}}$$

On substituting value of k_l, it becomes:

$$k_l=\frac{t}{r_p\left(r_p+t\right)\int_{r_p}^{r_p+t}\frac{dr}{r^2\left[\frac{r_p}{2t}\left\{\left(k_p-k_m\right)\left(\left(\frac{r_p+t}{r_p}\right)^2-1\right)+k_m\left(\lambda^2-1\right)\right\}\right]}} \tag{9}$$

This on solving the integral becomes:

$$k_l=\frac{\sqrt{\left(k_p-k_m\right)\left(k_p-k_m\lambda^2\right)}}{\ln\left[\left(\frac{\sqrt{k_p-k_m\lambda^2}+\sqrt{k_p-k_m}}{\sqrt{k_p-k_m\lambda^2}-\sqrt{k_p-k_m}}\right)\left(\frac{r_p\sqrt{k_p-k_m\lambda^2}-\left(r_p+t\right)\sqrt{k_p-k_m}}{r_p\sqrt{k_p-k_m\lambda^2}+\left(r_p+t\right)\sqrt{k_p-k_m}}\right)\right]} \tag{10}$$

Where $\lambda=\frac{k_p-k_m}{t}$

Determination of effective thermal conductivity of nanofluid

Yu and Choi [10] proposed model for effective thermal conductivity of non aggregated particles expressed as:

$$k_{non-agg}=\frac{k_{pe}+2k_m+2\left(k_{pe}-k_m\right)\left(1+\delta\right)^3\phi}{k_{pe}+2k_m-\left(k_{pe}-k_m\right)\left(1+\delta\right)^3\phi}k_m \tag{11}$$

Where equivalent particle thermal conductivity (k_{pe}) is taken as:

$$k_{pe} = \left[\frac{\left(2(1-\gamma)+(1+\delta)^3(1+2\gamma)\right)\gamma}{(\gamma-1)+(1+\delta)^3(1+2\gamma)} \right] k_p \tag{12}$$

Where $\delta = \frac{t}{r_p}$ and $\gamma = \frac{k_l}{k_p}$

Feng et al. [11] developed a model for finding the effective thermal conductivity on the basis of existence of both nanolayer on the surface of the nanoparticles in base fluid (non- aggregating particles) and also the fact that some nanoparticles in nanofluids are in contact with each other to form Cluster (aggregating particle) expressed as:

$$k_{eff} = (1-\phi_e)k_{non-agg} + \phi_e k_{agg} \tag{13}$$

The above expression shows that the effective thermal conductivity is depend upon the effective volume fraction, thermal conductivity of aggregate and non-aggregate particles.

IV. Results and Discussion:

The variation of effective thermal conductivity of nanofluid with particle volume fraction is shown for various existing models. Figure (4 and 5) shows a close agreement of results between the existing model and experimental measurements. The results of present model are found to be precise and close to experimental findings. Present model incorporates the effect of nanoparticle aggregation in addition to the liquid layering effect around the nanoparticle.

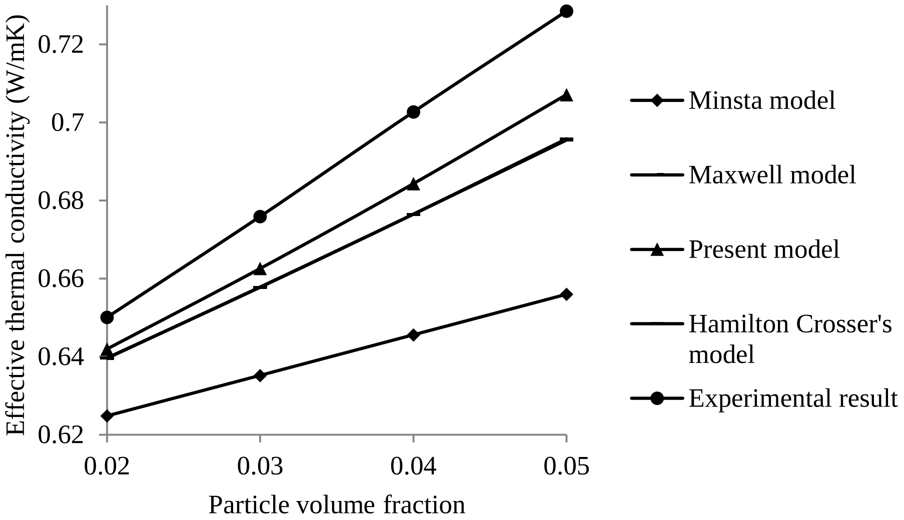

Fig.4. Effective thermal conductivity of Aluminium oxide (30nm)-water nanofluid.

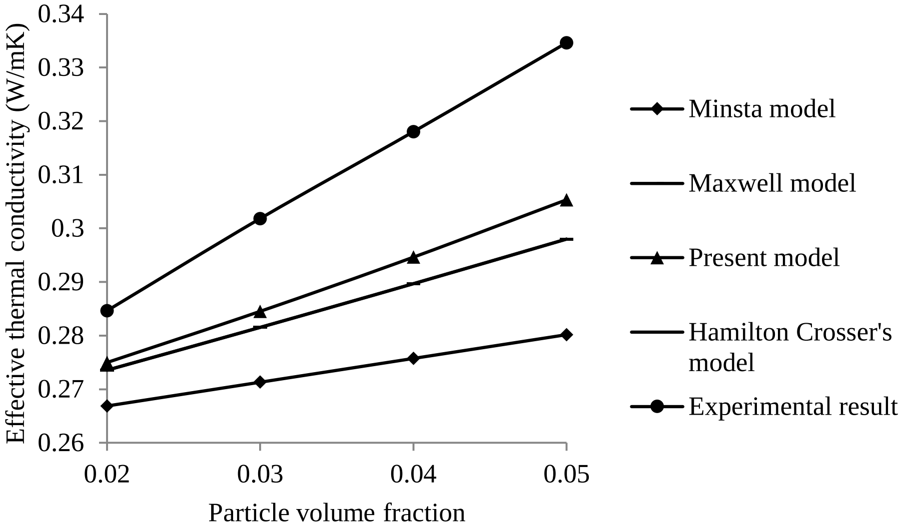

Fig. 5. Effective thermal conductivity of Aluminium oxide (30nm)-EG nanofluid.

V. Conclusions:

In this work, non-linear model of thermal conductivity within the ordered nanolayer have been formulated for Al_2O_3 based nanofluids and a new model for prediction of thermal conductivity has been proposed. Results predicting the thermal conductivity of nanofluids using this correlation were compared with experimental results and studies by other researchers. It has been found that the proposed model gives value of thermal conductivity of nanofluid more accurately than other models and are found closer to the experimental findings. As the effect of interfacial layer enhances the effective thermal conductivity; it is suggested that this effect should be taken into account for determining thermal conductivity of nanofluid.

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