Study on Parameters of Thermal Conductivity Enhancement in Oxide Nanofluids

Khagendra Kumar Upman, Amit Srivastava

Abstract— A mathematical model for thermal conductivity of metal oxides nanofluids was developed incorporating the following: considering the effects of temperature, volume fraction and size of the nanoparticle is developed and presented. For development of thermal conductivity model first we have to analyze the Brownian motion of nanoparticle. The particles suspended in the liquid are very small, Brownian movement of the particles is quite possible. Using nonlinear regression analysis and solving this in MATLAB for find out the unknown parameter, an empirical correlation is developed to predict the thermal conductivity of TiO2, ZnO & Al2O3 nanofluids.

The expression developed was successfully validated against experimental data obtained from the literature. The models was able to comprehensively explain the enhanced thermal conductivity of nanofluids. Following the validation with experimental data and existing models. It was found that in this study that the contribution of Brownian motion of nanoparticles to the overall thermal conductivity of nanofluids was found to be very important parameter.

Index Terms— Thermal conductivity, nanoparticle, Brownian motion, nanofluids.

I. INTRODUCTION

Heat transfer is one of the most important processes in many industries. Passive enhancement methods such as enhanced surfaces are usually employed in thermo fluid systems. Conventional heat transfer fluids widely used in industries (e.g. water, ethylene glycol and oil) However, inherently low thermal conductivity is a primary limitation in developing energy-efficient heat transfer fluids. Therefore, the development of advanced heat transfer fluids with higher thermal conductivity and improved heat transfer is in strong need to enhance heat transfer. The use of additives is another technique applied to enhance the heat transfer performance of base fluids. In general, most of the solids have better heat transfer properties compared to traditional heat transfer fluids.

It is found an effective way of improving the thermal conductivity of fluids is to suspend small solid particles in the fluids. The suspended metallic or nonmetallic particles change the transport properties and heat transfer characteristics of the base fluid. In the past, solid particles of micrometer or millimeter magnitudes were mixed in the base liquid. On the basis of this concept Conventional Solid–Liquid Suspension technique used by Maxwell (1873), Maxwell dispersed micrometer sized particles in heat transfer fluids. The major problem with suspensions containing micrometer sized particles is the rapid settling of micro particles. If the fluid is kept circulating to prevent particle settling, micrometer-sized particles would wear out pipes, pumps, and bearings so abrasion, fouling of components and clogging of flow passages these problems are also occurred. By using micrometer sized particle it is conclude that particle size is of primary importance in developing stable and highly conductive nanofluids.

In 1995, Choi created the concept of nanofluids (Choi, 1999) by suspending nano-sized metals, metal oxides, metal carbides and carbon nanotubes in conventional base fluids (such as water, ethylene glycol and oil). Mainly due to their smaller sizes, nanofluids offer lot of advantages over conventional heat transfer fluids, such as stay suspended much longer and possess a much higher surface area (The surface/volume ratio of nanoparticles is 1000 times larger than that of microparticles). Furthermore, because nanoparticles are so small, they may reduce erosion and clogging. Other benefits envisioned for nanofluids include decreased demand for pumping power showing significant energy savings. These novel properties make nanofluids attractive to various industries requiring heat transfer applications - such as microelectronics, transportation, biomedical, micro fluids, nuclear, automobile, generation of power and X-ray etc.

II. MATERIALS FOR NANOPARTICLES AND DIFFERENT BASE FLUIDS

Nanoparticles are the particles with average size below 100 nm. Nanoparticles have superior Electrical, mechanical, optical, magnetic and thermal properties than that of conventional bulk materials due to coarse grain structure with enhanced heat transfer area.

A. Nanoparticle materials

In general, most of the solids have better heat transfer properties compared to traditional heat transfer fluids. It is found an effective way of improving the thermal conductivity of fluids is to suspend small solid particles in the fluids. Many different particle materials are used for nanofluid preparation. Al2O3, CuO, TiO2, SiC, TiC, Ag, Au, Cu, and Fe nanoparticles are frequently used in nanofluid research (Das et al., 2000; Choi, 1999; Yoo et al., 2007; Zhu et al., 2006 and Yu et al., 2009). Carbon nanotubes are also utilized due to
their extremely high thermal conductivity.

B. Base fluids

Base fluids mostly used in the preparation of nanofluids are the common working fluids of heat transfer applications; such as, water, ethylene glycol and engine oil. In order to improve the stability of nanoparticles inside the base fluid, some additives are also added to the mixture in small amounts. (Das et al., 2007, Choi, 1999)

III. PRODUCTION METHODS

A. Production of Nanoparticles

Fabrication of nanoparticles can be classified into two broad categories: (Kimoto et al., 1963; Granqvist and Buhrman, 1976; Gleiter 1989).

(i) Physical synthesis and (ii) Chemical synthesis. Production techniques of nanofluids as follows:

(i) Physical Synthesis

Mechanical grinding: The grinding is a fine particle production method by applying mechanical energy on the solid materials to break the bonding between atoms or molecules. It is the oldest technique. Nowadays the particle size requirement for grinding is getting finer and finer. The grinding limit has long passed the submicrons and reaches the Nano sized range in recent days. This method is not so used. (Wei Yu and Huaqing Xie)

Inert gas condensation technique: In this method, the nanoparticle is made in the gas phase by creating a condition of supersaturation. The condition in the preparation chamber is made such that the solid phase is more stable than the gas phase. At this point the cluster nucleates and deposits from the gas phase. The deposition will lead to aggregation and can be controlled suitably by surfactants or suitable protecting agents. Recent study of nanomaterials prepared by inert gas condensation using ultra high vacuum chamber. (SRAMASAMY, P THANGADURAI)

(ii) Chemical Synthesis:

Chemical precipitation: Traditional chemical precipitation methods are frequently used in recent years. Homogeneous chemical precipitation method is often considered economically viable for preparation of mono disperse metal oxide particles of different shapes and sizes. The method also provides better control of chemical and morphological characteristics.

Chemical vapor deposition: CVD is a well-known process in which a solid is deposited on a heated surface via a chemical reaction from the vapor or gas phase, first molecules and atoms are separated by vaporization and then allowed to deposit in a carefully controlled and orderly manner to form nanoparticles. CVD classified by method of activation of reaction (Jong he park) as Plasma CVD, Laser CVD and photo-laser CVD. In plasma CVD, the reaction is activated by plasma at high temperature. In laser CVD reaction occurs when laser thermal energy heats an absorbing substrate. In photo-laser CVD, the chemical reaction is induced by ultra violet radiation which has sufficient photon energy, to break the chemical bond in the reactant molecules. Now a day’s chemical Vapor Synthesis (CVS) is a modified Chemical Vapor Deposition (CVD) method where the process parameters are adjusted to form nanoparticles instead of film. (Nanoparticle process technology NPTT)

Micro-Emulsions: Microemulsions are colloidal ‘nano-dispersions’ of water in oil (or oil in water) stabilized by a surfactant film (M. Arturo Lopez Quintela). These thermodynamically stable dispersions can be considered as truly nanoreactors which can be used to carry out chemical reactions and, in particular, to synthesize nanomaterials. The main idea behind this technique is that by appropriate control of the synthesis parameters one can use these nanoreactors to product tailor-made products down to a nanoscale level with new and special properties.

Spray pyrolysis: Spray pyrolysis is the aerosol process that atomizes a solution and heats the droplets to produce solid particles. It is very convenient method for synthesis of nanoparticles that provide good control of particle size and narrow particle size distribution and it is suitable for usage of available and cheap precursors. (George Biskos)

B. Production of Nanofluids:

There are mainly two methods of nanofluid production, namely-

1. Two-step technique and
2. One-step technique

In the two-step method, nanoparticles were first separately produced, and then the prepared nanoparticles were dispersed in the base fluid with the assistance of various physical treatment techniques, including the stirrer, the ultrasonic bath, the ultrasonic disruptor, and the high-pressure homogenizer. Two-step technique is play an important role when mass production of nanofluids is considered. The main disadvantage of the two-step technique is that the nanoparticles form clusters during the preparation of the nanofluid which prevents the proper dispersion of nanoparticles inside the base fluid. Eastman et al. (1997), Wang et al. (1999) and Lee et al. (1999) have used ultrasonic method to prepare Al2O3 nanofluids. Similarly Murshed et al. (2005) employed the same method to prepare TiO2 nanofluids. It was observed that this technique holds good for the preparation of nanofluids having oxides nanoparticles. While for metallic nanoparticles this method was less successful.

One-step method combines the production of nanoparticles and dispersion of nanoparticles in the base fluid into a single step. Magnetron sputtering process is generally applied in one step technique. This technique is more advantageous for considering dispersion characteristics of nanofluids produced, better than those produced with two-step technique. The main disadvantage of one-step techniques is that they are not proper for mass production in comparison to two step method, which limits their commercialization. Choi et al developed a Direct Evaporation technique for the production of nanofluids in one step. Zhu et al. (2004) presented a one-step chemical method for the preparation of Cu nanofluids.
IV. OBJECTIVES:

Specific objectives include:

1. To evaluate the effects of different properties of particle and experimental conditions on nanofluids thermal conductivity.

2. To evaluate the accuracy of existing models for thermal conductivity of nanofluids/ two phase system by comparing the calculated values with available experimental data.

3. Development of new empirical model for the thermal conductivity of metal oxides (Al2O3,ZnO& TiO2water as base fluid) nanofluid by using wide range of available experimental data in literature.

The research conducted under this paper was aimed at developing a more comprehensive model including critical factors responsible for the abnormal thermal conductivity behavior of nanofluids. Considering the factors like effects of temperature, volume fraction and size of the nano-particle an empirical correlation was developed. To understand the accuracy of the predicted results and relative improvement in the predictability, the results from developed model were compared to experimental observation and prediction obtained from other models in existence. After that, an evaluation was carried out to develop an insight of the dependence of effective thermal conductivity of nanofluids on the properties of nanoparticles and base fluid.

V. EFFECTS OF SOME PARAMETERS ON THERMAL CONDUCTIVITY OF NANOFLUIDS

A. Thermal conductivity variation at different concentrations:

There are many studies in the literature about the effect of particle volume fraction on the thermal conductivity of nanofluids. Masuda et al. measured the thermal conductivity of nanofluids containing Al2O3 (13 nm), SiO2 (12 nm), and TiO2 (27 nm) nanoparticles. This is the first experimental study regarding the thermal conductivity of nanofluids. Water was used as the base fluid and a two-step preparation method was utilized. An enhancement as high as 32.4% was observed for the effective thermal conductivity of 4.3 vol. % Al2O3/water nanofluid at room temperature. Lee et al. studied the room temperature thermal conductivity of nanofluids by dispersing Al2O3 (38.5 nm) and CuO (23.6 nm) nanoparticles. a linear relationship was observed between thermal conductivity and particle volume fraction (thermal conductivity increases with particle volume fraction). Highest enhancement was 20%, which was observed for 4 vol. %CuO/ethylene glycol nanofluid.
A linear relationship was observed between thermal conductivity and particle volume fraction (thermal conductivity increases with particle volume fraction). Highest enhancement was 20%, which was observed for 4 vol. %CuO/ethylene glycol nanofluid. A similar study was performed by Wang et al., who examined the thermal conductivity performance of nanofluids with Al₂O₃ (28 nm) and CuO (23 nm) nanoparticles. Particle volume fraction is a parameter that is investigated in almost all of the experimental studies and the results are usually in agreement qualitatively. Many researchers report increasing thermal conductivity with increasing particle volume fraction and the relation found is usually linear. But there are lots of differences between experimental data of researchers and reason behind this difference is as all authors have considered various factors for their model formulation. These factors include fluid temperature, phonon dispersion, size and shape of nanoparticle, clustering of particles, Brownian motion of nanoparticles, liquid layering at the particle surface, agglomeration and interfacial layer between the fluid and the particle.

Thermal conductivity variation due to particle size:
Particle size is another important parameter of thermal conductivity of nanofluids. It is possible to produce nanoparticles of various sizes, ranging between 5 to 100 nm. Mintsa et al. measured the thermal conductivity of Al₂O₃/water nanofluids. Two different sizes of Al₂O₃ nanoparticles were used in the experiment (36 and 47 nm). Particle volume fraction was varied between 0 and 18% and temperature was varied between 20 and 50°C. It was observed that the thermal conductivity enhancements were nearly the same for the two different particle sizes of Al₂O₃ nanoparticles at room temperature. However, at higher temperatures, Al₂O₃/water nanofluid with smaller particles showed higher enhancement.

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was observed that for the same nanofluids, different groups with different nanoparticle size report different enhancements. The result was summarized in Fig. 6 as it depicts that Al₂O₃ (33 nm) / Water nanofluid show 29% enhancement for 5% volume fraction while same nanoparticle of diameter 20 nm at 1% volume fraction shows 16% enhancement. Similarly CuO nanoparticle of dimension 36 nm and 50 nm when mixed with water shows an enhancement of 60% for 5% volume fraction and 17% for 0.4% volume fraction respectively.

Figure 6 Comparison of experimental results of the enhanced thermal conductivity of nanofluids [Murshed et al.]

Tengt. al produced nanofluid from direct synthesis method ultrasonic vibration was used for dispersing the different particle sizes (20, 50, and 100 nm) into four weight fractions (0.5, 1.0, 1.5, 2.0 wt %)(figure 7)

Figure 7 Comparison between the experimental data and the results of regression of the thermal conductivity ratio of Al₂O₃/water nanofluid

The results shown in Figs. 7 reveal the comparison between the experimental data and the results of regression of the thermal conductivity ratio of Al₂O₃/water nanofluid that change with different particle sizes under different temperatures and weight fraction. The nominal particle sizes of the nanoparticles were 20, 50, and 100 nm respectively. The experimental results indicate that increase in temperature and shrinkage of particle size enhances the thermal conductivity ratio of nanofluid. As the temperature of the three samples rose to 30 C, the thermal conductivity ratios could be enhanced by 5.1e12.8%, 1.4e6.9%, and 0.7e5.3%, respectively.

Experimental results depict that thermal conductivity of nanofluid increases when particle concentration is increased but the experimental values obtained increase in a nonlinear fashion. The general trend in the experimental data is that the thermal conductivity of nanofluids increases with decreasing particle size. This trend is theoretically supported by two mechanisms of thermal conductivity enhancement; Brownian motion of nanoparticles and liquid layering around nanoparticles. However, there is also a significant amount of contradictory data in the literature that indicate decreasing thermal conductivity with decreasing particle size. In fact, for the case of nanofluids with Al₂O₃ nanoparticles, such results are more common than the results showing increasing thermal conductivity with decreasing particle size. Decreasing thermal conductivity with decreasing particle size may be the result of severe clustering of nanoparticles in the associated samples.
Thermal conductivity variation with different base fluids:

Wang et al., (figure 8) Al$_2$O$_3$ and CuO nanoparticles were used to prepare nanofluids with several base fluids; water, ethylene glycol, vacuum pump fluid, and engine oil.

According to experimental result with Al$_2$O$_3$ nanoparticles, the highest thermal conductivity ratio was observed when ethylene glycol was used as the base fluid. Engine oil showed somewhat lower thermal conductivity ratios than ethylene glycol. Water and pump fluid showed even smaller ratios, respectively. With CuO nanoparticles, only ethylene glycol- and water-based nanofluids were prepared and it is interesting to note that they showed exactly the same thermal conductivity ratios for the same particle volume fraction.

The effect of the base fluid on the thermal conductivity of nanofluids was also analyzed by Xie et al. (figure 9) Nanofluids with Al$_2$O$_3$ nanoparticles were prepared by using different base fluids; deionized water, glycerol, ethylene glycol, and pump oil. In addition, ethylene glycol-water and glycerol-water mixtures with different volume fractions were also used as base fluids and the variation of the thermal conductivity ratio with thermal conductivity of the base fluid mixture was examined.

It was seen that, thermal conductivity ratio decreased with increasing thermal conductivity of the base fluid.

Thermal conduction variation at different temperature:

The temperature dependence of the thermal conductivity of Al$_2$O$_3$(38.4 nm)/water and CuO (28.6 nm)/water nanofluids was studied by Das et al.
Figure 10 shows the enhancement of thermal conductivity of Al2O3 based nanofluids with temperature. It is interesting to see both for 1% and 4% volume. Particle concentrations there are a considerable increase in the enhancement from 21°C to 51°C. With 1% particles at room temperature ~21°C. The enhancement in only about 2%, but at 51°C this value increases to about 10.8%. The measurement with 4% concentration shows enhancement goes from 9.4% to 24.3% with temperature rising from 21°C to 51°C. Thus it can be said that the enhancement of thermal conductivity shows a dramatic increase with temperature and the rate of this increase depends on the concentration of nano particles.

Li and Peterson also investigated the effect of temperature (figure 11) on thermal conductivity of CuO (29 nm)/water and Al2O3 (36 nm)/water nanofluids.

Effect on Viscosity of Nanofluids:

Choi et. al performed an experiment to measure effective viscosity of Al2O3 using a viscometer of oscillating type, the effective viscosities of Al2O3 nanofluids with low concentrations from 0.01 to 0.03 vol % are measured at the temperature range from 21°C to 39°C.

For both nanofluid types, it was observed that at a constant particle volume fraction thermal conductivity ratio increased with temperature. In addition, it was noted that for Al2O3/water nanofluid, the dependence of thermal conductivity ratio on particle volume fraction became more pronounced with increasing temperature. A regression analysis based on the experimental data showed that particle volume fraction dependence of thermal conductivity is much higher than the temperature dependence.

Figure 12 Effective viscosities of Al2O3-nanofluids with low concentration from 0.01 to 0.3 vol. % as a function of temperature. [Choi. et. al ]

Figure 12 shows the effective viscosities of Al2O3-nanofluids with various concentrations of Al2O3 nanoparticles as a function of temperature as effective viscosity of Al2O3-Water nanofluids decreases with increasing temperature.

Models of the effective viscosity of nanofluids based on the experimental data are limited to certain nanofluids. Masuda et al. were the first to measure the viscosity of Several water-based nanofluids for temperatures ranging from room condition to 67°C. Wang et al. obtained, using three different preparation methods, some data for the dynamic viscosity of Al2O3-water and Al2O3-ethylene glycol mixtures at various temperatures. Because the formulas such as the one proposed by Einstein and later improved by Brinkman and Batchelor underestimate the viscosity of the nanofluids when compared to the measured data, Maiga et al. performed a least-square curvefitting of some experimental data of Wang et al. including Al2O3 in water and Al2O3 in ethylene glycol. Table 1 illustrates a summary of the viscosity models at room
temperature based on the experimental data available in the literature.

Table 1 Summary of Viscosity Models at Room Temperature Based on experimental data

<table>
<thead>
<tr>
<th>Models</th>
<th>Effective Viscosity (Regression)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maiga et al.</td>
<td>$\mu_{\text{eff}} = (1 - 7.3\phi + 12.8\phi^2)$</td>
<td>Least-squares curve fitting of Maiga et al.</td>
</tr>
<tr>
<td>Maiga et al.</td>
<td>$\mu_{\text{eff}} = (1 - 0.009\phi + 30.6\phi^2)$</td>
<td>Least-squares curve fitting of experimental data [5,57]</td>
</tr>
<tr>
<td>Khazaei and Vafai</td>
<td>$\mu_{\text{eff}} = (1 - 0.006\phi + 30.3\phi^2)$</td>
<td>Least-squares curve fitting of experimental data [5,57]</td>
</tr>
<tr>
<td>Barajas et al.</td>
<td>$\mu_{\text{eff}} = (1 - 29.11\phi + 533.9\phi^2)$</td>
<td>Curve fitting of Peh and Cho [16] data</td>
</tr>
<tr>
<td>Barajas et al.</td>
<td>$\mu_{\text{eff}} = (1 + 5.03\phi + 106.2\phi^2)$</td>
<td>Curve fitting of Peh and Cho [16] data</td>
</tr>
<tr>
<td>Khazaei and Vafai</td>
<td>$\mu_{\text{eff}} = (1 - 29.09\phi + 382.3\phi^2)$</td>
<td>Curve fitting of Peh and Cho [16] data</td>
</tr>
<tr>
<td>Khazaei and Vafai</td>
<td>$\mu_{\text{eff}} = (1 - 5.44\phi + 169.4\phi^2)$</td>
<td>Curve fitting of Peh and Cho [16] data</td>
</tr>
<tr>
<td>Nguyen et al.</td>
<td>$\mu_{\text{eff}} = (1 - 0.009\phi + 20.6\phi^2)$</td>
<td>Curve fitting of the experimental data</td>
</tr>
<tr>
<td>Nguyen et al.</td>
<td>$\mu_{\text{eff}} = (1 - 0.009\phi + 20.6\phi^2)$</td>
<td>Curve fitting of the experimental data</td>
</tr>
<tr>
<td>Tsang and Lin</td>
<td>$\mu_{\text{eff}} = 1.367 \times 35.863\phi^2$</td>
<td>Sheet rate $= 1000$ s$^{-1}$</td>
</tr>
</tbody>
</table>


Moreover, Fig. shows a comparison of the relative dynamic viscosity of Al$_2$O$_3$–water nanofluid from various sources at room temperature.

Figure 13 Relative viscosity measurement as a function of the volume fraction, $\phi$, at ambient temperature (Al$_2$O$_3$–water nanofluid). (Reprinted from K. Khanafer and K. Vafai. 2011, A critical synthesis of thermophysical characteristics of nanofluids, International Journal of Heat and Mass Transfer 54, 4410–4428, Copyright 2011

MODELS USED FOR THERMAL CONDUCTIVITY OF NANOFLOUIDS:
A large body of literature has been contributed to the theoretical modeling of effective thermal conductivity of liquids containing suspended solid particles but currently, there is no reliable theory to predict the anomalous thermal conductivity of nanofluids. From the experimental results it is concluded that the thermal conductivity of nanofluids depends on various parameters like thermal conductivities of the base fluid and the nanoparticles, the volume fraction, the surface area, and the shape of the nanoparticles, and the temperature. There are no theoretical formulas currently available to predict the thermal conductivity of nanofluids satisfactorily. There are several models presented by researchers for calculating the effective thermal conductivity of nanofluids these are discussed below.

Maxwell Model (1876): Early attempts to explain this behavior have made use of the classical model of Maxwell. Maxwell was one of the first persons to investigate conduction analytically through a suspension particle.

$$k_{\text{eff}} = k_p + 2k_f + 2\phi_p(k_p - k_f)$$

It was one of the classical models present to determine the thermal conductivity ratio of nanofluids. This model relates
the thermal conductivity of spherical particles, base fluid and the volume fraction. Although the model was presented long back still it is used for comparing the values predicted experimentally. It should be noted that even given its form, Maxwell’s equation is only a first-order approximation and applies only to mixtures with low particle-volume concentrations.

\[ k_{\text{eff}} = \frac{k_p + (n - 1)k_f - (n - 1)f_p (k_f - k_p)}{k_f + (n - 1)f_p (k_f - k_p)} \]

For spherical shape nanoparticles \( \Psi = 3 \)

\[ k_{\text{eff}} = \frac{1}{4} \left[ (3f_p - 1)k_p + (2 - 3f_p)k_f \right] + \frac{k_f}{4} \sqrt{\Delta} \]

\[ \Delta = (3f_p - 1)^2 \left( \frac{k_p}{k_f} \right)^2 + (2 - 3f_p)^2 + 2(2 + 3f_p - 9f_p^2) \left( \frac{k_p}{k_f} \right) \]

This model can be applied to spherical particles with no limitations on the concentration of inclusions. For low solid concentrations, the Bruggeman model results in almost the same results as the Maxwell model but as concentration goes on increasing its values deviate from values of Maxwell model.

\[ \Psi = \frac{3}{\Psi} \]

For cylindrical shape nanoparticles \( \Psi = 6 \)

\[ k_{\text{eff}} = \frac{k_p + 2k_f + 2f_p (k_p - k_f) (1 + \beta)^3}{k_f + 2k_f - f_p (k_p - k_f) (1 + \beta)^3} \]

**Wang et al.** Wang et al proposed a statistical structural model to determine the macroscopic characteristics of clusters, and then the thermal conductivity of nanofluids can be estimated according to the existing effective media approximation theory. The proposed statistical model was sound in physical concepts and potentially useful as an effective tool for screening and optimizing nanofluids as advanced working fluids.
Table 2 A brief summary of the currently available theoretical models for predicting the effective thermal conductivity of nanofluid

<table>
<thead>
<tr>
<th>Proponents</th>
<th>Model Expression</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>Maxwell (1881)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = 1 + \frac{3(\alpha - 1)\phi}{(\alpha + 2) - (\alpha - 1)\phi} )</td>
<td>Only spherical particles are considered; Accurate to ( o(\phi) ), applicable to low volume fraction.</td>
</tr>
<tr>
<td>Maxwell-Garnett model (Maxwell, 1881)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = \frac{(1 - \phi)(k_p + 2k_i) + 3\phi k_p}{(1 - \phi)(k_p + 2k_i) + 3\phi k_i} )</td>
<td>Applicable to suspensions with low concentration particle inclusions.</td>
</tr>
<tr>
<td>Bruggeman model (1935)</td>
<td>( \phi \left( \frac{k_p - k_{\text{eff}}}{k_p + 2k_{\text{eff}}} \right) + (1 - \phi) \left( \frac{k_i - k_{\text{eff}}}{k_i + 2k_{\text{eff}}} \right) = 0 )</td>
<td>No limit on concentration of inclusions.</td>
</tr>
<tr>
<td>Hamilton &amp; Crosser (1962)</td>
<td>( k_{\text{eff}} = \frac{k_p + (n-1)k_i - (n-1)\alpha(k_p - k_i)}{k_p + (n-1)k_i + \alpha(k_p - k_i)} )</td>
<td>Spherical and non-spherical particles are considered, Accurate to ( o(\phi) ), applicable to low volume fraction.</td>
</tr>
<tr>
<td>Jeffrey (1973)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = 1 + 3\beta\phi + \phi^3 \left[ 3\beta^2 + \frac{3\beta^2}{4} + \frac{9\beta^3}{16} + \frac{\alpha^2}{2\alpha + 3} + \frac{3\beta^4}{2^6 + \ldots} \right] )</td>
<td>High order terms represent pair interaction of randomly dispersed spheres.</td>
</tr>
<tr>
<td>Wasp (1977)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = \frac{k_p + 2k_i - 2\phi(k_i - k_p)}{k_p + 2k_i + \phi(k_i - k_p)} )</td>
<td>Special case of HC model with sphericity equal to 1.</td>
</tr>
<tr>
<td>Davis (1986)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = 1 + \frac{3(\alpha - 1)}{(\alpha + 2) - (\alpha - 1)\phi} \left[ \phi + f(\alpha)\phi^3 + o(\phi^4) \right] )</td>
<td>High order terms represent pair interaction of randomly dispersed spheres.</td>
</tr>
<tr>
<td>Lu &amp; Lin (1995)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = 1 + a\phi + b\phi^2 )</td>
<td>Applicable to both spherical and non-spherical.</td>
</tr>
<tr>
<td>Xue (2003)</td>
<td>( \frac{k_{\text{eff}}}{k_i} = 9(1 - \frac{\phi}{\alpha}) \frac{k_p - k_{\text{eff}}}{2k_{\text{eff}}} + \phi \left[ \frac{k_{\text{eff}} - k_{\text{eff}}}{k_i + B_{2,2}(k_{\text{eff}} - k_{\text{eff}})} \right] + 4 \frac{k_{\text{eff}} - k_{\text{eff}}}{2k_{\text{eff}}} + (1 - B_{2,2}(k_{\text{eff}} - k_{\text{eff}})) = 0 )</td>
<td>Elliptical particles are considered, only suitable for particles at nanometer size.</td>
</tr>
<tr>
<td>Yu &amp; Choi (2003)</td>
<td>( k_{\text{eff}} = \frac{2(1 - \gamma) + (1 + \beta)(1 + 2\gamma)}{(1 - \gamma) + (1 + \beta)(1 + 2\gamma)} k_p )</td>
<td>Modified Maxwell model, nanoparticle liquid layering is considered.</td>
</tr>
<tr>
<td>Bonnecaze &amp; Brady (1990)</td>
<td>N/A</td>
<td>Near and far field interactions among two or more particles are considered.</td>
</tr>
</tbody>
</table>
CONCLUSION

From the review of above literature following conclusions can be drawn:

1. Among the discussed models, there are a few of them which able to significantly explain the thermal conductivity enhancement in nanofluids. The review of literature indicated that a single factor is not responsible for high thermal conductivity of the nanofluids. Instead a combination of factors will provide the answer for the overall thermal conductivity of nanofluids.

2. Nanofluids having small amounts of nanoparticles have substantially higher thermal conductivity than those of base fluids. The thermal conductivity enhancement of nanofluids depends on various factors such as particle volume fraction, type of base fluid, size and shape of nanoparticles, temperature and also with type of nanoparticles used.

3. A general form of thermal conductivity model is not so accurate they show a large difference in thermal conductivity enhancement with experiments value. An empirical correlation for the thermal conductivity of two most promising nanofluids Al_2O_3 with water, ZnO and TiO_2 water, considering the effects of temperature, volume fraction and size of the nanoparticle is developed and presented.

REFERENCES


