NANOFLUID THERMAL CONDUCTIVITY-A REVIEW

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ABSTRACT

The fluids dispersed with nanoparticles known as nanofluids are promising for heat transfer enhancement due to their high thermal conductivity. In the present study, a literature review of nanofluid thermal conductivity is performed. The possible mechanisms are presented for the high thermal conductivity of nanofluids. The effect of some parameters such as particle volume fraction, particle size, and temperature on thermal conductivity is presented. Theoretical models are explained, model predictions are compared with experimental data, and discrepancies are indicated.

KEYWORDS: *Thermal conductivity, Volume Fraction, Particle size, Temperature*

I. INTRODUCTION

Cooling is one of the most important challenges facing numerous industrial sectors. Despite the considerable amount of research and development focusing on industrial heat transfer requirements, major improvements in cooling capabilities have been lacking because conventional heat transfer fluids have poor heat transfer properties. One of the usual methods used to overcome this problem is to increase the surface area available for heat exchange, which usually leads to impractical or unacceptable increases in the size of the heat management system. Thus there is a current need to improve the heat transfer capabilities of conventional heat transfer fluids.

Choi et al. [1] reported that the nanofluids (the fluids engineered by suspending metallic nanoparticles in conventional heat transfer fluids) were proved to have high thermal conductivities compared to those of currently used heat transfer fluids, and leading to enhancement of heat transfer. Choi et al. [2] produced nanofluids by suspending nanotubes in oil and experimentation had carried out to measure effective thermal conductivity of nanofluids. They reported a 150 % thermal conductivity enhancement of poly (α-olefin) oil with the addition of multiwalled carbon nanotubes (MWCNT) at 1 % volume fraction. The results showed that the measured thermal conductivity was anomalously greater than theoretical predictions and is nonlinear with nanotube concentration. When compared to other nanofluids, the nanofluids with nanotubes provide the highest thermal conductivity enhancement.

Yang et al [3] addressed the effects of dispersant concentration, dispersing energy, and nanoparticle loading on thermal conductivity and steady shear viscosity of nanotube-in-oil dispersions. Thermal conductivity enhancement 200% was observed for poly (α-olefin) oil containing 0.35 % (v/v) MWCNT. It was found that fluids with large scale agglomerates have high thermal conductivities. Dispersion energy, applied by sonication, can decrease agglomerate size, but also breaks the nanotubes, decreasing both the thermal conductivity and viscosity of nanotube dispersions.

In the present work first experimental studies on thermal conductivity of nanofluids affected by parameters like volume fraction, particle size, temperature etc are presented followed by theoretical models. Comparison of theoretical and experimental results is performed and possible mechanisms are explained for the discrepancy.

II. EXISTING STUDIES ON NANOFLUID THERMAL CONDUCTIVITY

Studies regarding the thermal conductivity of nanofluids showed that high enhancements of thermal conductivity than base fluids. It is possible to obtain larger thermal conductivity enhancements with low particle volume fraction [4-8]. Such enhancement values exceed the predictions of theoretical models developed for suspensions with larger particles. This is considered as an indication of the presence of additional thermal transport enhancement mechanisms of nanofluids.

2.1. Effect of particle Volume Fraction

There are many studies in the literature about the effect of particle volume fraction of nanofluid, which is the volumetric concentration of the nanoparticles in the fluid, on the thermal conductivity. Eastman et al. [4] prepared Cu-ethylene glycol nanofluids and found that these fluids have much higher effective thermal conductivity than either pure ethylene glycol. The effective thermal conductivity of ethylene glycol was shown to be increased by up to 40% with an addition of approximately 0.3 vol. % Cu nanoparticles of mean diameter ≪10 nm. The addition of dispersant yielded a greater thermal conductivity than the same concentration of nanoparticles in the ethylene glycol without the dispersant and no effect of either particle size or particle thermal conductivity was observed.

Jana et al. [5] used conductive nanomaterials such as carbon nanotubes (CNTs), copper nanoparticles (Cu) and gold nanoparticles (Au), as well as their hybrids such as CNT-Cu or CNT-Au to enhance the thermal conductivity of fluids. They observed a 70 % thermal conductivity enhancement for 0.3 % (v/v) Cu nanoparticles in water. The results demonstrated that mono-type nanoparticle suspensions have greatest enhancement in thermal conductivity, among which the enhancement with Cu nanoparticle was the highest. The experimentally measured thermal conductivities of several nanofluids were consistently greater than the theoretical predictions obtained from existing models.

Liu et al [6] dispersed Cu nanoparticles in ethylene glycol, water, and synthetic engine oil using chemical reduction method (one-step method). Experimental results illustrated that nanofluids with low concentration of Cu have considerably higher thermal conductivity than those of base liquids. For Cu-water at 0.1 vol.%, thermal conductivity is increased by 23.8%. A strong dependence of thermal conductivity on the measured time was observed for Cu-water nanofluid.

Murshed et al [7] prepared nanofluids by dispersing TiO_2 nanoparticles (in rod-shapes and in spherical) shapes in deionized water. The experimental results demonstrated that the thermal conductivity increases with an increase of particle volume fraction. The particle size and shape also have effects on this enhancement of thermal conductivity.Zhu et al [8] studied thermal conductivities of Fe_3O_4 aqueous nanofluids. The results illustrated that Fe_3O_4 nanofluids have higher thermal conductivities than other oxide aqueous nanofluids at the same volume fraction. The experimental values are higher than those predicted by the existing models. The abnormal thermal conductivities of Fe_3O_4 nanofluids are attributed to the observed nanoparticle clustering and alignment.

Ceylan et al [9] prepared Ag-Cu alloy nanoparticles by the inert gas condensation (IGC) process. X-ray diffraction (XRD) patterns demonstrated that particles were phase separated as pure Cu and Ag with some Cu integrated in the Ag matrix. Thermal transport measurements have shown that there is a limit to the nanoparticle loading for the enhancement of the thermal conductivity. This maximum value was determined to be 0.006 vol. % of Ag-Cu nanoparticles, which led to the enhancement of the thermal conductivity of the pump oil by 33 percent.

Zhang et al [10] measured the effective thermal conductivities and thermal diffusivities of Au/toluene, Al_2O_3/water, and carbon nanofiber (CNF)/water nanofluids and the influence of the volume fraction on thermal conductivity of the nanofluids was discussed. The measured results demonstrated that the effective thermal conductivities of the nanofluids show no anomalous enhancements.

Putnam et al [11] described an optical beam deflection technique for measurements of the thermal diffusivity of fluid mixtures and suspensions of nanoparticles with a precision of better than 1%. Solutions of C60–C70fullerenes in toluene and suspensions of alkanethiolate-protected Au nanoparticles were measured to maximum volume fractions of 0.6% and 0.35 vol %, respectively.

The largest increase in thermal conductivity they have observed was 1.3%±0.8% for 4 nm diameter Au particles suspended in ethanol.

As seen in the Fig. 1, there exists significant discrepancy between experimental and theoretical data. This discrepancy can be explained by the fact that parameters such as PH of the nanofluid, dispersant, severity of clustering, and method of production of nanofluids usually differ in each experiment. Experimental results of Wen and Ding [59] are relatively higher than the results of other research groups and they are predicted best by the model of Koo and Kleinstreuer [57].

However, since the size distribution of particles is not known in detail, it is difficult to reach a conclusion about the validity of the models. Dependency of the data of Lee et al. [21] on particle volume fraction is somewhat low and none of the models have such a small slope in the figures. Hamilton and Crosser [54] model is relatively closer to the experimental data of Lee et al. [21] and Das et al. [15]. It was noted that clusters as large as 100 nm were observed in the study of Lee et al. [21]. Therefore, it may be suggested that those samples are closer to the validity range of the Hamilton and Crosser model. However, Das et al. [15] also considered the effect of temperature in their study and indicated that this agreement is just a coincidence.

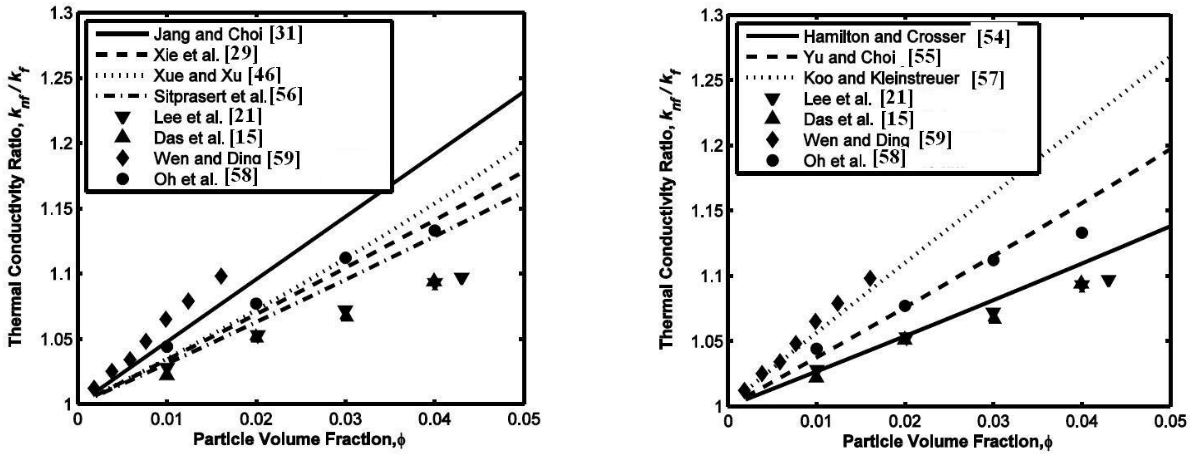

Figure 1. Comparison of the experimental results of the thermal conductivity ratio for Al_2O_3 nanofluid with theoretical model as a function of particle volume fraction (Özerinç et al [23]).

2.2. Effect of Particle Size

Particle size is another important parameter of thermal conductivity of nanofluids. It is possible to produce nanoparticles of various sizes, generally ranging between 5 and 100 nm. Xie et al [12] prepared nanofluids containing Al_2O_3 nanoparticles with diameters in a range of 12 nm and 304 nm. Nanoparticle suspensions, containing a small amount of Al_2O_3, have significantly higher thermal conductivity than the base fluid. The enhanced thermal conductivity increases with an increase in the difference between the PH value of aqueous suspension and the isoelectric point of Al_2O_3 particle. They concluded that there is an optimal particle size which yields the greatest thermal conductivity enhancement.

Kim et al [13] measured thermal conductivity of water- and ethylene glycol-based nanofluids containing alumina, zinc-oxide, and titanium-dioxide nanoparticles using the transient hot-wire method. Measurements were conducted by varying the particle size and volume fraction. For nanofluids containing 3 vol. % TiO_2 in ethylene glycol, the thermal conductivity enhancement for the 10 nm sample (16 %) was approximately double the enhancement for the 70 nm sample. The results illustrated that the thermal-conductivity enhancement ratio relative to the base fluid increases linearly with decreasing the particle size but no existing empirical or theoretical correlation can explain the behaviour.

Li et al [14] used a steady state technique to evaluate the effective thermal conductivity of Al_2O_3/distilled water nanofluids with nanoparticle diameters of 36 and 47 nm. Tests were conducted over a temperature range of 27–37 °C for volume fractions ranging from 0.5% to 6.0%. It was observed that up to 8 % greater thermal conductivity enhancement for aqueous nanofluids containing 36 nm Al_2O_3 particles compared to nanofluids containing 47 nm Al_2O_3 particles. The thermal conductivity enhancement of the two nanofluids demonstrated a nonlinear relationship with respect to temperature, volume fraction, and nanoparticle size.

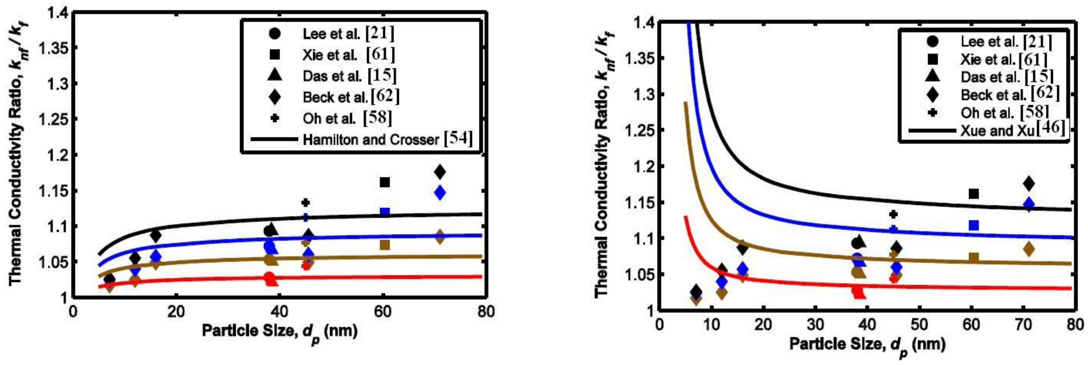

Figure 2. Comparison of the experimental results of the thermal conductivity ratio for Al_2O_3/water nanofluid with Hamilton and Crosser model [54] and Xue and Xu [46] as a function of the particle size at various values of the particle volume fraction (Özerinç et al [23]).

The most significant finding was that the effect of variations in particle size had on the effective thermal conductivity of the Al_2O_3/distilled water nanofluids. The largest enhancement difference observed occurred at a temperature of approximately 32 °C and at a volume fraction of between 2% and 4%. From the experimental results it can be observed that an optimal size exists for different nanoparticle and base fluid combinations.

When Fig. 2 (Colours indicate different values of particle volume fraction; red 1%, brown 2%, blue 3%, and black 4%)was observed, it was seen that Hamilton and model predicts increasing thermal conductivity with increasing particle size. The Hamilton and Crosser model [54] does not take the effect of particle size on thermal conductivity into account, but it becomes slightly dependent on particle size due to the fact that particle thermal conductivity increases with increasing particle size. However, the model still fails to predict experimental data for particle sizes larger than 40 nm since particle size dependence diminishes with increasing particle size. This trend of increasing thermal conductivity with decreasing particle size is due to the fact that these models are either based on Brownian motion (Koo and Kleinstreuer [57] and Jang and Choi [31] models) or based on liquid layering around nanoparticles (Yu and Choi [55], Xie et al. [29], Xue and Xu [46], and Sitprasert et al. [56] models). Fig.2 demonstrates thermal conductivity ratio for Al_2O_3/water nanofluid with Xue and Xu model [46] as a function of the particle size at various values of the particle volume fraction. Colors indicate different values of particle volume fraction; red 1%, brown 2%, blue 3%, and black 4%. Whereas Xue and Xu [46] model illustrates the trend of increasing thermal conductivity with decreasing particle size is due to the fact that these models are either based on Brownian motion (Koo and Kleinstreuer [57] and Jang and Choi [31] models) or based on liquid layering around nanoparticles (Yu and Choi [55], Xie et al. [39], Xue and Xu [46], and Sitprasert et al. [56] models).

Although the general trend for Al_2O_3/water nanofluids was as presented, there is also experimental data for Al_2O_3/water nanofluids, which shows increasing thermal conductivity with decreasing particle size [19, 20, 61, 32, 35, and 58]. It should be noted that clustering may increase or decrease the thermal conductivity enhancement. If a network of nanoparticles is formed as a result of clustering, this may enable fast heat transport along nanoparticles. On the other hand, excessive clustering may result in sedimentation, which decreases the effective particle volume fraction of the nanofluid.

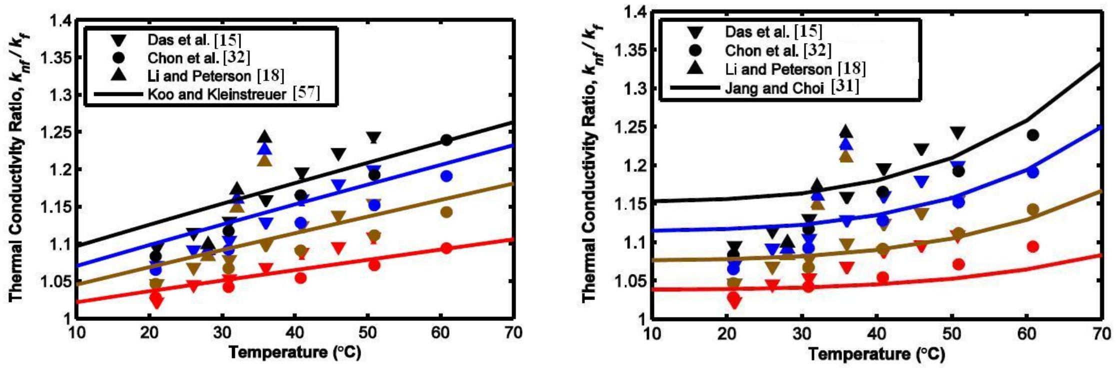

Figure 3. Comparison of the experimental results of the thermal conductivity ratio for Al_2O_3/water nanofluid with Koo and Kleinstreuer model [57] and Jang and Choi model [31] as a function of temperature at various values of particle volume fraction. Colors indicate different values of particle volume fraction; red 1%, brown 2%, blue 3%, and black 4% (Özerinç et al [23]).

2.3. Effect of Temperature

In conventional suspensions of solid particles (with sizes on the order of millimeters or micrometers) in liquids, thermal conductivity of the mixture depends on temperature only due to the dependence of thermal conductivity of base liquid and solid particles on temperature. Das et al [15] investigated the increase of thermal conductivity with temperature for nanofluids with water as base fluid and particles of Al_2O_3 or CuO as suspension material. A temperature oscillation technique was used for the measurement of thermal diffusivity and thermal conductivity. The results indicated an increase of enhancement characteristics with temperature, within the limited temperature range considered gradual curve appeared as linear.

Yang et al [16] studied the temperature dependence of thermal conductivity enhancement in nanofluids containing Bi_2Te_3 nanorods of 20nm in diameter and 170mm in length. The 3ω-wire method had been developed for measurement of the thermal conductivity of nanofluids. The thermal conductivity enhancement of nanofluids has been experimentally found to decrease with increasing temperature, in contrast to the trend observed in nanofluids containing spherical nanoparticles. They observed a decrease in the effective thermal conductivity as the temperature increased from 5 to 50 ºC. The contrary trend was featured mainly to the particle aspect ratio.

Honorine et al [17] reported effective thermal conductivity measurements of alumina/water and copper oxide/water nanofluids. The effects of particle volume fraction, temperature and particle size were investigated. Readings at ambient temperature as well as over a relatively large temperature range were made for various particle volume fractions up to 9%. Results clearly illustrated that the predicted overall effect of an increase in the effective thermal conductivity with an increase in particle volume fraction and with a decrease in particle size. Furthermore, the relative increase in thermal conductivity was found to be more important at higher temperatures.

The experimental results From Fig. 3 it should be noted that the presented data of Li and Peterson [18] was obtained by using the line fit provided by the authors since data points create ambiguity due to fluctuations. In the models, particle size is selected as 40 nm since most of the experimental data is close to that value, as explained in the previous sections suggests that thermal conductivity ratio increases with temperature. It is seen that the temperature dependence of the data of Li and Peterson [18] is much higher than the results of other two research groups. On the other hand, the results of Chon et al. [32] show somewhat weaker temperature dependence. This might be explained by the fact that the average size of nanoparticles in that study is larger when compared to others, since increasing particle size decreases the effect of both Brownian motion and nanolayer formation. It should also be noted that dependence on particle volume fraction becomes more pronounced with increasing temperature in all of the experimental studies [18].

When it comes to theoretical models, predictions of Hamilton and Crosser model [54], Yu and Choi model [55], Xue and Xu model [46], and Xie et al. [29] model does not depend on temperature except for a very slight decrease in thermal conductivity ratio with temperature due to the increase in the thermal conductivity of water with temperature. Therefore, these models fail to predict the mentioned

trends of experimental data. Since the predictions of these four models with respect to temperature do not provide any additional information; associated plots are not shown here.
The model proposed by Koo and Kleinstreuer [57] considered the effect of Brownian motion on the thermal conductivity and the predictions of this model are presented in Fig. 3. The presented model of Koo and Kleinstreuer predicts the trend in the experimental data correctly. The model proposed by Jang and Choi [31] was presented in Fig. 3. It
was noted that this model predicts nonlinear temperature dependence of thermal conductivity, whereas other two models predict linear behavior. Experimental results of Das et al. [15] and Li and Peterson [18] show nearly linear variation of thermal conductivity ratio with temperature, which is contradictory with the model. On the other hand, result of Chon et al. [32] suggests nonlinear variation and the associated trend is somewhat in agreement with the model of Jang and Choi.

III. NANOFLUID THERMAL CONDUCTIVITY MODELS

The thermal conductivity enhancement of nanofluids was higher than those predicted from conventional models for larger size particle dispersions as in Fig.4. Therefore, different researchers (Keblinski et.al [27] Li and Xuan [28]) Xie etal [29]) explored the mechanisms of heat transfer in nanofluids, and proposed four possible reasons for the contribution of the system:

1. Brownian motion of the particle
2. Molecular-level layering of the liquid at the liquid/solid interface
3. The nature of the heat transport in nanoparticles
4. The effects of nanoparticles clustering

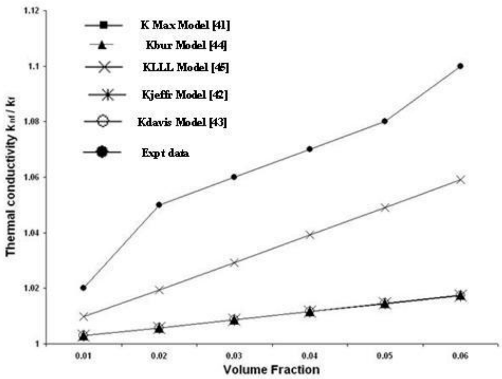

Figure 4. Comparison of conventional models with the experimental data

Keblinski et al [27] investigated the effect of nanoparticle size on thermal conductivity of nanofluids. Thermal conductivity was found to be increased with the reduction in grain size of nanoparticles within the nanofluid. They concluded that the key factors for thermal properties of nanofluids are the ballistic, rather than diffusive, nature of heat transport in the nanoparticles, combined with direct or fluid-mediated clustering effects that provide paths for rapid heat transport.
Krischer [30] developed an empirical model to describe the irregular arrangement of suspended particles. The greater surface area associated with smaller particles promotes heat conduction. The higher specific surface area of nanoparticles improves a greater degree of aggregation than with a suspension of larger particles. Most nanofluid thermal conductivity models were developed based on one or more of these mechanisms.

3.1. Brownian motion

Jang et al [31] found that the Brownian motion of nanoparticles at the molecular and nanoscale level is a key mechanism governing the thermal behavior of nanofluids. They used a theoretical model that accounts for the fundamental role of dynamic nanoparticles in nanofluids. The model not only captures the concentration and temperature-dependent conductivity, but also predicts strongly size-dependent conductivity. The model is based on a linear combination of contributions from the liquid, the suspended particles, and the Brownian motion of the particles to give:

$$\frac{k_{\text{eff,m}}}{k_1} = (1-\phi) + \varepsilon\alpha\phi + C_1 \frac{d_f}{d} \text{Re}^2 \,\text{Pr}\,\phi \tag{1}$$

where ε is a constant related to the Kapitza resistance, C_1 is a proportionality constant, d_f is the diameter of a fluid molecule, and Re and Pr are the Reynolds the Prandtl numbers of the fluid, respectively. The Reynolds number, Re, is defined by,

$$\text{Re} = \frac{\rho k_B T}{3\pi\mu^2 l_f} \tag{2}$$

where k_B is the Boltzmann constant, l_f is the mean free path of a fluid molecule, and ρ and μ are the density and viscosity of the fluid, respectively. Their model reflects strong temperature dependence due to Brownian motion and a simple inverse relationship with the particle diameter.

Based on the Jang and Choi model, Chon et al. [32] employed the Buckingham-Pi theorem to develop the following empirical correlation,

$$\frac{k_{\text{eff,m}}}{k_1} = 1 + 64.7\phi^{0.7460} \left(\frac{d_f}{d}\right)^{0.3690} \alpha^{0.7476}\, \text{Pr}^{0.9955}\, \text{Re}^{1.2321} \tag{3}$$

where the Reynolds and Prandtl numbers are the same as in the Jang and Choi model [31]. The equation was fit to their measurements of aqueous nanofluids containing three sizes of alumina particles. However, their correlation was of limited use, since it was based on measurements over a limited temperature range (20 – 70 ºC) and it was fit to thermal conductivity data for a single nanoparticle material in a single base fluid. Chon et al [32] did not demonstrated any ability of their model to predict the thermal conductivity of other nanofluids. Other models are available that are fitted to similarly limited nanofluid data and include no consideration for the more conventional thermal conductivity models [33-35]. However, some researchers have used conventional heterogeneous thermal conductivity models as a starting point and extended these to include a particle size dependence based on Brownian motion.

Xuan et al [36] adopted the concepts of both the Langevin equation of the Brownian motion and the concept of the stochastic thermal process to describe the temperature fluctuation of the nanoparticles suspended in base fluids. They developed an extension of the Maxwell equation to include the micro convective effect of the dynamic particles and the heat transfer between the particles and fluid to give:

$$\frac{k_{\text{eff,m}}}{k_1} = \frac{\alpha + 2 + 2\phi(\alpha - 1)}{\alpha + 2 - \phi(\alpha - 1)} + \frac{18\phi HAT}{\pi^2 \rho d^6 k_1}\tau \tag{4}$$

where H is the overall heat transfer coefficient between the particle and the fluid, A is the corresponding heat transfer area, and τ is the comprehensive relaxation time constant. The heat transfer area should be proportional to the square of the diameter, thus the effective thermal conductivity is proportional to the inverse of the particle diameter to the fourth power. Such strong particle size dependence has yet to be demonstrated experimentally. Additionally, the equation reduces to the Maxwell equation with increasing particle size. As discussed previously, thermal conductivity enhancements greater than those predicted by the Maxwell equation have been reported for nanofluids containing relatively large nanoparticles (d > 30 nm) [37]. It is therefore obvious that models that reduce to the Maxwell equation at large nanoparticle sizes will not be able to represent published data.

Numerous thermal conductivity models have been developed for heterogeneous systems and specifically for nanofluids. Theoretical models such as those by Maxwell [37] and Bruggeman [38] were derived by assuming a homogeneous or random arrangement of particles. However, these assumptions are not valid for dispersions containing aggregates. Empirical models [20, 22] have been successfully employed to account for the spatial arrangement of particles. More recently, particle size has been incorporated into many models in an attempt to describe the thermal conductivity of nanofluids. Several mechanisms have been described that may affect the thermal conductivity of nanofluids, including Brownian motion of the particles, ordered liquid molecules at the solid / liquid interface, nanoparticle clustering, and interfacial thermal resistance. However, there is no consent as to which mechanism has the dominant effect on the thermal conductivity.

3.2. Interfacial layering of liquid molecules

Nan, et al [39, 40] addressed the effect of interfacial resistance (Kapitza resistance) on thermal conductivity of particulate composites due to weak interfacial contact. They set up a theoretical model to predict thermal conductivity of composites by including interfacial resistance. According to this model, the effective thermal conductivity should decrease with decrease of the nanoparticle size which is contrary to most of the experiment results for nanofluids. Yu et al [41] reported that molecules of normal liquids close to a solid surface can organize into layered solid like structure. This kind of structure at interface is a governing factor in heat conduction from solid surface to liquid. Choi et al [42] pointed out that this mechanism contributed to anomalous thermal conductivity enhancement in nanotube dispersions. However, Keblinski et al [27] indicated that the thickness of the interfacial solid-like layer is too small to dramatically increase of the thermal conductivity of nanofluids because a typical interfacial width is only on the order of a atomic distance (1nm). So this mechanism only can be applied to very small nanoparticles (<10nm).

Xue [45, 46] developed a novel model which was based on Maxwell theory and average polarization theory for effective thermal conductivity of nanofluids by including interface effect between solid particle and base liquid. In this work solid nanoparticle and interfacial shell (nanolayer of liquid molecules) considered as a “complex nanoparticle” and set up the model based on this concept. The theoretical results obtained from this model were in good agreement with the experimental data for alumina nanoparticle dispersions (Xue, Wu et al. [46]) and showed nonlinear volume fraction dependence for thermal conductivity enhancement in nanotube dispersions. Ren, Xie et al. [47] and Xie, Fujii et al.[48] investigated the effect of interfacial layer on the effective thermal conductivity of nanofluids. A model has been derived from general solution of heat conduction equation and the equivalent hard sphere fluid model representing microstructure of particle suspensions. Their simulation work showed that the thermal conductivity of nanofluids increased with decrease of the particle size and increase of nanolayer thickness. The calculating values were in agreement with some experimental data (Lee, Choi et al. [42]; Eastman, Choi et al. [43]). Recently, a new thermal conductivity model for nanofluids was developed by Yu et al [49]. This model was based on the assumption that monosized spherical nanoparticle are uniformly dispersed in the liquid and are located at the vertexes of a simple cubic lattice, with each particle surrounded by an organized liquid layer. A nonlinear dependence of thermal conductivity on particle concentration was showed by this model and the relationship changed from convex upward to concave upward.

In order to find the connection between nanolayer at interface and the thermal conductivity of nanofluids, Yu et al. [41] modified the Maxwell equation for spherical particles and Hamilton-Crosser equation for non-spherical particles to predict the thermal conductivity of nanofluid by including the effect of this ordered nanolayer. The result was substituted into the Maxwell model and the following expression was obtained.

$$\frac{k_{nf}}{k_f} = \frac{k_{pe} + 2k_f + 2\left(k_{pe} - k_f\right)\left(1+\beta\right)^3 \phi}{k_{pe} + 2k_f - \left(k_{pe} - k_f\right)\left(1+\beta\right)^3 \phi} k_f \tag{5}$$

where k_{pe} is the thermal conductivity of the equivalent nanoparticle;

$$k_{pe} = \frac{\left[2\left(1-\gamma\right) + \left(1+\beta\right)^3 \left(1+2\gamma\right)\right]\gamma}{\left[-\left(1-\gamma\right) + \left(1+\beta\right)^3 \left(1+2\gamma\right)\right]} k_p \tag{6}$$

Where

$$\gamma = \frac{k_l}{k_p} \tag{7}$$

and k_l is thermal conductivity of the nanolayer. β is defined as:

$$\beta = \frac{t}{r_p} \tag{8}$$

where t is nanolayer thickness and r_p the nanoparticle radius.

Yu and Choi later applied the same idea to the Hamilton and Crosser [54] model and proposed a model for nonspherical particles [65]. Another model that considers non-spherical particles was developed by Xue [66].

Xie et al. [29] also studied the effect of the interfacial nanolayer on the enhancement of thermal conductivity with nanofluids. A nanolayer was modeled as a spherical shell with thickness t around the nanoparticle similar to Yu et al [41]. However, the thermal conductivity was assumed to change linearly across the radial direction, so that it is equal to thermal conductivity of base liquid at the nanolayer–liquid interface and equal to thermal conductivity of the nanoparticle at the nanolayer–nanoparticle interface. The associated expression for the determination of the thermal conductivity of nanofluid was given as:

$$\frac{k_{nf} - k_f}{k_f} = 3\Theta\phi_T + \frac{3\Theta^2\phi_T{}^2}{1 - \Theta\phi_T} \tag{9}$$

Where

$$\Theta = \frac{\beta_{lf}\left[(1+\gamma)^3 - \frac{\beta_{pl}}{\beta_{fl}}\right]}{(1+\gamma)^3 + 2\beta_{pl}\beta_{fl}} \tag{10}$$

and

$$\beta_{lf} = \frac{k_l - k_f}{k_l + 2k_f}$$

$$\beta_{pl} = \frac{k_p - k_l}{k_p + 2k_l}$$

$$\beta_{fl} = \frac{k_f - k_l}{k_f + 2k_l}$$

where ϕ_T is the total volume fraction of nanoparticles and nanolayers. k_l is the thermal conductivity of the nanolayer,

ϕ_T can be determined using

$$\phi_T = \phi(1+\gamma)^3$$

Where

$$\gamma = t/r_p$$

k_l was defined as:

$$k_l = \frac{k_f M^2}{(M-\gamma)\ln(1+M) + \gamma M}$$

Where

$$M = \varepsilon_p(1+\gamma) - 1$$

$$\varepsilon_p = k_p / k_f$$

When the thermal conductivity of the nanolayer is taken as a constant, this model gives the same results as Yu and Choi [41] model. It was shown that for a chosen nanolayer thickness, the model is in agreement only with some of the experimental data. As a result, it was concluded that liquid layering around nanoparticles is not the only mechanism that affects the thermal conductivity of nanofluids.

Xue and Xu [46] presented another theoretical study for the effective thermal conductivity of nanofluids. In their derivation, nanoparticles were assumed to have a liquid layer around them with a specific thermal conductivity. First, an expression for the effective thermal conductivity of the "complex particle," which was defined as the combination of the nanoparticle and nanolayer, was determined. Then, by using Bruggeman's effective media theory [38], the effective thermal conductivity of the nanofluid was determined. The resulting implicit expression for thermal conductivity of nanofluids is

$$\left(1-\frac{\phi}{\alpha}\right)\frac{k_{nf}-k_f}{2k_{nf}+k_f}+\frac{\phi}{\alpha}\frac{\left(k_{nf}-k_l\right)\left(2k_l+k_p\right)-\alpha\left(k_p-k_l\right)\left(2k_l+k_{nf}\right)}{\left(2k_{nf}+k_l\right)\left(2k_l+k_p\right)+2\alpha\left(k_p-k_l\right)\left(k_l-k_{nf}\right)}=0 \tag{11}$$

where subscript l refers to nanolayer. α is defined as

$$\alpha=\left(\frac{r_p}{r_p+t}\right)^3 \tag{12}$$

where t is the thickness of the nanolayer.

Li et al. [67] considered the effect of Brownian motion, liquid layering around nanoparticles, and clustering together. The effect of temperature on average cluster size, Brownian motion, and nanoparticle thermal conductivity was taken into account. Nanoparticle thermal conductivity is calculated by using the following expression:

$$k_p=\frac{3r^*/4}{\left(3r^*/4\right)+1}k_b \tag{13}$$

Here, k_b is thermal conductivity of the bulk material and $r^*=r_p/\lambda$ where λ is the mean-free path of phonons. Mean-free path of phonons can be calculated according to the following expression:

$$\lambda=\frac{10aT_m}{\gamma T} \tag{14}$$

Here, *a* is crystal lattice constant of the solid, γ Gruneisen constant, T temperature, and T_m the melting point (in K). It is assumed that thermal conductivity of the nanolayer is equal to the thermal conductivity of nanoparticles. As a result, particle volume fraction is modified according to the expression:

$$\phi_{eff}=\left(1+t/r_p\right)^3\phi \tag{15}$$

r_p is particle radius in this equation. The expressions presented above are substituted into the Xuan et al. [28] model (Eq. 16) to obtain:

$$\frac{k_{nf}}{k_f}=\frac{k_p+2k_f-2\phi\left(k_f-k_p\right)}{k_p+2k_f+\phi\left(k_f-k_p\right)}+\frac{\rho_p\phi c_{p,p}}{2k_f}\sqrt{\frac{k_BT}{3\pi r_{cl}\mu_f}} \tag{16}$$

Another study regarding the effect of nanolayers was made by Sitprasert et al. [56]. They modified the model proposed by Leong et al. [68] by taking the effect of temperature on the thermal conductivity and thickness of nanolayer into account. Leong et al.'s static model is as follows:

$$k_{nf}=\frac{\left(k_p-k_l\right)\phi k_l\left[2\beta_1^3-\beta^3+1\right]+\left(k_p+2k_l\right)\beta_1^3\left[\phi\beta^3\left(k_l-k_f\right)+k_f\right]}{\beta_1^3\left(k_p+2k_l\right)-\left(k_p-k_l\right)\phi\left[\beta_1^3+\beta^3-1\right]} \tag{17}$$

Here, subscript l refers to nanolayer. β and β_1 are defined as:

$$\beta=1+\frac{t}{r_p}$$

$$\beta_1=1+\frac{t}{2r_p}$$

t is the thickness of the nanolayer and r_p is the radius of the nanoparticles. This model was modified by providing the following relation for the determination of nanolayer thickness:

$$t = 0.01\left(T-273\right){r_p}^{0.35} \tag{18}$$

where T is temperature in K and r_p the particle radius in nanometers. After the determination of nanolayer thickness, thermal conductivity of the nanolayer should be found according to the expression:

$$k_l = C\frac{t}{r_p}k_f \tag{19}$$

where C is 30 and 110 for Al_2O_3 and CuO nanoparticles, respectively. It should be noted that the above expressions provided for the determination of the thickness and thermal conductivity of the nanolayer were determined by using experimental data (which is known to have great discrepancies and uncertainties) and no explanation was made regarding the physics of the problem.

When the theoretical models based on nanolayer formation around nanoparticles are considered, it is seen that the main challenge is finding the thermal conductivity and thickness of the nanolayer.

3.3. Nature of heat transfer in nanoparticles

Keblinski et al [27] estimated the mean free path of a phonon in Al_2O_3 crystal is ~35nm. Phonons can diffuse in the 10nm particles but have to move ballistically. In order to make the ballistic phonons initiated in one nanoparticle to persist in the liquid and reach another nanoparticle, high packing fractions, soot-like particle assemblies, and Brownian motion of the particles will be necessary to keep the separation among nanoparticles to be small enough. However, Xie et al. [12] found in their research about alumina nanofluids that when the particle size close to the mean free paths of phonons, the thermal conductivity of nanofluid may decrease with particle size because the intrinsic thermal conductivity of nanoparticle was reduced by the scattering of phonon at particle boundary. However, this result was not in agreement with most of the experimental results from other groups. Choi et al [42] indicated that sudden transition from ballistic heat conduction in nanotubes to diffusion heat conduction in liquid would severely limit the contribution of ballistic heat conduction to overall thermal conductivity of nanotube dispersions. They suggested that both ballistic heat conduction and layering of liquid molecules at interface contributed to the high thermal conductivity of nanotube dispersions. The nature of heat transfer in nanoparticles or the fast ballistic heat conduction cannot be the mechanism works alone to explain thermal conductivity enhancement of nanofluids due to the barrier caused by slow heat diffusion in liquid. Other mechanisms need to be combined with it to fully understand the enhancement of the thermal conductivity in nanofluids.

3.4. Nanoparticle clusters

Xuan et al. [38] studied the thermal conductivity of nanofluids by considering Brownian motion and clustering of nanoparticles. An equation was proposed to predict the thermal conductivity of nanofluids:

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2k_f - 2\phi\left(k_f - k_p\right)}{k_p + 2k_f + \phi\left(k_f - k_p\right)} + \frac{\rho_p \phi c_{p,p}}{2k_f}\sqrt{\frac{k_B T}{3\pi r_{cl}\mu_f}} \tag{18}$$

Here, r_{cl} is the apparent radius of the nanoparticle clusters, which should be determined by experiment. T is temperature in K. μ_f is the dynamic viscosity of the base fluid and it can be calculated from the study of Li and Xuan [36]. The first term on the right-hand side of Eq. (18) is the Maxwell model [37] for thermal conductivity of suspensions of solid particles in fluids. The second term on the right-hand side of Eq. (18) adds the effect of the random motion of the nanoparticles into account. For the contribution of this term, the following values were presented for Cu (50 nm)/water nanofluid: For $\varphi = 0.03\%$, contribution of the second term is 11% when clustering occurs and 17% when clustering does not occur. For $\varphi = 0.04\%$, contribution of the second term is 14% when clustering occurs and 24% when clustering does not occur. It was indicated that Brownian motion of nanoparticles becomes more effective with increasing temperature. On the other hand, as nanoparticles (or clusters) become larger, their random motion becomes slower and this decreases the enhancement in thermal conductivity. It should be noted that the second term on the right-hand side of the equation is not nondimensional, which is an indication of a mistake in the analysis.

Chen et al. [63] measured the viscosity of TiO_2/water and TiO_2/ethylene glycol nanofluids and proposed a way of calculating the thermal conductivity of nanofluids by using the data. Two types of nanoparticles were used; spherical particles (25 nm) and cylindrical particles (10 nm in diameter and 100 nm in length). The model was found to be a function of cluster radius, and cluster radius values of the sample nanofluids were determined by matching the predictions of the modified model with experimental data. Then, the determined cluster radius values were used in the thermal conductivity model proposed, which is a modification of Hamilton and Crosser [54] model .

$$\frac{k_{nf}}{k_f} = \frac{k_{cl} + (n-1)k_f - (n-1)\phi_{cl}(k_f - k_{cl})}{k_{cl} + (n-1)k_f + \phi_{cl}(k_f - k_{cl})} \tag{19}$$

where k_{cl} and $\varphi_{cl}$are the thermal conductivity and volume fraction of the clusters, respectively. n was taken as 3 for the spheres and 5 for the cylinders in this work.

$$\phi_{cl} = \phi\left(r_{cl}/r_p\right)^{3-D}$$

where r_{cl} and r_p are the radii of the clusters and nanoparticles, respectively. D is the fractal index, which was taken as 1.8 in the viscosity model and the same value might be used here. r_{cl} / r_p values are equal to 2.75 and 3.34, for TiO_2/water (spherical) and TiO_2/ethylene glycol (spherical) nanofluids, respectively. For the estimation of k_{cl}, the following expression was proposed for spherical particles [38]:

$$\frac{k_{cl}}{k_f} = \frac{1}{4}\left\{ \begin{aligned} &(3\phi_{in}-1)\frac{k_p}{k_f} + (3(1-\phi_{in})-1) \\ &+\left[\left((3\phi_{in}-1)\frac{k_p}{k_f} + (3(1-\phi_{in})-1)\right)^2 + 8\frac{k_p}{k_f}\right]^{1/2} \end{aligned} \right\} \tag{20}$$

where ϕ_{in} is the solid volume fraction of clusters and it is defined as

$$\phi_{in} = \phi\left(r_{cl}/r_p\right)^{D-3}$$

For the estimation of k_{cl}, the following expression was proposed for nanotubes [64].

$$\frac{k_{cl}}{k_f} = \frac{3+\phi_{in}\left[2\beta_x(1-L_x) + \beta_z(1-L_z)\right]}{3-\phi_{in}\left[2\beta_x L_x + \beta_z L_z\right]} \tag{21}$$

Where

$$\beta_x = (k_x - k_f)\Big/\left[k_f + L_x(k_t - k_f)\right] \tag{22}$$

Where

$$\beta_z = (k_z - k_f)\Big/\left[k_f + L_z(k_t - k_f)\right] \tag{23}$$

k_x and k_z are the thermal conductivity of nanotubes along transverse and longitudinal directions, respectively. k_t is the isotropic thermal conductivity of the nanotube k_x, k_z and k_t can be taken to be equal to k_p as an approximation. L_x and $L_z$are defined as:

$$L_x = \frac{p^2}{2(p^2-1)} - \frac{p^2}{2(p^2-1)^{3/2}}\cosh^{-1}(p) \tag{24}$$

Where

$$L_z = 1 - 2L_x$$

r_{cl} / r_p values are equal to 5.40 and 12.98 for TiO_2/ethylene glycol (nanotube) and TiO_2/water (nanotube) nanofluids, respectively. p is the aspect ratio of the nanotubes defined as length of nanotube divided by diameter of nanotube. The modified Hamilton and Crosser [44] model (Eqs. 2, 3) was compared with experimental data for both spherical particles and nanotubes, and a good agreement was observed.

IV. CONCLUSION

The available literature on nanofluid was thoroughly reviewed in this article. Some of the most relevant experimental results were reported for thermal conductivity several nanofluids. Thermal conductivity was found to be increased with the increase in particle volume fraction of nanoparticles. However, Effect of particle size on the thermal conductivity of nanofluids has not been completely understood yet. It is expected that Brownian motion of nanoparticles results in higher thermal conductivity enhancement with smaller particle size. However, some of the experiments show that the thermal conductivity decreases with decreasing particle size. This contradiction might be due to the uncontrolled clustering of nanoparticles resulting in larger particles. Particle size distribution of nanoparticles is another important factor and it is suggested that average particle size is not sufficient to characterize a nanofluid due to the nonlinear relations involved between particle size and thermal transport. Temperature dependence is an important parameter in the thermal conductivity of nanofluids. Limited study has been done about this aspect of the thermal conductivity of nanofluids up to now. Investigation of the thermal performance of nanofluids at high temperatures may widen the possible application areas of nanofluids.

V. SCOPE FOR FUTURE WORK

The experimental results show that there exists significant discrepancy in the experimental data for nanofluid properties. An important reason of discrepancy in experimental data is the clustering of nanoparticles. Although there are no universally accepted quantitative values, it is known that the level of clustering affects the properties of nanofluids. Since level of clustering is related to the pH value and the additives used, two nanofluid samples with all of the parameters being the same can lead to completely different experimental results if their surfactant parameters and pH values are not the same. Therefore, the researchers providing experimental results should give detailed information about the additives utilized and pH values of the samples.

REFERENCES

[1]. S. Choi, , "Enhancing thermal conductivity of fluids with nanoparticles", In Development and Applications of Non-Newtonian Flows, Ed. D A Siginer, H P Wang, New York: *ASME*. 1995 pp 99-105.

[2]. Choi, S.U.S., Z.G. Zhang, W. Yu, F.E. Lockwood, and E.A. Grulke" Anomalous thermal conductivity enhancement in nanotube suspensions," *Applied Physics Letters*, 2001. 79(14): p. 2252-2254.

[3]. Yang, Y., E.A. Grulke, Z.G. Zhang, and G.F. Wu, "Thermal and rheological properties of carbon nanotube-in-oil dispersions," *Journal of Applied Physics*, 2006. 99(11).

[4]. Eastman, J.A., S.U.S. Choi, S. Li, W. Yu, and L.J. Thompson "Anomalously increased effective thermal conductivities of ethylene glycol-based nanofluids containing copper nanoparticles," *Applied Physics Letters*, 2001. 78(6): p. 718- 720.

[5]. Jana, S., A. Salehi-Khojin, and W.H. Zhong "Enhancement of fluid thermal conductivity by the addition of single and hybrid nano-additives," *Thermochimica Acta*, 2007. 462(1-2): p. 45-55.

[6]. Liu, M.S., M.C.C. Lin, C.Y. Tsai, and C.C. Wang "Enhancement of thermal conductivity with Cu for nanofluids using chemical reduction method," *International Journal of Heat and Mass Transfer*, 2006. 49(17-18): p. 3028-3033.

[7]. Murshed, S.M.S., K.C. Leong, and C. Yang"Enhanced thermal conductivity of TiO2 - water based nanofluids," *International Journal of Thermal Sciences*, 2005. 44(4): p. 367-373.

[8]. Zhu, H.T., C.Y. Zhang, S.Q. Liu, Y.M. Tang, and Y.S. Yin" Effects of nanoparticle clustering and alignment on thermal conductivities of Fe_3O_4 aqueous nanofluid ," *Applied Physics Letters*, 2006. 89(2).

[9]. Ceylan, A., K. Jastrzembski, and S.I. Shah "Enhanced solubility Ag-Cu nanoparticles and their thermal transport properties," *Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science*, 2006. 37A(7): p. 2033-2038.

[10]. Zhang, X., H. Gu, and M. Fujii 'Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles," *Journal of Applied Physics*, 2006. 100(4): p. 044325.
[11]. Putnam, S.A., D.G. Cahill, P.V. Braun, Z.B. Ge, and R.G. Shimmin "Thermal conductivity of nanoparticle suspensions," *Journal of Applied Physics*, 2006. 99(8)
[12]. Xie, H.Q., J.C. Wang, T.G. Xi, Y. Liu, F. Ai, and Q.R. Wu ,"Thermal conductivity enhancement of suspensions containing nanosized alumina particles," Journal of Applied Physics, 2002. 91(7): p. 4568-4572.
[13]. Kim, S.H., S.R. Choi, and D. Kim "Thermal conductivity of metal-oxide nanofluids: Particle size dependence and effect of laser irradiation," *Journal of Heat Transfer-Transactions of the ASME*, 2007. 129(3): p. 298-307.
[14]. Li, C.H. and G.P. Peterson " The effect of particle size on the effective thermal conductivity of Al2O3-water nanofluid," *Journal of Applied Physics*, 2007. 101(4): p. 044312.
[15]. Das, S.K., N. Putra, P. Thiesen, and W. Roetzel "Temperature dependence of thermal conductivity enhancement for nanofluids," Journal *of Heat Transfer- Transactions of the ASME*, 2003. 125(4): p. 567-574.
[16]. Yang, B. and Z.H. Han "Temperature-dependent thermal conductivity of nanorodbased nanofluids," *Applied Physics Letters*, 2006. 89(8).
[17]. Honorine Angue Mintsa, Gilles Roy, Cong Tam Nguyen, Dominique Doucet, " New temperature dependent thermal conductivity data for water-based nanofluids" *International Journal of Thermal Sciences* ,Volume 48, Issue 2, February 2009, Pages 363–371.
[18]. Li, C.H. and G.P. Peterson" Experimental investigation of temperature and volume fraction variations on the effective thermal conductivity of nanoparticle suspensions (nanofluids)," *Journal of Applied Physics*, 2006. 99(8).
[19]. Eastman, J.A., U.S. Choi, S. Li, L.J. Thompson, and S. Lee" Enhanced thermal conductivity through the development of nanofluids," *Materials Research Society Symposium Proceedings*, 1997. 457(Nanophase and Nanocomposite Materials II): p. 3-11.
[20]. Wang, X.W., X.F. Xu, and S.U.S. Choi "Thermal conductivity of nanoparticle-fluid mixture," *Journal of Thermophysics and Heat Transfer*, 1999. 13(4): p. 474- 480.
[21]. Lee, S., S.U.S. Choi, S. Li, and J.A. Eastman" Measuring thermal conductivity of fluids containing oxide nanoparticles," *Journal of Heat Transfer-Transactions of the ASME*, 1999. 121(2): p. 280-289.
[22]. Hwang, Y.J., Y.C. Ahn, H.S. Shin, C.G. Lee, G.T. Kim, H.S. Park, and J.K. Lee, "Investigation on characteristics of thermal conductivity enhancement of nanofluids," *Current Applied Physics*, 2006. 6(6): p. 1068-1071.
[23]. Özerinç, S., Kakaç, S., and Yazıcıoğlu, A. G., , "Enhanced Thermal Conductivity of Nanofluids: A State-of-the-Art Review," *Microfluid. Nanofluid*., 2010 8(2), pp. 145-170.
[24]. Wright, B., D. Thomas, H. Hong, L. Groven, J. Puszynski, E. Duke, X. Ye, and S. Jin "Magnetic field enhanced thermal conductivity in heat transfer nanofluids containing Ni coated single wall carbon nanotubes," *Applied Physics Letters*, 2007.
[25]. Hong, H.P., B. Wright, J. Wensel, S.H. Jin, X.R. Ye, and W. Roy "Enhanced thermal conductivity by the magnetic field in heat transfer nanofluids containing carbon nanotube," *Synthetic Metals*, 2007. 157(10-12): p. 437-440.
[26]. Wensel, J., B. Wright, D. Thomas, W. Douglas, B. Mannhalter, W. Cross, H.P. Hong, J. Kellar, P. Smith, and W. Roy "Enhanced thermal conductivity by aggregation in heat transfer nanofluids containing metal oxide nanoparticles and carbon nanotubes," *Applied Physics Letters*, 2008.
[27]. Keblinski, P., S.R. Phillpot, S.U.S. Choi, and J.A. Eastman "Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids)," *International Journal of Heat and Mass Transfer*, 2002. 45(4): p. 855-863.
[28]. Xuan, Y., Li, Q., Hu, W., Aggregation structure and Thermal conductivity of Nanofluids, *AIchE Journal*, vol. 49, no. 4, 2003, pp. 1038-1043.
[29]. Xie, H., Fujii, M., and Zhang, X., Effect of interfacial Nanolayer on the effective thermal conductivity of Nanoparticle fluid Mixture, *International Journal of Heat and Mass transfer*, vol. 48, 2005, pp.2926-2932.
[30]. Krischer, O., Die wissenschaftlichen Grundlagen der Trocknungstechnik (The Scientific Fundamentals of Drying Technology). 2nd ed. 1963, Berlin: Springer- Verlag
[31]. Jang, S.P. and S.U.S. Choi "Role of Brownian motion in the enhanced thermal conductivity of nanofluids," *Applied Physics Letters*, 2004. 84(21): p. 4316-4318.
[32]. Chon, C.H., K.D. Kihm, S.P. Lee, and S.U.S. Choi "Empirical correlation finding the role of temperature and particle size for nanofluid (Al_2O_3) thermal conductivity enhancement ,"*Applied Physics Letters*, 2005. 87(15).
[33]. Turian, R.M., D.J. Sung, and F.L. Hsu" Thermal conductivity of granular coals, coal-water mixtures and multi-solid/liquid suspensions," *Fuel*, 1991. 70(10): p. 1157-1172.
[34]. Patel, H.E., T. Sundararajan, T. Pradeep, A. Dasgupta, N. Dasgupta, and S.K. Das" A micro-convection model for thermal conductivity of nanofluids," *Pramana- Journal of Physics*, 2005. 65(5): p. 863-869.

[35]. Patel, H.E., T. Sundararajan, and S.K. Das "A cell model approach for thermal conductivity of nanofluids," *Journal of Nanoparticle Research*, 2008. 10(1): p. 87- 97.
[36]. Xuan, Y.M., Q. Li, X. Zhang, and M. Fujii "Stochastic thermal transport of nanoparticle suspensions," *Journal of Applied Physics*, 2006. 100(4).
[37]. Maxwell, J.C., A Treatise on Electricity and Magnetism. 3rd ed. Vol. II. 1892, *London: oxford University Press*.
[38]. Bruggeman, D.A.G., "Calculation of various physics constants in heterogenous substances I Dielectricity constants and conductivity of mixed bodies from isotropic substances", *Annalen Der Physik*, 1935. 24(7): p. 636-664.
[39]. Nan, C.W., Liu, G., Lin, Y., Li., M., "Interface effective thermal conductivity of carbon nanotube composites", *Applied Physics Letters*, vol. 85, 2004, pp.3549-3551.
[40].Nan, C.W., Birringer, R.," Effective Thermal conductivity of particulate composites with interfacial thermal resistance", *Journal of Applied Physics*, vol. 81, 1997, pp.6692-6699.
[41]. Yu, C.J., Richter, A.G., Datta, A., Durbin, M.K., Dutta, P., "Molecular layering in a liquid on a solid substrate: An x-Ray reflectivity study", *Physica B*, vol. 283, 2000, pp.27-31.
[42]. Choi, S.U.S., Lee, S., Li, S., Eastman, J.A., "Measuring Thermal Conductivity of Fluids Containing Oxide Nanoparticles", *Journal of Heat Transfer*, vol.121, 1999, pp.280-289.
[43]. Eastman, J.A., Choi, S.U.S., Li, S., Thompson, L.J., Lee, S., "Enhanced thermal conductivity through development of nanofluids", *Proceedings of Materials Research Society Symposium, Materials Research Society Pittsburgh*, PA, USA, Boston, MA, USA, vol.457, 1997, pp. 3-11.
[44]. Xue, L., Keblinski, P., Phillpot, S.R., Choi, S.U.S., Eastman, J.A., "Effect of liquid layering at the liquid-solid interface on thermal transport", *International Journal of Heat and Mass transfer*, vol.47, 2004, pp.4277-4284.
[45]. Xue, Q.Z., "Model for thermal conductivity of Carbon nanotube based composites", Physica B, vol.368, 2005, pp.302-307.
[46]. Xue, Q., and Xu, W.M., "A model of thermal conductivity of nanofluids with interfacial shells", *Materials Chemistry and Physic*, vol.90, 2005, pp.298-301.
[47]. Ren, Y., Xie, H., Cai, A., "Effective thermal conductivity of Nanofluids containing spherical Nanoparticles", *Journal of Physics D: Apllied Physics*, vol. 38, 2005, pp.3958-3961.
[48]. Xie, H., Fujii, M., and Zhang, X., "Effects of Interfacial Nanolayer on the effective thermal conductivity of nanoparticle-fluid mixture", *International Journal of Heat and Mass Transfer*, vol. 48, 2005, pp.2926-2932.
[49]. Yu, W., Choi, S.U.S., "A effective thermal conductivity model of nanofluids with a cubical arrangement of spherical particles", *Journal of Nanoscience and Nanotechnology*, vol.5, 2007, pp. 580-586.
[50]. Garboczi, E.J., Snyder, K.A., Douglas, J.F., "Geometrical percolation threshold of overlapping ellipsoids", *Physical review E*, vol.52, 1995, pp.819-828.
[51]. Li, Q. and Xuan, Y., "Convective heat transfer and flow characteristics of Cu+ water nanofluids", *Science in China, Series E: Technological Sciences*, vol. 45, 2002, pp.408-416.
[52]. Wang, B., Zhou, L., Peng, X., "Fractal model for predicting the effective thermal conductivity of liquid with suspension of nanoparticle", *International Journal of heat and mass transfer*, vol. 46, 2003, pp.2665-2672.
[53]. Gao, L., Zhou, X.F., "Differential effective medium theory for thermal conductivity in nanofluids", *Physics Letters A*, vol. 348, 2006, pp.355-360.
[54]. Hamilton, R. L., and Crosser, O. K., 1962, "Thermal Conductivity of Heterogeneous Two-Component Systems," *Ind. Eng. Chem. Fund*., 1(3), pp. 187-191.
[55]. Yu, W., and Choi, S. U. S., 2003, "The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Maxwell Model," J. *Nanopart. Res*., 5(1), pp. 167-171.
[56]. Sitprasert, C., Dechaumphai, P., and Juntasaro, V., 2009, "A Thermal Conductivity Model for Nanofluids Including Effect of the Temperature-Dependent Interfacial Layer," *J. Nanopart. Res*., 11(6), pp. 1465-1476.
[57]. Koo, J., and Kleinstreuer, C., 2004, "A New Thermal Conductivity Model for Nanofluids," *J. Nanopart. Res*., 6(6), pp. 577-588.
[58]. Oh, D., Jain, A., Eaton, J. K., Goodson, K. E., and Lee, J. S., 2008, "Thermal Conductivity Measurement and Sedimentation Detection of Aluminum Oxide Nanofluids by Using the 3ω Method," *Int. J. Heat Fluid Fl*., 29(5), pp. 1456-1461.
[59]. Wen, D., and Ding, Y., 2004, "Experimental Investigation into Convective Heat Transfer of Nanofluids at the Entrance Region under Laminar Flow Conditions," *Int. J. Heat Mass Tran*., 47(24), pp. 5181-5188.
[60]. Nimtz, G., Marquardt, P., and Gleiter, H., 1990, "Size-Induced Metal-Insulator Transition in Metals and Semiconductors," *J. Cryst. Growth*, 86(1-4), pp. 66-71.
[61]. Xie, H., Wang, J., Xi, T., Liu, Y., and Ai, F., 2002, "Dependence of the Thermal Conductivity of Nanoparticle-Fluid Mixture on the Base Fluid," *J. Mater. Sci. Lett*., 21(19), pp. 1469-1471.
[62]. Beck, M., Yuan, Y., Warrier, P., and Teja, A., 2009, "The Effect of Particle Size on the Thermal Conductivity of Alumina Nanofluids," *J. Nanopart. Res*., 11(5), pp. 1129-1136.

[63]. Chen, H., Witharana, S., Jin, Y., Kim, C., and Ding, Y., 2009, "Predicting Thermal Conductivity of Liquid Suspensions of Nanoparticles (Nanofluids) Based on Rheology," *Particuology*, 7(2), pp. 151-157.
[64]. Nan, C. W., Shi, Z., and Lin, Y., 2003, "A Simple Model for Thermal Conductivity of Carbon Nanotube-Based Composites," *Chem. Phys. Lett.*, 375(5-6), pp. 666-669.
[65]. Xue Yu, W., and Choi, S., 2004, "The Role of Interfacial Layers in the Enhanced Thermal Conductivity of Nanofluids: A Renovated Hamilton–Crosser Model," *J. Nanopart. Res*., 6(4), pp. 355-361.
[66]. Xue, Q., 2003, "Model for Effective Thermal Conductivity of Nanofluids," Phys. Lett. A, 307(5-6), pp. 313-317.
[67]. Li, Y., Qu, W., and Feng, J., 2008, "Temperature Dependence of Thermal Conductivity of Nanofluids," *Chinese Phys. Lett*., 25(9), pp. 3319-3322.
[68]. Leong, K., Yang, C., and Murshed, S., 2006, "A Model for the Thermal Conductivity of Nanofluids – The Effect of Interfacial Layer," *J. Nanopart. Res*., 8(2), pp. 245-254.

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