COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL RESULTS FOR THERMAL CONDUCTIVITY OF NANOFLUIDS

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Abstract. *Suspensions of nanoparticles in liquids, known as nanofluids, have generated considerable interest for their potential to enhance the heat transfer in thermal systems, and reduce the possibility of erosion, sedimentation and clogging that plagued earlier solid-liquid mixtures with larger particles. Nanofluids have attracted enormous interest from research and industry due to high thermal conductivity and their potential for high rate of heat exchange incurring a little penalty in pressure drop. It has been found that the thermal conductivity of nanofluids is notably higher than that of the base fluid. Many attempts in this field have been made to formulate appropriate effective thermal conductivity. The goal of this study is to evaluate and compare several experimental results for thermal conductivity obtained in the literature with correlations developed to predict this property in order to determine the best correlation that fit reasonably the experimental data.*

Keywords: *nanofluids, thermal conductivity, correlation, experimental results*

1. NOMENCLATURE

k	Thermal Conductivity
r	Nanoparticles Radius
h	Nanolayer Thickness
Greek Symbols	
Φ	Volumetric Concentration
Subscripts	
p	Particle
lr	Nanolayer
bf	Base fluid
nf	Nanofluid
eff	effective

2. INTRODUCTION

Nanofluids are fluid formed by dispersing solid particles of size ranging 1-100 nm (nanoparticles) in a given base fluid such as water or oil, for example. Regarding to the thermal potential, the researches on nanofluids increased significantly in the last years, as can be observed in Fig. 1. Thermal conductivity is the property that has catalyzed the attention of the nanofluids research community the most. As dispersions of solid particles in a continuous liquid matrix, nanofluids are expected to have a thermal conductivity that obeys the effective medium theory developed by Maxwell in 1873. Normally, as expected, these fluids are homogeneous and stable solutions for a short period of time, which in some applications, equipment and process are not desired. To prolong the stability of nanofluids is common the use of surfactants, which are substances that cause electrostatic repulsion between nanoparticles and the base fluid molecules. However, this process changes the thermal properties of the pure nanofluid, in general, reducing the thermal conductivity and consequently, the heat transfer potential.

Due to the higher thermal conductivity of nanoparticles, nanofluids have the higher thermal conductivity, as well, in comparison with the respective base fluids. In this sense, nanofluids have a great potential in heat transfer applications, such as single-phase flow or two-phase flow.

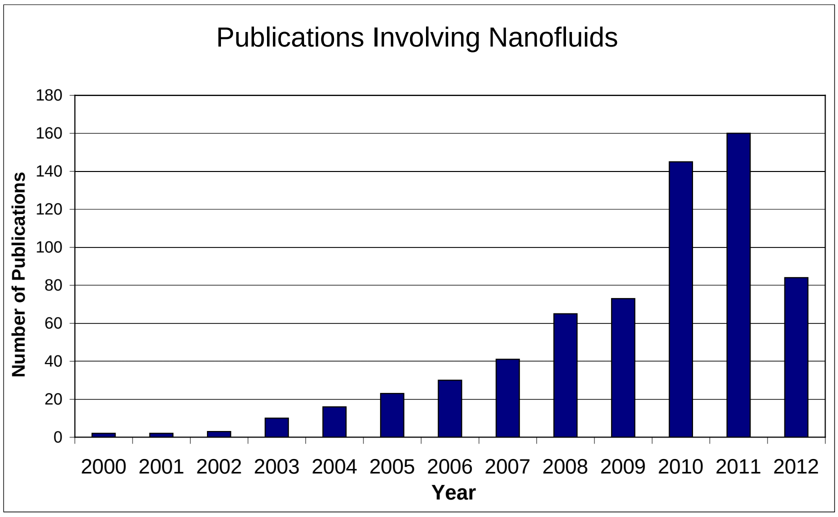

Figure 1: Number of publications involving nanofluids in thermal applications.

3. THERMAL CONDUCTIVITY OF NANOFLUIDS

The higher thermal conductivity is the one of the main advantage of nanofluids, since in heat transfer this property is taken into account, directly, in the Nusselt number and indirectly through the Prandtl number. This interest can explain the higher number of publication in this area, such as in experimental or numerical field and some theories proposed to describe tendencies and behaviors for the thermal conductivity of nanofluids.

There are many factors that affect the thermal conductivity of nanofluids and must be analyzed separately, such as the nanoparticle concentration, size, temperature, additives, nanoparticle type and so on. Understanding the influence of these factors is essential to determine the thermal conductivity of the nanofluids. Some others authors describe the thermal conductivity increment due to others factors such as the interfacial layer between the nanoparticles and base fluid (nanolayer), Brownian motion and agglomeration.

3.1 Theoretical Models for Thermal Conductivity of Nanofluids

Several models were developed in the last years to find the thermal conductivity of nanofluids. Some old models, mainly related to mixtures, are often used to calculate this property. One of the most used is the Maxwell model. The main goal of this work was to analyse the parameters that are taken into account in each model used. These models were proposed, in principle, for nanofluids with spherical nanoparticles, with exception of Xue model (2003). For the models the effective conductivity was considered and this is a relative parameter, as follow:

$$k_{eff} = \frac{k_{nf}}{k_{bf}} \tag{1}$$

Gao and Zhou Model (2006)

$$1-\phi = \left[\left(k_p - k_{nf}\right)/\left(k_p - k_{bf}\right)\right]\cdot\left(k_{bf} / k_{nf}\right)^{1/3} \tag{2}$$

Leong Model (2005)

$$k_{eff} = \frac{\left(k_p - k_{lr}\right)\cdot\phi\cdot k_{lr}\cdot\left(2\beta_1^3 - \beta^3 + 1\right) + \left(k_p + 2k_{lr}\right)\beta_1^3\cdot\left(\phi\cdot\beta^3\cdot\left(k_{lr} - k_{bf}\right) + k_{bf}\right)}{\left(\beta_1^3\cdot\left(k_p + 2k_{lr}\right)\right) - (k_p - k_{lr})\cdot\phi\cdot\left(\beta_1^3 + \beta^3 - 1\right)\cdot k_{bf}} \tag{3}$$

where: $\beta_1 = 1 + \frac{\gamma}{2}$ $\beta = 1 + \gamma$ $\gamma = \frac{h}{r}$ $k_{lr} = 3k_{bf}$

Xue e Xu Model (2005)

$$\left(1-\frac{\phi}{\alpha}\right)\cdot\left(\frac{k_{nf}-k_{bf}}{2k_{nf}+k_{bf}}\right)+\frac{\phi}{\alpha}\cdot\left(\frac{(k_{nf}-k_{lr})\cdot(2k_{lr}+k_{p})-(\alpha\cdot(k_{p}-k_{lr})\cdot(2k_{lr}+k_{nf}))}{(2k_{nf}+k_{lr})\cdot(2k_{lr}+k_{p})+2\alpha\cdot(k_{p}-k_{lr})\cdot(k_{lr}-k_{nf})}\right)=0 \quad \text{, where } \alpha=\left(\frac{r}{r+h}\right)^{3} \tag{4}$$

Xie Model (2005)

$$k_{nf}=1+3\theta\cdot\phi_{t}+3\theta^{2}\cdot\left(\frac{\phi_{t}}{1-\theta\cdot\phi_{t}}\right) \tag{5}$$

Where,

$$\phi_{t}=\phi\cdot(1+\gamma^{3}) \quad \theta=\beta_{lf}\cdot\left[\frac{(1+\gamma)^{3}-(\beta_{pl}/\beta_{fl})}{(1+\gamma)^{3}+2\beta_{lf}\cdot\beta_{pl}}\right] \quad \beta_{fl}=\frac{k_{bf}-k_{lr}}{k_{bf}+2k_{lr}} \quad \beta_{pl}=\frac{k_{p}-k_{lr}}{k_{p}+2k_{lr}} \quad \beta_{lf}=\frac{k_{lr}-k_{bf}}{k_{lr}+2k_{bf}}$$

$$\gamma=\frac{h}{r} \qquad M=\varepsilon(1+\gamma)-1 \qquad \varepsilon=\frac{k_{p}}{k_{bf}} \quad k_{lr}=\frac{M^{2}}{(M-\gamma)\cdot\ln(1+M)+\gamma\cdot M}$$

Xue Model (2003)

$$9\left(1-\frac{\phi}{\lambda}\right)\left(\frac{k_{nf}-k_{bf}}{2k_{nf}+k_{bf}}\right)+\frac{\phi}{\lambda}\left[\frac{k_{nf}-k_{cx}}{k_{nf}+B_{2x}\cdot(k_{cx}-k_{nf})}+4\cdot\frac{k_{nf}-k_{cy}}{2k_{nf}+(1-2B_{2x})\cdot(k_{cy}-k_{nf})}\right]=0 \tag{6}$$

Where,

$$\lambda=\frac{a\cdot b\cdot c}{(a+t)(b+t)(c+t)}$$

Yu and Choi Model (2003)

$$k_{eff}=\frac{k_{p}+2k_{bf}+(2\cdot(k_{p}-k_{bf})\cdot(1+\beta)^{3})\cdot\phi}{k_{p}+2k_{bf}-((k_{p}-k_{bf})\cdot(1+\beta)^{3})\cdot\phi} \qquad \beta=\frac{h}{r} \tag{7}$$

Maxwell Model (1873)

$$k_{eff}=k_{bf}+3\phi\left(\frac{k_{p}-k_{bf}}{2k_{bf}+k_{p}-\phi\cdot(k_{p}-k_{bf})}\right)\cdot k_{bf} \tag{8}$$

4. ANALYSIS OF RESULTS

4.1 Comparison Between Models and Experimental Results

An interesting comparison between models and experimental results was performed and the data must be replace the parameters of the correlations. The equations were implemented in the software EES and the values of the effective thermal conductivity were simulated in the same range of volumetric concentration in each experiment. It is important to observe that some models take in account parameters that cannot be measured in the experiments, such as thickness and conductivity of the nanolayer. In this case, it was maintained the original values proposed by the authors. It was just used spherical nanoparticles of different materials. Most of the models underestimate the experimental results found in the literature, indicating this thermal conductivity increment is more anomalous than expected. The best prevision results for thermal conductivity were found with the use of Maxwell correlation, however only for lower concentrations. Furthermore, for higher nanoparticles concentrations, the error increases significantly. Figure 2 shows that Maxwell model fits well the experimental data for low concentrations, but the effects of interactions among nanoparticles become anomalous at high concentrations, and the models are not able to predict it, as can be observed in Fig. 3.

Figures 4 and 5 show a comparison between correlations and some experimental results obtained in the Buongiorno's paper in 2009. In this research, many nanofluids were produced using the same process and sent to different laboratories in the world to measure the thermal conductivity. After the measurements, the laboratories sent back the results, where it was possible to compare these results obtained in different locations. It is interesting to observe that the experimental results were discrepants, despite being the same nanofluid. Furthermore, the results show higher than expected in the correlations, particularly at 3% concentration.

Fig. 6 depicts a comparison between experimental resultsfor alumina nanofluid dispersed in water. It was observed that, in general, the nanofluid with smaller nanoparticle diameter presented a higher increment in the thermal conductivity. However, it is possible to observe that some results don't follow the tendency. Beyond this, there is a discrepancy among the experimental results in the same concentration range and nanoparticles size, such as can be seen for 3% of concentration. It is important to mention that some of the authors used surfactants to stabilize the nanofluid, changing its properties.

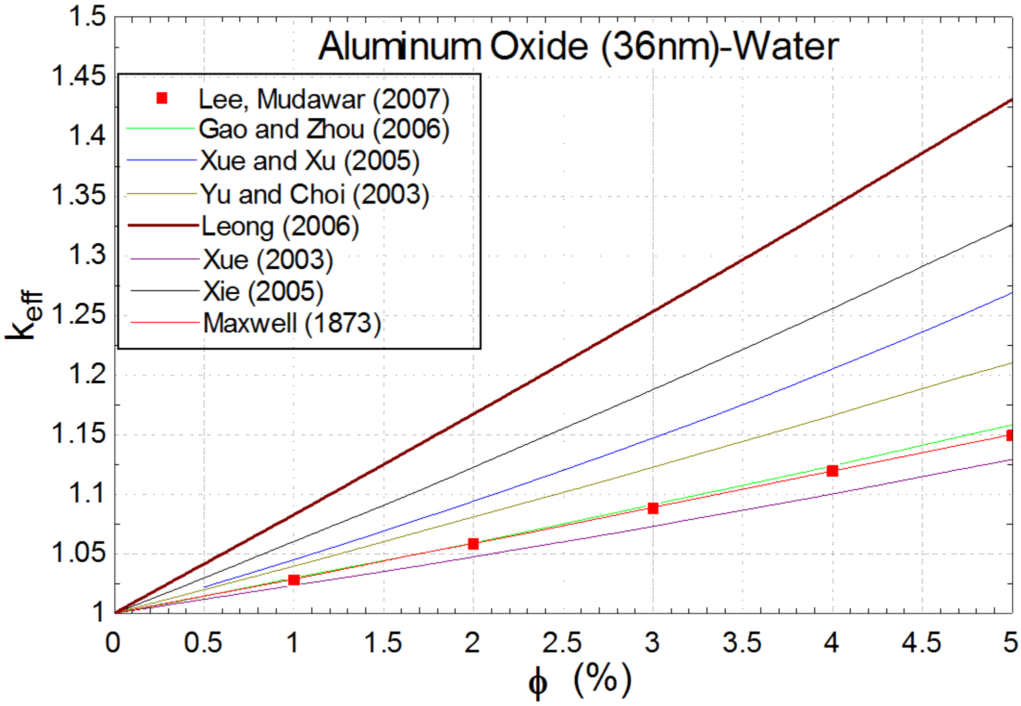

Figure 2: Comparison between experimental and theoretical results for thermal conductivity of nanofluids.

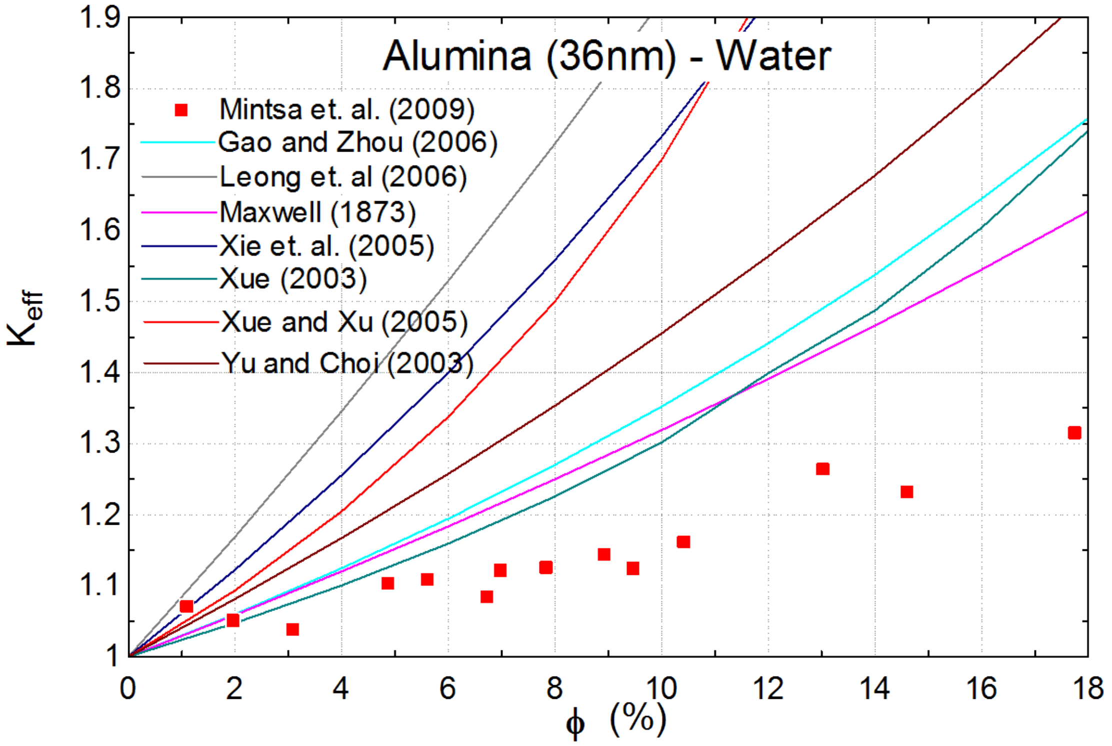

Figure 3: Comparison between experimental and theoretical results for thermal conductivity of nanofluids.

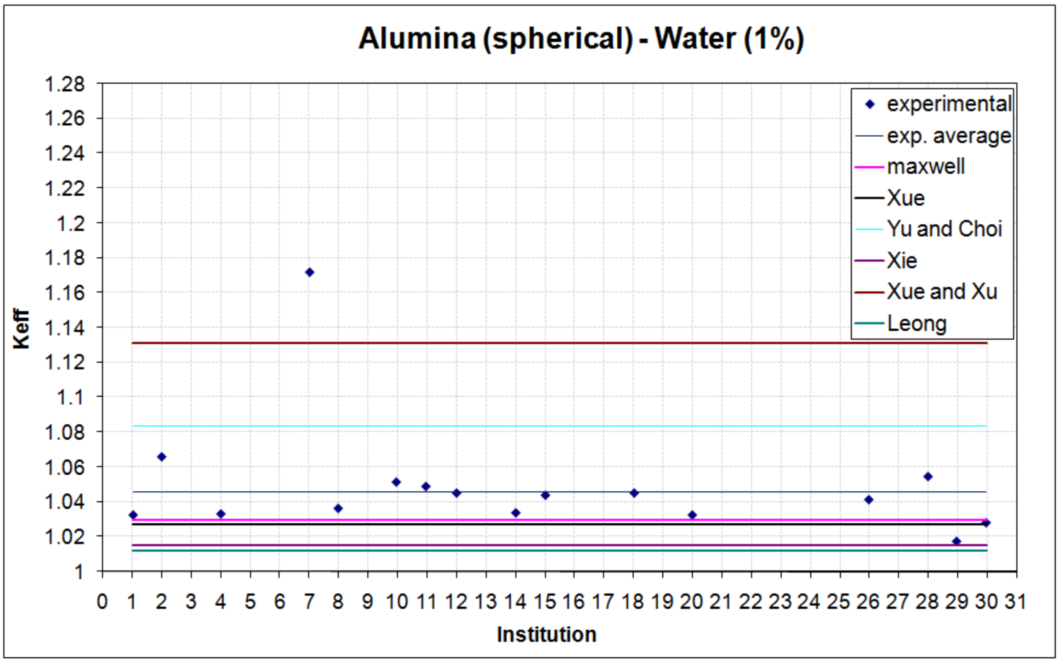

Figure 4: Comparison between experimental and theoretical results for thermal conductivity of nanofluids.

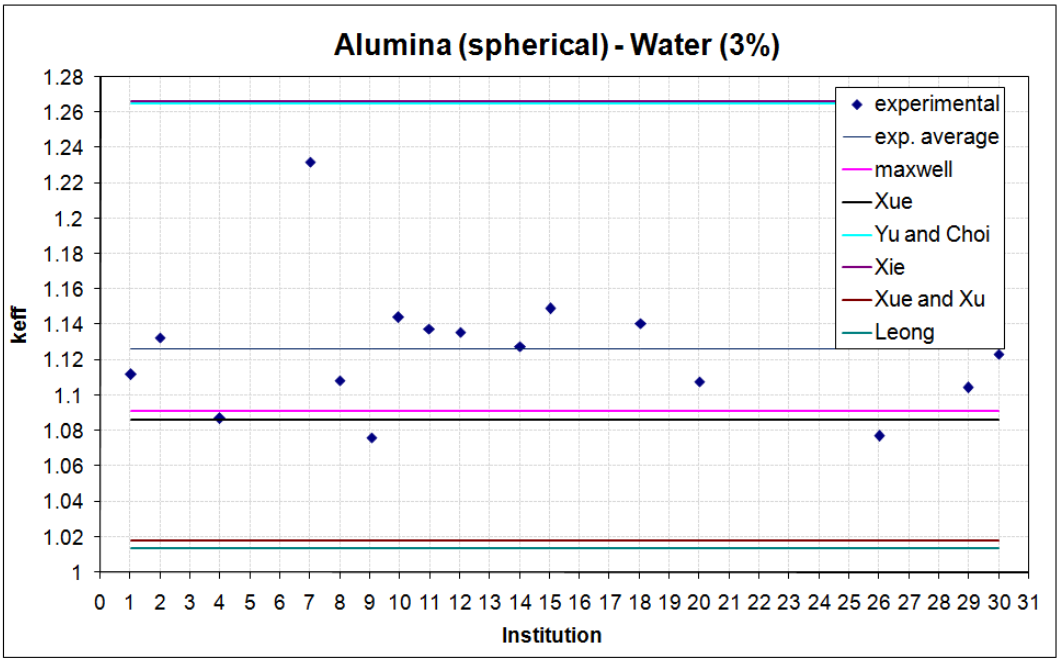

Figure 5: Comparison between experimental and theoretical results for thermal conductivity of nanofluids.

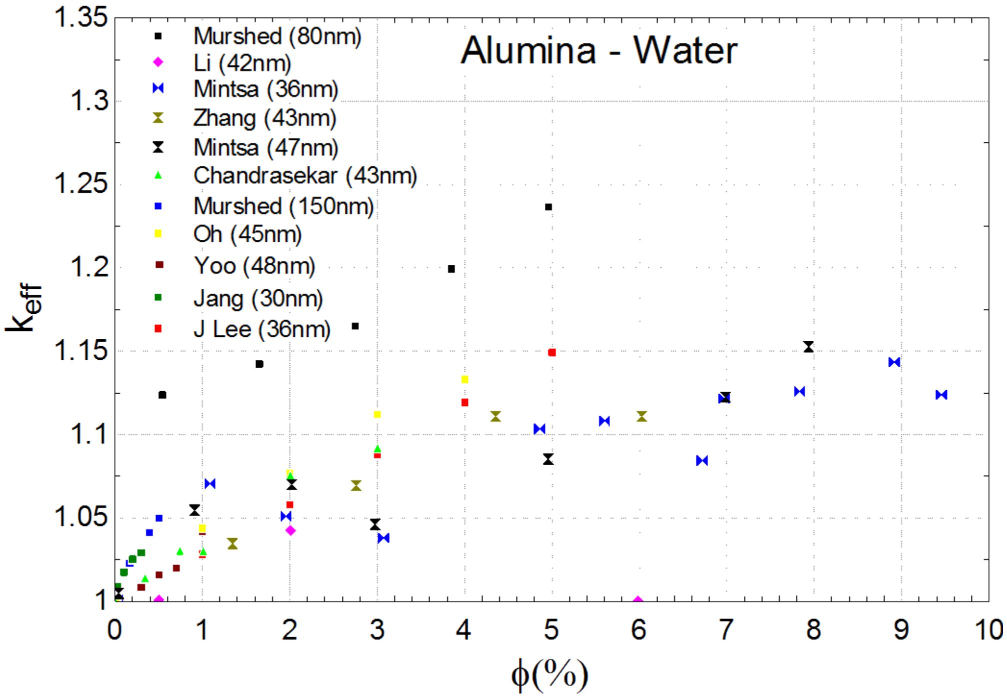

Figure 6: Comparison between experimental results for thermal conductivity of alumina-water nanofluids.

4.2 Nanoparticle Size Influence

Several researches consider the nanoparticle size as one of the most important parameters to determine the thermal conductivity of nanofluids. Therefore an analysis of influence of nanoparticle diameter in the thermal conductivity was conducted, according to the models that take into account this parameter. It is important to note that for a same concentration, as lower the nanoparticles (spherical), higher must be the thermal conductivity, since the contact total area is higher between the nanoparticles and the base fluid. As can be seen in Fig. 7 that the thermal conductivity decreases significantly with the increase of the nanoparticle diameter, up to 20nm. However, after 40nm the thermal conductivity remains, basically, constant with the increase of diameter. Therefore, according to these models, the nanoparticle size is relevant in case of the nanoparticles were lower than 30-40nm.

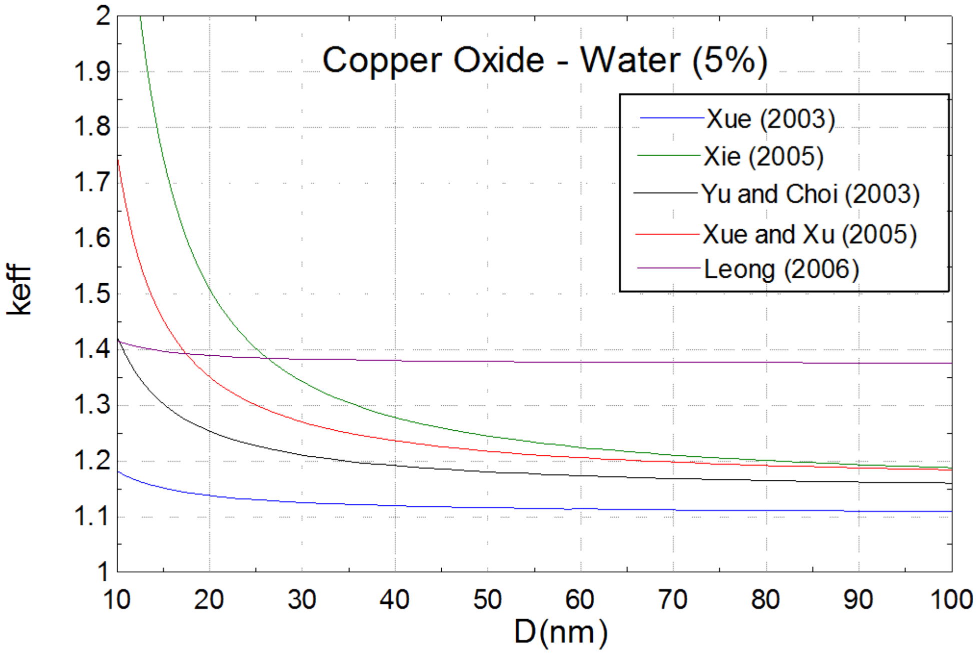

Figure 7: Nanoparticle size influence on thermal conductivity of nanofluids according to the correlations.

5. CONCLUSIONS

Nanofluids have a great potential in thermal applications, however to use this new heat transfer fluid several aspects should be clarified and better understood. This paper clearly indicates that the scientific basis for the mechanisms of enhanced thermal conductivity of nanofluids is not clear. A fair comparison between modeling and experimental results of thermal conductivity of nanofluids are quite difficult and can be improved with some standard techniques, such as production in large scale of nanofluids, careful preparation and synthesis methods with an accurate characterization.

The comparison between the experimental results obtained in the literature show inconsistencies among authors, that found different increments for same nanofluids and concentration, such as observed in Buongiorno’s research.

A critical analysis of various models in the literature to predict the thermal conductivity of nanofluids was conducted in this study. Although the models have been developed based on microstructural details such as size, shape, composition and physical properties of materials, it was possible to observe a huge discrepancy between these models and experimental results, and there is no reliable correlation to predict the thermal conductivity of nanofluids.

6. ACKNOWLEDGEMENTS

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8. RESPONSIBILITY NOTICE

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