THERMAL CONDUCTIVITY ENHANCEMENT IN NANOFLUIDS: COMPARATIVE ANALYSIS BETWEEN PREDICTION MODELS AND EXPERIMENTAL RESULTS

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Abstract. *The use of nanoparticles to improve the thermal conductivity of fluids used in heat transfer processes has been studied and implemented in the last years. The development of correlations to describe and characterize these nanofluids has shown great interest of the scientific community and also the industry. Due to the enormous challenge to understand the behavior of nanofluids, this report provide a comparation between the models proposed for predicting the thermal conductivity of nanofluids with experimental results obtained by different authors. Specifically, the experimentals results and theorical prediction regarding the enhancement of the thermal conductivity of nanofluids relative to heat transfer process. As can be observed, these models present discrepancies, showing that there is no general model for prediction of the thermal conductivity.*

Keywords*: Thermal conductivity, Nanofluids, Nanoparticle, Correlation, Heat Transfer.*

1. INTRODUCTION

Models based on correlation parameters have been used to calculate the increase in thermal conductivity, since they allow the understanding of the mechanisms involved in heat transfer nanofluids and could possibly lead to a model for the prediction of properties of interest. Several analytical models have been proposed for deriving the thermal conductivity of nanofluids. Since the idea of dispersing particles in fluids to enhance heat transfer is not new, the first studies referred to suspensions of micro-sized particles (Hamilton and Crosser [1], Jeffrey [2], Davis [3], Lu and Lin [4], Hasselman and Johnson [5]. These schemes were applied for the prediction of the thermal conductivity enhancement for some typical suspensions chosen arbitrarily.

Actually, investigators have proposed physical mechanisms and mathematical models to describe and predict the enhancement of thermal conductivity and to explicate the heat transfer phenomena into nanofluids. Models based on correlation parameters have been used to calculate the increase in thermal conductivity, since they allow the understanding of the mechanisms involved in heat transfer nanofluids and could possibly lead to a model for the prediction of properties of interest. In most models considered, the correlations depend on parameters with values that were experimentally determined by observing the increase in thermal conductivity. Parameters such as thickness of the liquid and its thermal conductivity, intrinsic properties of the fluid and the interaction with the particles as well as some correlation factors constant lead to satisfactory results for those who developed the model, however inadequate when evaluated by other researchers in which operating conditions are different. Although, in addition to observations, in this investigations have been detected eight parametric effects on nanofluids thermal conductivity, isolated from experimental data, are particle volume concentration, particle material, particle size, particle shape, base fluid material, temperature, additive and acidity. Each of these parameters will be considered separately from the standpoint of data trend, magnitude, and corroboration by multiple workers.

Factors suggested by other investigators that could also contribute to the enhancement of the thermal conductivity are: the ordered structure of the liquid at the solid–liquid interfaces [6,7] , the interfacial resistance [8, 9, 10] and Brownian motion of the nanoparticles enabling the formation of loosely packed clusters [6, 8, 11] and convection-like effects at the nanoscale [8, 10].

Based on Maxwell theory [16] and average polarization theory, Xue [12] presents a model to determine the effective thermal conductivity of nanofluids composed of nanotube/oil and Al2O3/Water. In the theoretical results could interpret the anomalous increase in conductivity of nanotube/oil and its nonlinearities by applying a specific amount of these particles.

2. THEORETICAL MODELS

Figure 1 shows some results based in theoretical models or correlations about thermal conductivity enhancement in nanofluids. Each color line corresponds to a specific nanofluid or solution nanoparticle/base fluid.

In most models considered in this article, the correlation depends on parameters developed in which its value was determined experimentally.

Based on Maxwell theory [1] and the media bias theory, Xue [11] presents a model to determine the effective thermal conductivity of nanofluids composed of nanotube/oil and Al2O3/água. In the theoretical results could interpret the anomalous increase in conductivity of nanotube/oil and its nonlinearities by applying a specific amount of these particles. The model developed by Xue [11] to predict the thermal conductivity for nanofluid is represented by Eq 1.

$$9\left(\frac{\nu}{\lambda}-1\right)\frac{k_e-k_m}{2k_e+k_m}=\frac{\nu}{\lambda}\left[\frac{k_e-k_{c,x}}{k_e+B_{2,x}(k_{c,x}-k_e)}+4\frac{k_e-k_{c,y}}{2k_e+(1-B_{2,x})(k_{c,y}-k_e)}\right] \tag{1}$$

Wang et al [13] proposed a fractal model for predicting the thermal conductivity of liquid with a dilute suspension of non-metallic nanoparticles. This model shows the trend of variation of effective thermal conductivity of nanofluid fit adequately analyzed and the experimental results obtained for particles of 50 nm CuO diluted in deionized water when the volume fraction is less than 0.5%.The prediction developed [13] for enhancement thermal conductivity of nanoparticle suspensions and that considers the clustering and distribution of this agglomeration is represented in Eq 2.

$$\frac{k_{eff}}{k_f}=\frac{(1-\phi)+3\phi\int_0^\infty \frac{k_{cl}(r)n(r)}{k_{cl}(r)+2k_f}dr}{(1-\phi)+3\phi\int_0^\infty \frac{k_f n(r)}{k_{cl}(r)+2k_f}dr}$$

Where ϕ is the volume fraction, $k_{cl}(r)$ is the thermal conductivity of clusters and $n(r)$ is the radio of function distribution.

The Jang and Choi [8] model, mentions that the Brownian motion of nanoparticles in molecular scale and nanoscale is the key mechanism for governing the thermal behavior of nanofluids. This study suggests a connection between the phenomenon and fluctuations measured macro molecular / nanoscale. Additionally, this model can predict the particle size and temperature dependence of nanofluid, while there are no theories explaining or predicting this effect.

The model [8] represented by Eq. 3, was based in Kittel [13] and Kapitza [14] works.

$$keff=k_f(1-f)+k_{nano}f+3C1\frac{d_{BF}}{d_{nano}}k_f\,\mathrm{Re}^2_{d_{nano}}\,\mathrm{Pr}\,f \tag{3}$$

Where k_f and k_{nano} are the thermal conductivity of base fluid and nanoparticles respectively, f is the volume fraction, d_{BF} and d_{nano} the diameter of the molecules base fluid and of the nanoparticles respectively, $C1$ the proportionality constant, Re_{dnano} the Reynolds number for this specific model and Pr the Prandtl number.

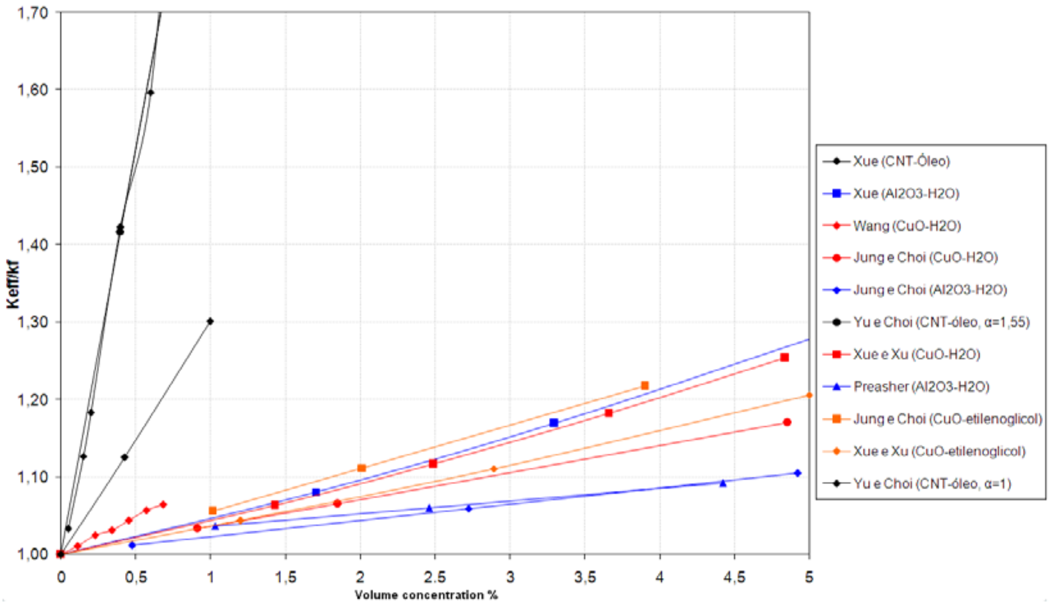

Figure 1- Theoretical results on thermal conductivity enhancement in nanofluids.

Yu and Choi [14] developed a new model, represented in Eq. 4, for predicting the thermal conductivity of three-phase suspensions of ellipsoidal particles in liquid. The solid / liquid interface is described as a confocal ellipsoid with a solid particle. This model, expressed mathematically in terms of equivalent thermal conductivity and volume fraction of equivalent ellipsoids complexes, predicts the conductivity of nanotube suspensions/oil, however it can predict the nonlinear behavior of the thermal conductivity of nanofluid. One factor associated with a generalized empirical model modified Hamilton-Crosser is proposed to show the importance of the interfaces solid/liquid has to increase conductivity.

$$keff = \left(1 + \frac{n f_e A}{1 - f_e A}\right) k_l \qquad A = \frac{1}{3} \sum_{j=a,b,c} \frac{k_{pj} - k_l}{k_{pj} + (n-1) k_l} \tag{4}$$

Where, n is the empirical shape factor and f_e is the volume concentration, equivalent of complex ellipsoids.

Compared with conventional models and solutions using CuO/water and CuO/ethylene glycol, Xue and Xu [15] derived an expression for modeling the effective thermal conductivity of nanofluids. This new expression, as in previous models, depends not only on the conductivity of solid and liquid particles in suspension and the volume fraction, but also the size and the interface properties of the particle. They assume the existence of an "interfacial shell" between nanoparticles and base fluid, considering the set shell-nanoparticle as "complex" nanoparticle Therefore, the nanofluid is regarded as complex nanoparticles diluted in base fluid. The correlation derived to predict the effective thermal conductivity of nanofluids is represented by Equation (5)

$$\left(\frac{v}{\alpha} - 1\right) \frac{ke - km}{2ke + km} = \frac{v}{\alpha} \frac{(ke - k2)(2k2 + k1) - \alpha(k1 - k2)(2k2 + ke)}{(2ke - k)(2k2 + k1) + 2\alpha(k1 - k2)(k2 - ke)} \tag{5}$$

v e v/α is the volume fraction of nanoparticles and nanoparticle complex, respectively. km, k_1, k_2 are the thermal conductivity of base fluid, of the spherical nanoparticles and of spherical shell, respectively.

Prasher et al. [10] showed that convection due to Brownian motion of nanoparticles is the main cause of conductivity enhancement in colloidal nanofluids. In this model, they note that, due to the convective nature of heat transfer, any proposed model has a semi-empirical essence included that requires numerical simulation. Here we considered three possible mechanisms to describe the heat transfer and energy in nanofluids: the translational Brownian motion, the existence of a potential between the particles and fluid convection due to Brownian motion of particles. The Prasher's predictive model is represented by Eq. 6.

$$\frac{k_{eff}}{k_m} = (1 + A\,\mathrm{Re}^m\,\mathrm{Pr}^{0.333}\,\phi)\left[\frac{(1+2\alpha) + 2\phi(1-\alpha)}{(1+2\alpha) - \phi(1-\alpha)}\right] \tag{6}$$

Where, A e m are constants, α is function of diameter and of the interfacial resistance of nanoparticles, Re the Reynolds number and Pr the Prandtl number.

3. EXPERIMENTAL RESULTS

The most used method for measuring the thermal conductivity is the *hot wire method*. This method is a standard transient dynamic technique based on the measurement of the temperature rise in a defined distance from a linear heat source (hot wire) embedded in the test material. If the heat source is assumed to have a constant and uniform output along the length of test sample, the thermal conductivity can be derived directly from the resulting change in the temperature over a known time interval.

Figure 2 shows a gallery of experimental results by different authors about thermal conductivity relative behavior of nanofluids with volume fraction nanofluid variation. To measure this property was used (in most cases) hot wire method, earlier mentioned.

In the Fig. 2, each color corresponds to a specific nanofluid. Blue lines correspond to CNTs/water and Red lines correspond to Al2O3/Water solution, Green lines represents thermal conductivity relative variation of nanofluid containing carbon nanotube (CNT) nanoparticles diluted in ethylene glycol as fluid base and Orange lines represents nanofluids composed of carbone nanotubes (CNT) diluted in oil as base fluid. It´s important to note, that the comparison was not performed between identical oils, but among similar oils. Finally, Black lines represents nanofluids composed of CuO/Water.

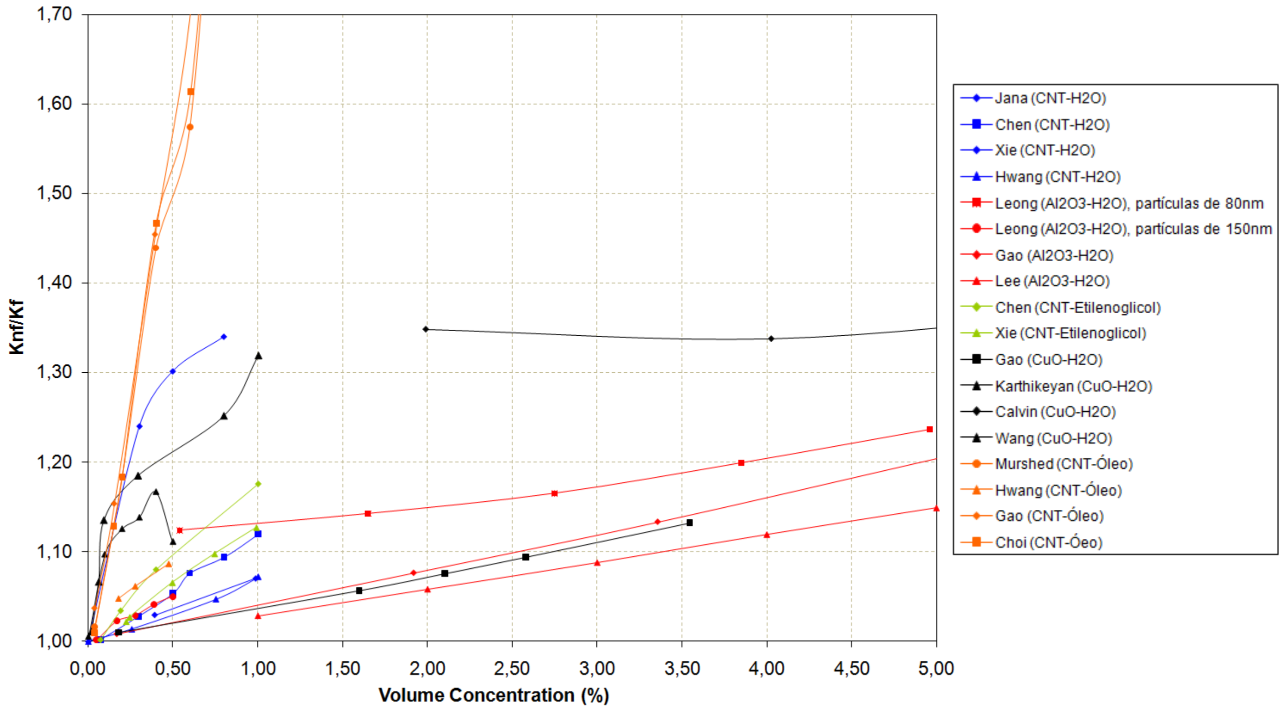

Figure 2- Experimental results about thermal conductivity enhancement in nanofluids

Jana et al. [2], used carbon nanotubes (CNT) with mean diameter of 10nm and length ranging between 5 and 10µm.Was made a polarization CNTs by chemical treatment to obtain a better dispersion. This chemical treatment consisted of 1 gram of CNTs suspended in 40ml of a mixture of nitric acid and sulfuric acid at a temperature of 140 ° C for 1 hour.

Chen et al. [3] used nanoparticles with diameter and length of 15nm and 30µm, respectively. Potassium hydroxide was used to modify the surface of CNTs.

Xie et al. [4] used nanoparticles chemically treated with nitric acid and sulfuric acid.

Hwang et al. [5] used multi-walled nanotubes (MWCNT - Multi Walled Carbon Nanotubes), with the addition of SDS dispersant in deionized water. With this addition, the thermal conductivity of the suspension increased significantly.

The better results was obtained in the Jana´s experiment, where a concentration of 0.8% by volume of CNTs resulted in a gain of 34% compared to the thermal conductivity of pure water. Can be observed also, that thermal conductivity shows a behavior non-linear with the volume fraction of nanoparticles.

Experimental results of Chen et al. [3] and Xie et al. [4] shows a substantial increase in thermal conductivity. Significant increase in thermal conductivity was found in Chen´s experiment, where a level of 1% by volume of CNTs resulted in an increase of 17.5% compared to the thermal conductivity of pure ethylene glycol. The thermal conductivity shows a non-linear behavior with the volume fraction of nanoparticles.

Gao et al. [6] obtained experimental results analyzing a depolarization factor, associate to spheroidal shape of CuO nanoparticles. Karthikeyan et al. [7] used 8nm particles of mean diameter, without addition of dispersant in base fluid. Wang et al. [8], performed experiments with CuO nanoparticles with mean diameter of 50nm. For this nanofluid, the experiments showed differing trends, which may be explained by the adoption of different parameters for measuring the thermal conductivity. It is easily seen that the thermal conductivity of CuO nanofluid increases non-linearly with increasing volume fraction of nanoparticles. Karthikeyan et al. [7] found that for 1% by volume of CuO nanoparticles, the increase in thermal conductivity was 31.6%.

In the Wang´s experiments [8], there was a decrease in the thermal conductivity gain by increasing the volume fraction of nanoparticles, this occurred at concentrations above 0.4% by volume; however, at these authors argue that this inconsistency would be due to formation agglomerations (clusters), proving that the settlements were formed from more intense volume fraction of CuO nanoparticles larger than 0.4% by volume.

Leong et al. [9] used nanoparticles of 80 and 150nm in diameter and was used Cetyl Trimethyl Ammonium Bromide (CTAB) as dispersant. Gao et al. [6] used a spherical depolarization factor of 1 / 3 to nanoparticles of Al2O3. Lee et al. [10] used nanoparticles with mean diameter of 36nm.

The largest increase in thermal conductivity can be observed in the experiment conducted by Leong et al. [9] with Al2O3 nanoparticles of 80nm in diameter, where to a concentration of 5% by volume, obtain a thermal conductivity gain of 24%. In the same article, the authors proved that the size of nanoparticles interfere with the gain given to the fluid thermal conductivity base because, for the same experimental conditions of 0.5% in volume and the nanoparticle dimension of about 150nm, the increase thermal conductivity was found in about 5%, whereas for the nanoparticle of 80nm increment was approximately 13%. The thermal conductivity of nanofluids containing Al2O3, exhibit nonlinear behavior with the increase nanoparticles concentration.

Murshed et al. [11] used as motor oil base fluid and CNTs with thermal conductivity of 2000 W / mK, while the conductivity of the used oil was 0.145 W / mK. Dispersant CTAB was added to ensure no formation of nanoparticles clusters. Hwang et al.[5] used MWCNTs dispersed in oil with density 0.915 g/cm3 and thermal conductivity 0.107 W/ mK. Gao and Zhou [6] performed experiments with synthetic polyalphaolefin oil (PAO). Choi et al. [12] used MWCNTs whit diameter and length of 25nm and 50μm, respectively, dispersed in oil synthetic polyalphaolefin (PAO).

Figure 6 illustrates a significant thermal conductivity enhancement in Gao and Zhou [6] and Choi et al. [12] experiments, where both used the same PAO synthetic oil, getting to a fraction of 1% by volume, an increase in thermal conductivity of 150%. In his articles, the authors report that the results were better than predicted by theoretical models such as Maxwell [13], Hamilton-Crosser [14], Bonnecaze and Brady [15,16]. Another important factor obsereved, is the fact that the thermal conductivity of CNT nanofluids in oil behaves nonlinearly with the volume fraction of nanoparticles.

4. COMPARISON BETWEEN PREDICTION MODELS AND EXPERIMENTAL RESULTS

Establish a theoretical model that represents the thermal conductivity behavior of nanofluids is not easy. As already mentioned, the proposed models were the product of manipulation of mathematical models with experimental results. Therefore is very difficult to establish a general mathematical model to be applied in a nanofluid specific.

4.1 CNTs/Oil nanofluids

Figure 3 shows experimental results obtained by Murshed et al. [11], Hwang et al.[5], Gao and Zhou [6] and Choi et al. [12] compared with predictive models proposed by Xue [11] e Yu and Choi [14] to CNTs-oil nanofluids. Can be observed that, experimental results show significant differences compared with theoretical results. It´s due to the parameters used to deduce these correlations, mentioned before.

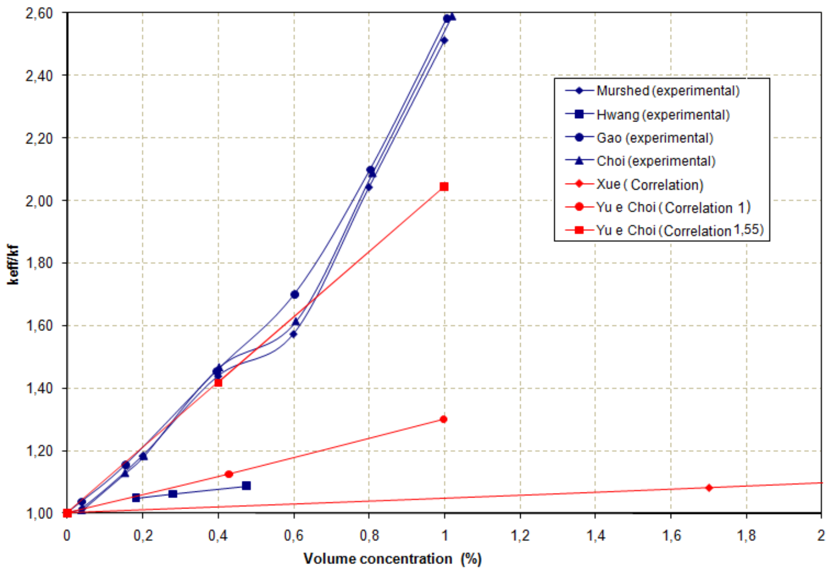

Figure 3. Comparison between experimental results and predictive models proposed for CNTs/oil nanofluids.

4.2 Al2O3/H2O nanofluids

In this case, by comparing experimental results obtained by Leong et al. [9], Lee et al. [10] Murshed et al. [11] and Gao and Zhou [6] with results of theoretical model proposed by Xue [11], Yu and Choi [8], and Prasher et al. [10] for solutions Al2O3 acute, can be observed that exist a good relation between the suggested model and empirical results.

Xue correlation shows a different trend, this due to an interfacial shell nanoparticle analyzed in his work.

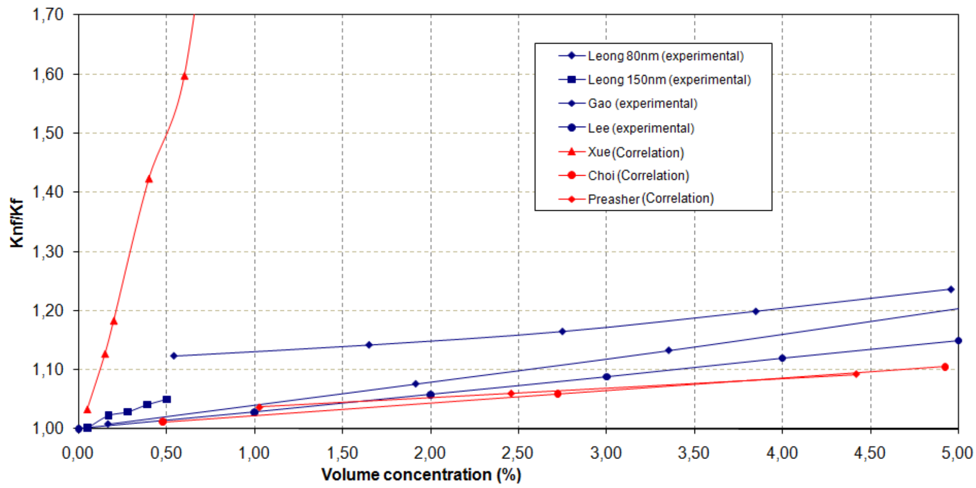

Figure 4. Comparison between experimental results and predictive models proposed for Al2O3/Water nanofluids.

4.3 CuO/H2O nanofluids

Comparison between experimental results and theoretical models to predict the thermal conductivity enhancement in nanofluids is shown in the Fig. 5. Can be observed that predictive models have a similar trend among them, but experimental results are different to theoretical results. This, because each author established own parameter to develop his correlation.

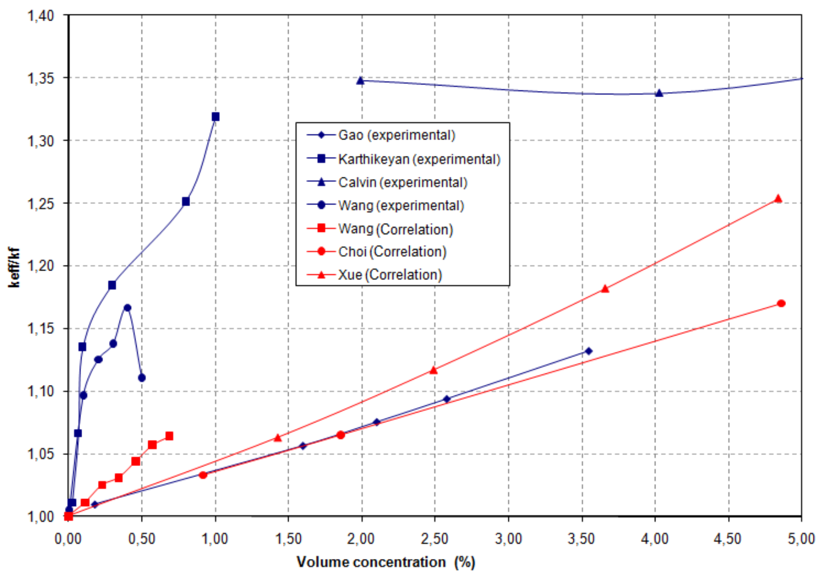

Figure 5. Comparison between experimental results and predictive models proposed for CuO/Water nanofluids.

CONCLUSIONS

The thermal conductivity enhancement ratio has been calculated from the information given in technical papers. This enhancement is defined as the ratio of the thermal conductivity of the nanofluid to the thermal conductivity of the base fluid.

The main goal of this work was the assessment of the experimental results found on thermal conductivity of nanofluids, obtained by many researchers to verify trends and inconsistencies. It was noted that, in general, the thermal conductivity of nanofluids in a non-linear increases with the addition of nanoparticles.

Among the factors that affect the thermal performance of nanofluids, it is possible to observe the clusters formation, use of dispersants and nanoparticles sedimentation.

Considering the comparisons, the nanofluids that have oil as the base fluid showed the best results in relation to the thermal conductivity, obtaining a greater increase, around two times compared with the base fluid.

For the CNT nanofluids in water, CNT-ethylene glycol, CuO nanoparticles in water and Al2O3 nanoparticles in water the best results found in thermal conductivity were 34%, 17.5%, 31.6% and 24%, respectively. The nanofluids have a great thermal potential and it is necessary to increase the researches to obtain satisfactory results, and thus can provide a more accurate and efficient to measure the thermal conductivity and in the end apply in the industry.

In the most models found, the correlation depends on parameters that have been determined experimentally by observation, which leads to satisfactory results for those who developed the model, however inadequate when measured by other researchers in which the operational conditions are different.

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