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Review

A survey of practical equations for prediction of effective thermal conductivity of spherical-particle nanofluids

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ABSTRACT

Over the last two decades a large number of compact and convenient analytical and empirical equations for predicting effective thermal conductivity of nanofluids have appeared in the literature. The equations themselves are expressions of the underlying physics thought responsible for the enhancement to thermal conductivity, including effects of base fluid and particle properties, particle diameter, morphology, concentration, temperature, interfacial phenomena, Brownian motion, nano-scale heat transport and particle clustering. It is found that while all correlations appear well supported with experimental data when originally published, the relative importance given to the various mechanisms is in conflict. Representative equations for nanofluid thermal conductivity are compared with a much larger, updated experimental data set. While classical analytical continuum models generally under-predict the enhancement, surprisingly, there are also a small number of nanofluid data with anomalously low thermal conductivity. Models which take into account nanoscale effects are generally found to over-predict the enhancement when compared with a larger number of data. The most successful predictions come from empirical equations where a regression analysis has fitted the correlation to a significant number of experimental data. In this paper, a review of the latest experimental work is given, theoretical, analytical and empirical investigations for predicting thermal conductivity of nanofluids are introduced and critical comparisons of equations with available data are presented.

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1. Introduction

From the vast body of literature on nanofluids that has arisen over the last two decades, it is clear that suspension of fine particles in conventional heat transfer fluids such as water, ethylene glycol and engine oil, is a very promising approach for heat transfer enhancement. From a practical point of view it is convenient to model this enhancement as an increase in effective thermal conductivity of the fluid (e.g. [1,2]) . The earliest existing equation useful for predicting the effective thermal conductivity of such fluids was derived by Maxwell towards the end of the 19th century [3]. It gives no consideration to particle size (or motion) and was originally developed for predicting electrical resistance of substances with dilute concentrations of spherical inclusions. In spite of this, Maxwell's equation has often been applied successfully in predicting effective thermal conductivities of composite materials and fluids. Suspensions containing millimeter or micrometer-sized particles appear to be most appropriate for such continuum-based models and some practical success for heat transfer enhancement has been achieved with large particles [4]. However, it is clear that large-particle suspensions also suffer from numerous disadvantages including settling of particles, erosion and clogging of pipelines, agglomeration of particles and consequently pressure drop. The use of nanometer-sized particles appears to be the key to removing these obstacles. The suspension of ultrafine particles in fluids for the first time was studied by Masuda [5] and Choi [6] who coined the term ‘nanofluid’. Choi's study sparked enormous interest (and some controversy) in that the experimental results not only demonstrated the practical success of using nanometer-sized particles, but also highlighted questions about the mechanisms for heat transfer since the reported effective thermal conductivities were well in excess of anything that could be explained by Maxwell's model or by other classical continuum-based mixing rules.

Many attempts have been made to verify and explain the anomalously high thermal conductivities of nanofluids reported by some research groups. During the last two decades, there have been numerous studies on preparation of nanoparticles and nanofluids, stabilizing, measurement techniques and applications of nanofluids in industry. Summaries of these investigations are available in the literature [7–11]. Also, there have been a large number of investigations on experimentally measuring and determining parameters that have an effect on the thermal conductivity of nanofluids. In parallel, much effort has been invested into theoretically determining the mechanism of the observed thermal conductivity enhancement. Several review papers introducing different approaches for prediction of thermal conductivity of nanofluids have been published [12–14]. It has been shown that different parameters such as particle volume fraction, thermal conductivity of base fluid and particle, size and shape of particles, temperature and particle aggregation all have a significant influence on the effective thermal conductivity of nanofluids [5,15–30].

In spite of the controversies surrounding nanofluids, the unanswered questions and the conflicting results among research groups, there appears to be an emerging body of self-consistent experimental data, giving confidence that progress is being made towards producing nanofluids with reliable and predictable properties. In a recent study, Corcione [31] developed an empirical correlation given by Eq. (1) showing very good agreement with a vast number of experimental results. The experimental data used were from eleven publications with either water or ethylene glycol as the base fluid and four different nanoparticle types with various sizes, temperatures and volume fractions. Eq. (1) is also a good illustration of the parameters typically considered important for nanofluid effective thermal conductivity. The thermal conductivity ratio (k_{eff}/k_{bf}) is expressed in terms of dimensionless groups made up of fluid properties, particle properties and the volume fraction of particles (ϕ).

$$\frac{k_{eff}}{k_{bf}} = 1 + 4.4\left(\frac{\rho_f u_B d_p}{\mu_f}\right)^{0.4} Pr^{0.66}\left(\frac{T}{T_{fr}}\right)^{10}\left(\frac{k_p}{k_f}\right)^{0.03}\phi^{0.66} \tag{1}$$

In this equation Brownian motion is considered to have an influence via u_B which represents the mean or effective Brownian velocity given by:

$$u_B = \frac{2k_b T}{\pi \mu_f d_p^2}. \tag{2}$$

Because of the promising agreement of this equation shown in the reference, we have selected Corcione's empirical correlation (Eq. (1)) as a convenient point of reference for discussion and comparison with other theoretical models and correlations in this review.

There are many other practical correlations and theoretical equations available that have not been compared with data sets as large as that given in original work of Corcione. Therefore the aim of this study is to bring together an extensive experimental data set including some more recent results and quantitatively compare these data with representative classical, theoretical and empirical correlations for the effective thermal conductivity of spherical-particle nanofluids. To achieve this end, first a review of experimental works will be presented. Then, key theoretical and analytical investigations for prediction of thermal conductivity of nanofluids will be explained and critical comparisons between experimental data and model predictions will be carried out to show the accuracy of existing models. In most of the experimental investigations to date, Al_2O_3, CuO and TiO_2 suspended in water and ethylene glycol (EG) have been used. Therefore here we have focused on these types of nanofluids for our comparisons. We have also restricted the study to approximately spherical particles to avoid the added complication of particle morphology. Readers interested in carbon nano-tube nanofluids are referred to the recent review by Murshed and Nieto de Castro [32]. This study also could be of value to researchers working on simulation of the thermal and hydraulic performance of nanofluids in different applications where selection of an appropriate thermal conductivity equation is required. Maxwell's spherical particle equation in particular has been used in both single-phase and two-phase treatments of nanofluids for a range of applications [33–37].

2. Experimental investigations

Table 1 [5,15–30,39–62] gives a summary of some key experimental investigations on the effective thermal conductivity of nanofluids. It is evident from the table that a range of particle sizes and types, base fluids and particle volume fractions have been considered. The most popular choice for the base fluid is water and the most commonly considered particle type is aluminum oxide. This is probably due to relatively low cost and high thermal conductivity of aluminum oxide nanoparticles. It is also observed that in most cases, the transient hot wire (THW) method has been used to measure the thermal conductivity of suspensions. This is due to the higher precision and faster response of the THW method compared to other measurement techniques [11,63].

2.1. Effect of particle diameter

By definition, the particle size is the feature that distinguishes nanofluids from other types of particle suspensions. In addition to the anomalous enhancement observed for small concentrations of nanoparticles, variation of effective thermal conductivity with particle size is strong evidence for non-classical nanoscale behavior. The thermal conductivity of nanofluids with different particle size distributions has been measured using several techniques during the past two decades to study anomalous enhancement beyond that expected from classical model predictions. One of the first studies on nanofluids was carried out by Masuda et al. [5] where they reported a 30% increase in thermal conductivity of Al_2O_3–water nanofluid with 4.3% volume fraction. The effect of particle diameter is shown in the difference between the results of Masuda et al. with an average particle diameter of 13 nm and those for Lee et al. [15], where they obtained only 15% enhancement in thermal conductivity of the same nanofluid with the same volume fraction, but