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An investigation into the effect of nanoclusters growth on perikinetic heat conduction mechanism in an oxide based nanofluid

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ABSTRACT

Thermal conductivity enhancement of nanofluids primarily depends upon the factors affecting their heat transport mechanisms. More insight into the phenomenon of thermal heat conduction in nanofluids has been presented in this paper. The growth of nanoclusters in the water (DI) based nanofluid containing γ-Al_2O_3 (size 25–30 nm), has been investigated and studied. A comprehensive report on the suspension size distribution of the nanoparticles at different pH values, their zeta potential along with the stability ratio of suspensions, has been presented. A quantitative analysis on the thermal conductivity enhancement, along with an investigation on the role of nanoparticles present in the form of dead ends and backbone chains in an aggregate has been put forward. Their individual effect under perikinetic heat conduction conditions has been incorporated to address the thermal conductivity enhancements of Al_2O_3-H_2O nanofluid. Moreover, the effect of the basefluid layering around the nanoparticles in an aggregate has been highlighted. The possible and the different governing static/structural models which are capable to predict the nanocluster based thermal conductivity enhancements in nanofluids, have been investigated and modified. This has been done to include the effect of liquid layering on the thermal conductivity of the water present in an aggregate compared to the bulk water present outside to a nanocluster or an aggregate. While, modifying the equations and models, the focus has been laid down to the average hydrodynamic size of the nanoparticles in a suspension than the individual particle size. The modified model gives a fairly good prediction of the thermal conductivity enhancement of the nanofluid under investigation. The experimental and theoretical results of thermal conductivity of Al_2O_3 nanofluid have been correlated and found to be within the accuracy level of ±1 to ±2.3% at 0.05% volume fraction. The error analysis shows that the developed model is enough capable to predict the thermal conductivity enhancement with an average error of ±2.6% compared to the predictions made from the other existing theoretical models, where the error involved is found to be varying from ±3 to ±9% at volume fraction ranging from 0.01 to 0.12%.

1. Introduction

Nanofluid is a new class of colloidal suspensions prepared by suspending the nanoparticles into the different types of base fluids such as; water, ethylene glycol, oils etc. [1,2]. There are various research groups, who have investigated thoroughly, the unusual rise in the thermal conductivity of nanoparticle-dispersed fluidic systems having comparatively low volume fractions (<2.0% by volume) [1–4]. The various combinations of the base fluids and nanoparticles are being studied for their improved thermophysical properties at different temperatures along with varying concentrations of the surfactants [5–9]. The mechanism of the thermal conductivity enhancement in nanofluids is influenced by various factors such as; Brownian motion based microconvention, cluster formation of particles and their dynamics, formation of highly ordered layer around the nanoparticles, thermophoresis, diffusive or ballistic nature of the heat transport etc. [10–12]. Many researchers have emphasized that clustering is an important phenomenon responsible for the nanofluids' performance and which also helps to understand the mechanics of the heat transport and an unusual rise in their thermal conductivity [7,13–15,18,56,73]. The enhancement in thermal conductivity is due to the formation of a localized particle-rich zone that has lesser thermal resistance to heat flow compared to a particle-free zone [15,18]. On the other hand, due to a larger mass of nanoclusters they are likely to get settle down and creating a "particle-free" zone in the upper portion of a nanofluid, resulting into a decrease in its thermal heat transport capacity [7,15,18]. Thus, clustering of nanoparticles may have both positive and negative impacts on the thermal conductivity of nanofluids. It has been observed that the nanofluids with higher volume concentrations and with smaller nanoparticle size, are more prone to the clustering/agglomeration [11,12]. The Vander-Waals attraction increases with a decrease in the interparticle distance between the nanoparticles, which thereby increase their probability to agglomerate. Karthikeyan et al. [16] presented a

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microscopic observation on the cluster formation and their size in a nanofluid. A postulation was made about the structural appearance of the nanoclusters in the form of linear chains that span the whole cluster, called the "backbones", while the other particles, which do not span the whole cluster, are called "dead ends (backwaters)" [17]. Evans et al. [18] stressed upon the connectivity of these backbones and highlighted their crucial role in the thermal conductivity enhancement of nanofluids. Xuan et al. [19] developed a theoretical model to predict the thermal conductivity by taking into account the properties of both the base liquid and the nanoparticles specially, the structure of the nanoparticles and aggregates. Philip et al. [20] observed an unusually large enhancement in thermal conductivity when, chain-like aggregates were uniformly dispersed into the basefluid and suggested that the nanofluids containing well-dispersed nanoparticles (without aggregates) do not exhibit significant enhancement in the thermal conductivity. The effect of clustering on the thermal conductivity has been further emphasized by various research groups [7,15,21–23]. The authors have also laid down a significant emphasis on the formation of nanoclusters in their earlier published work, where, various models were evaluated for their accuracy to predict the thermal conductivity enhancement for Al_2O_3 based nanofluids with an error of $\pm 5\%$ [24].

There are various models available to predict the thermal conductivity enhancement of nanofluids which take into account the effect of factors such as; nanolayer, interfacial thermal resistance, percolation structure, agglomeration, surface charge state, Brownian motion of nanoparticles etc. [7,15,18,52–56,69,73,76]. These models have been developed by assuming that the nanoparticles are stationary or have negligible bulk movement in the basefluid. The models are based upon the effective medium theory approach and make assumptions such as; uniform dispersion and no interaction between the nanoparticles. The models are primarily based upon the initial volume concentration of the nanoparticles in the basefluid. They stressed upon to include the heat transport through the stationary medium in the host fluids, where particle-liquid-particle interaction can lead to a faster heat conduction. Hence, heat transportation through clusters may provide an alternative and effective mechanism for the enhancement of thermal conductivity of nanofluids [55–59]. Therefore, the introduction of properties of clusters and their structural arrangement into the modeling of the thermal conductivity of nanofluids will play a significant role, rather than doing thermal conductivity modeling only based upon the nominal or average diameter of the nanoparticles (which is generally the size measured from the nanopowder). The thermal conductivity of the liquid present inside the cluster is comparatively higher than the bulk of the surrounding fluid, which needs to be taken into consideration while modeling the effective thermal conductivity of nanofluids [26, 66,76,77]. Hence, the authors are of the view that the clustering and structural arrangement of the suspended nanoparticles and time dependent volume concentration of nanoparticles are the main factors effecting the thermodynamic properties and performance of the nanofluid apart from the nanoparticle diameter, primary volume fraction, pH, temperature etc. Therefore, the nanofluid suspensions require a thorough investigation into the existing relevant classical/structural models for thermal conductivity models along with the suitable amendments based upon the nanocluster morphology and their associated effects.

2. Experimental work

2.1. Preparation of nanofluids

The commercial available nanopowder of Al_2O_3 (γ) with an average size of nanoparticles 20–25 nm was procured from Intelligent Material Pvt. Ltd. (NANOSHEL, USA), whose, information is given in Table 1. The material characterization was performed with powder X-Ray diffraction (XRD) technique at the room temperature (25 °C). A complete analysis of XRD pattern, including lattice parameters and Bragg profile confirmed the existence of Al_2O_3 (γ) with 99.99% purity. In order to carry out the experimental work, various samples of nanofluid (20 ml each) were prepared by mixing the Al_2O_3 nanoparticles of 0.05% of volume fraction (38.80 mg) with water (DI). The Deionized (DI) water was chosen as the basefluid as it is non-toxic and, most commonly used fluid for a variety of cooling applications [26]. The anionic surfactant Sodium Dodecyl Benzene Sulphonate (SDBS) has been used to enhance the stability the nanofluid suspensions [25,26]. The effect of pH value on the suspension stability of the nanofluid has been investigated using hydrochloric acid (HCl) and sodium hydroxide (NaOH) of suitable analytical grades.

Table 1
Data used to predict the thermal conductivity enhancement of Al_2O_3-H_2O nanofluids.

Parameter/factor	Value
Crystal form	γ
Density, ρ_{Al2O3}	3.970 g/cm^3
Specific surface area (SSA)	15–20 m^2/g
Thermal conductivity, K_p	35 W/m-K
Relative dielectric constant of the liquid, ε_r	80 for H_2O
Dielectric constant of free space, ε_0 8.854×10^{-12} CV^{-1} M^{-1}	
Temperature, T	298 K
Resistance due to thermal boundary layer, R_{BL}	1×10^{-9} m^2 K/W
A constant, α	13.58×10^{20} s/m^3
Boltzmann constant, K_B	1.3807×10^{-23} J/K
Viscosity of base fluid, μ	0.89 mPa-s
Thermal conductivity of base fluid, K_f	0.6060 W/m K at 25 °C

2.2. Measurement of pH, zeta potential and hydrodynamic size of nanoparticles

The surface chemical effects are considered to be the key factors effecting the suspension stability and hence the thermal conductivity of nanofluids. These effects are attributed due to hydrophobic-to-hydrophilic conversion of the surface and generation of hydroxyl groups, which effect the pH value of the nanofluid and hence, their thermal performance [27,28]. The dispersion quality of Al_2O_3 nanoparticles in aqueous solution depends upon their electro-kinetic properties. A good quality dispersion can be obtained with a high surface charge density present on the nanoparticles, which shows the presence of the strong repulsive forces. Therefore, the measurement of the zeta potential (ζ) is considered to be an important aspect in order to understand the suspension behavior of a nanofluid. The measurements of zeta-potential of all the samples have been done using a zeta sizer, where, the average data have been obtained by repeating the experiments at least three times.

2.3. Thermal conductivity measurements

The thermal conductivity measurement of various samples of a nanofluid has been carried out by using a KD2 Pro thermal property analyzer (Decagon Devices, Inc., USA). This instrument has a display provision which can show the type of temperature sensor being used and an experimental error recorded during the measurements. The instrument is suitable to measure the thermal conductivity in the range from 0.2 to 2 W/m-K with an accuracy of $\pm 5\%$. Before using the instrument, it was calibrated by inserting the KS-1 sensor needle vertically into 20 ml of DI water and glycerine samples. The measured average values of the thermal conductivities of these samples were found to be $0.595 \pm 5\%$ W/m K and $0.275 \pm 5\%$ W/m K at 24.65 ± 0.5 °C. These measured values were validated by comparing with the thermal conductivity data available in literature (0.605 W/m-K and 0.285 W/m-K at 25 °C for DI water and glycerine, respectively) [26]. This method is known to be more accurate and quickest way to determine the thermal conductivity of nanofluids [29–33].