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Convective Heat Transfer Mechanisms and Clustering in Nanofluids

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Abstract. Nanofluids are suspensions of nanoparticles in fluids that show significant enhancement of their properties at modest nanoparticle concentrations. Nanofluids, due to anomalously high thermal conductivity, are important in heat transfer. Regarding the various models of thermal conductivity, we show that thermal dispersion model for explaining nanofluid heat transfer results have better agreement with experimental results. Investigation of the effect of nanofluid particle size and temperature on heat transfer results in complicated trends due to the opposing effects of thermal conductivity and thermal dispersion on heat transfer in terms of particle size dependence. Numerical results are compared with experimental and numerical data in the literature and good agreement is observed especially with experimental data.

Keywords: Nanofluids, Dispersion Model, Heat Transfer, Boundary Condition.

1. Introduction

The conventional method for enhancing heat transfer in a thermal system consists of increasing the heat transfer surface area as well as the flow velocity of the working fluid [1]. The dispersion of solid nanoparticles in heat transfer fluids is a relatively new method. Extended surfaces such as fins and microchannels (width <100 μm) have already been used to increase the heat transfer surface area. Their performance in effectively removing as much as 1000 W/cm2 has shown a great improvement in the area of cooling.

Heat transfer can be enhanced by employing various techniques and methodologies, such as increasing either the heat transfer surface or the heat transfer coefficient between the fluid and the surface, that allow high heat transfer rates in a small volume. Cooling is one of the most important technical challenges facing many diverse industries, including icroelectronics, transportation, solidstate lighting, and manufacturing.

Fluids behavior and spatial structure in the nanoscale fundamentally are different from behavior and structure in micron and larger dimensions. A nanofluid is the suspension of nanoparticles in a base fluid.. Studies show that the fluid has been confined or flow in nanochannels has non-continuum behavior and phenomena such as flux delaminate and unconventional density fluctuation appear. Furthermore, the role of interaction between flux and nano-channel is prominent and channel wall dynamic can be fundamentally affect fluid dynamics.

With the recent improvements in nanotechnology, the production of particles with sizes on the order of nanometers can be achieved with relative ease. As a consequence, the idea of suspending these nanoparticles in a base liquid for improving thermal conductivity has been proposed recently [2,3].

2. Improving Heat Transfer efficiency

Heat transfer plays an important role in numerous applications. For example, in vehicles, heat generated by the prime mover needs to be removed for proper operation. Similarly, electronic equipments dissipate heat, which requires a cooling system. Heating, ventilating, and air conditioning systems also include various heat transfer processes. Heat transfer is the key process in thermal power stations. In addition to these, many production processes include heat transfer in various forms; it might be the cooling of a machine tool, pasteurization of food, or the temperature adjustment for triggering a chemical process. In most of these applications, heat transfer is realized through some heat transfer devices; such as, heat exchangers, evaporators, condensers, and heat sinks. Increasing the heat transfer efficiency of these devices is desirable, because by increasing efficiency, the space occupied by the device can be minimized, which is important for applications with compactness requirements. Furthermore, in most of the heat transfer systems, the working fluid is circulated by a pump, and improvements in heat transfer efficiency can minimize the associated power consumption.

Researches show that, there is significant discrepancy in nanofluid thermal conductivity data in the literature. There are several mechanisms proposed to explain the thermal conductivity enhancement of nanofluids, such as Brownian motion of nanoparticles[4], clustering of nanoparticles [5] and liquid layering around nanoparticles. Due to the lack of systematic experimental data in the literature, it is difficult to analyze the relative significance of these mechanisms. Most of the theoretical models based on these mechanisms include some empirical constants. The effect of parameters such as temperature, particle volume fraction and particle size distribution of nanoparticles studied to heat transfer enhancement with nanofluids. It is possible to correctly predict experimental results to some extent by adjusting the values of these constants accordingly. On the other hand, at present, a complete theoretical model of thermal conductivity that takes all of the parameters into account is not available.

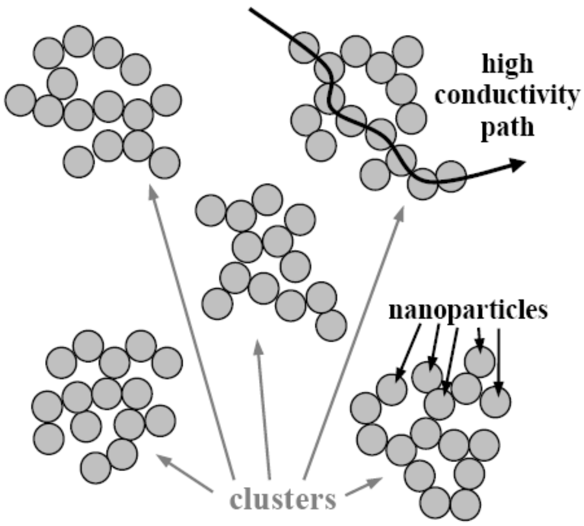

Fig.1: Schematic illustration representing the clustering phenomenon. High conductivity path results in fast transport of heat along large distances.

It was shown that the thermal conductivity was affected by factors such as temperature, particle size, and pH level. Several theoretical models have been proposed to explain the behavior of nanoparticles. Many of these models can be categorized as either static or dynamic models. Static models assume that the nanoparticles are stationary in the base fluid, forming a composite material. In these models, the thermal properties of nanofluids are predicted through conductionbased models such as that of Maxwell. One such model is the modified Maxwell theory of Hamilton and Crosser which gives the enhancement of thermal conductivity as

$$K_{nf} = \frac{K_P + 2K_f - 2(K_P - K_f)\phi}{K_P + 2K_f - (K_P - K_f)\phi} K_f \tag{1}$$

where K_{nf}, K_p and K_f are the thermal conductivity of the nanofluid, nanoparticles and base fluid, respectively. ϕ is the volume fraction of particles in the mixture.

Density of nanofluids can be determined by using the following expression

$$\rho_{nf} = \phi\rho_P + (1 - \rho_f) \tag{2}$$

And we can derived specific heat of nanofluids by

$$c_{P,nf} = \frac{\phi(\rho c_P)_P + (1-\phi)(\rho c_P)_f}{\rho_{nf}} \tag{3}$$

3. Clustering in Nanofluids

One of the main obstacles encountered in microfluid experiments was the agglomeration of particles. Even though research, such as that documented in [10, 11], shows a substantial increase in the thermal conductivity of the base fluid with the addition of nanoparticles, the movement towards practical applications has been hampered by the rapid settling of the nanoparticles. The settling of particles not only decreased the overall heat transfer of the fluid (by decreasing the effective surface area used for heat transfer), but also led to the abrasion of surfaces, clogging of microchannels, and a decrease in pressure which resulted in an increase in pumping power. Although nanosized particles have greatly reduced the problem of agglomerated particles, it still occurs and can hinder the thermal conductivity of the nanofluid, especially at concentrations over 5% agglomeration is more apparent when using oxide nanoparticles because they require a higher volume concentration compared to metallic nanoparticles in order to achieve the same thermal conductivity enhancement [12]. The tendency of particles to group together before they are dispersed in the fluid is due to the van der Waals forces. This is particularly seen in metallic particles since dipoles can occur easily in the molecules of these particles. The creation of dipoles prompts the attraction of other dipoles in the vicinity. The van der Waals forces stem from the attraction of these dipoles, which can be induced even in neutral particles. This attractive force is considered to be the main culprit behind the agglomeration of particles, especially in nanopowders. To alleviate this problem, there have been various proposals for the manufacture and dispersion of nanoparticles in fluids. One proposal involves adding surface treatments to the nanoparticles. It was seen that when copper nanoparticles were coated with a 2–10 nm thick organic layer a stable suspension would be achieved in ethylene glycol [13]. There is research currently being conducted towards improving the two-step process to produce well-dispersed nanofluids. Moreover, there exist a few one-step processes that result in nanoparticles being uniformly dispersed and stably suspended in the base fluid. One such method involves condensing copper nanopowders directly from the vapor phase into flowing ethylene glycol in a vacuum chamber [14]. Documents [15–17] also show stable, welldispersed suspensions in nanofluids containing TiO2, CuO, and Cu. In these experiments, a one-step process called submerged arc nanoparticle synthesis was used to create the nanoparticles. Various techniques have been implemented to reduce the clustering of particles once they are in the fluid [18, 19]. Usually, they involve some sort of agitation within the nanofluid to separate the clusters into individual particles and keep them from settling. These methods include the use of dispersants, changing the pH value of the base fluid, and using ultrasonic vibration to excite the particles [16]. Among these methods, the most commonly used ones are ultrasonic vibration and the use of dispersants. Both techniques are relatively effective, but when using dispersants, the amount added to the fluid must be a very low percentage (usually 1% or less). This is done so as to minimize its effects on the thermal conductivity of the nanofluid. However, it should be noted that loose particle chains may be responsible for some of the high thermal conductivities of nanofluids; see Prasher et al. [19]. The Argonne National Laboratory also developed the single-step and two-step processes for the dispersion of nanoparticles in a fluid [1]. The single-step process consists of simultaneously making and dispersing the particles in the fluid. The two-step method separates the manufacture and dispersion of particles into two steps (particles are manufactured first and then dispersed into the base fluid). The two-step process is the more commonly used method and is usually used in conjunction with ultrasonic vibration to reduce the amount of clustered particles in the fluid. Analysis of the reviewed literature shows that there is still no conclusive theory concerning the prevention of clustering in the nanoparticle suspensions. Before using nanofluids in practical applications, the problem of clustering must be consistently kept to a minimum. When looking at longterm effects, clustering of the particles will eventually cause a decrease in the thermal conductivity of the nanofluid and may also cause wear in the pipes or pumps through which it is flowing. Therefore, nanofluids cannot be used in systems designed for long-term use until this problem is solved. Otherwise, the use of nanofluids may decrease the life expectancy of a system, even if it improves the overall efficiency. In the mean time, an optimization and design problem persists when nanofluids are used in the field.

4. Conclusion

Convection heat transfer is recognized within nanofluids, but there is not enough research results published to develop a model that fully explains this behavior in nanofluids. Furthermore, several of the research papers available seem to contradict each other as some data shows an increase in convection as the particle volume fraction is increased, while other data shows deterioration in convective heat transfer as the particle density and concentration were increased.

Clustering still poses a problem in nanofluids even though the occurrence of agglomeration has decreased from the previous micrometer-sized particles suspensions. Various methods are currently used to keep particles from clustering together, but in the long run, it is inevitable. Clustering is a problem thatmust be solved before nanofluids can be considered for long-term practical uses. Although the increase in thermal conductivity would increase the efficiency of the systems where nanofluids are used, the life of the system may be decreased over time if particles begin to form clusters.

In figures 2 and 3 results of the numerical analysis for the hydrodynamically fully developed, thermally developing laminar flow of Al_2O_3/water nanofluid inside a straight circular tube under constant wall temperature and constant wall heat flux boundary conditions are presented. Numerical results are compared with experimental and numerical data available in the literature. Effects of particle size, heating and cooling on heat transfer enhancement are investigated.

It is seen that application of the thermal dispersion model to the governing energy equation provides meaningful results which are in agreement with the available experimental data in the literature [4]. This can be considered as an indication of the validity of the thermal dispersion model for nanofluid heat transfer analysis. Furthermore, it can be concluded that single phase analysis of nanofluid heat transfer is sufficiently accurate for practical applications as long as variation of thermal conductivity with temperature is taken into account in the associated calculations [6].

Figure 2 show the parameter of particle size in the nanofluid thermal conductivity that is observed with increasing particle size, thermal conductivity increases, which results from compliance with the experimental results is well. Investigation of the effect of nanofluid particle size on heat transfer results in complicated trends due to the opposing effects of thermal conductivity and thermal dispersion on heat transfer in terms of particle size dependence. It is seen that if empirical constant C in dispersed thermal conductivity expression is sufficiently small, the effect of thermal conductivity dominates particle size dependence which results in increasing heat transfer with decreasing particle size. On the other hand, if C is large, heat transfer increases with increasing particle size.

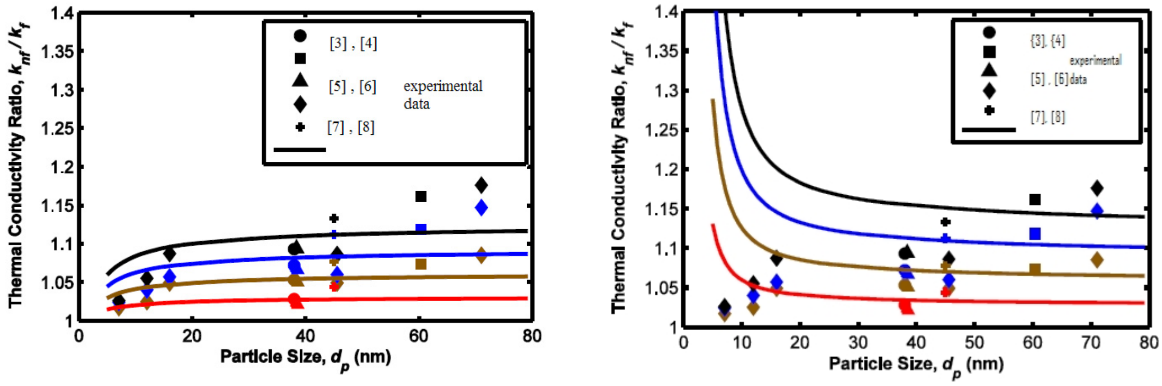

Fig. 2: Comparison of the experimental results of the thermal conductivity ratio for Al_2O_3/water nanofluid.

Figure 3 shows that the nanofluid heat transfer revealed that for the constant wall heat flux boundary condition. Investigation of the effects of cooling and heating on nanofluid heat transfer revealed that for the constant wall heat flux boundary condition, heat transfer and associated enhancement is higher when flow temperature is higher. When it comes to the constant wall temperature boundary condition, the dominant parameter that affects the heat transfer is the wall temperature. As the wall temperature increases, the heat transfer and the associated enhancement increases. These facts should be taken into account for the practical application of nanofluids in heat transfer devices.

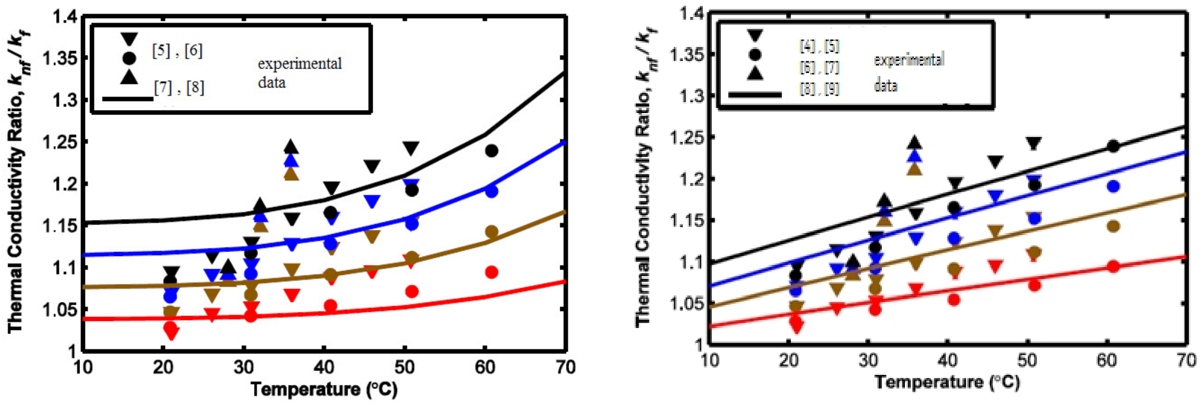

Fig.3: Comparison of the experimental results of the thermal conductivity ratio for Al_2O_3/water nanofluid.

Nanofluids have the potential to open the doors to major advancements in many high-tech industries where limits on cooling have posed limits on innovation. Since all other cooling options have been exhausted, nanofluids are the only option left with the possibility of increasing heat transfer capabilities of current systems. However, a full understanding of the mechanisms behind the enhancement of thermal conductivity in nanofluids has not been reached and there is still disagreement between some of the experimental results. This lack of agreement has led to the generation of various models. Once a general model that fully explains the behavior of nanoparticle suspensions has been developed, steps can be taken towards practical uses. Moreover, better techniques for the dispersion of particles in fluids must be created so as to minimize clustering. When these objectives have been reached, nanofluids will enter the practical arenas of science in a more meaningful way.

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