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Motion of Nano-fluids for the Thermal Conductivity Enhancement

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Abstract

This study involves the Brownian dynamics simulations of the real nanofluid system in which the inter-particle potential is determined based on Debye length and surface interaction of the fluid and the solid. The present paper shows that the Brownian motion will increase the thermal conductivity of the nanofluid by 6% primarily due to random walk motion and not only through diffusion. This increase is limited by maximum concentration for every particle size and is below that predicted by the theory of effective medium. Now over the maximum limit, the particle aggregates begin to form. The Brownian motion contribution stays as the constant beyond a certain particle diameter. Here, we use a kinetic theory based analysis of heat flow in fluid suspensions of solid nanoparticles i.e., nanofluids to show that the hydrodynamics effects associated with Brownian motion have only the minor effect on the thermal conductivity of the nanofluid. The results obtained by this analysis are same as that of the results of molecular dynamics simulations of the heat flow in the model nanofluid with well dispersed particles. The results analyzed in the present paper are consistent with the predictions of the effective medium theory as well as with recent experimental and theoretical results on the well dispersed metal nanoparticle suspensions.

Keywords: Brownian motion, Nanofluid, Thermal conductivity.

1. Introduction

According to the work of Einstein on the Brownian motion it is well known that the colloidal particles dispersed in the fluid of smaller molecules behave as thermodynamic system. The structure and the properties of this "macroparticle system" are normally observed by the forces of the interaction among macroparticles, the fluid or solvent enters in the form of the thermal bath that providing kinetic energy for each degree of freedom of the macroparticles the well known fluctuation dissipation theorem. The analysis and accuracy of the present description has been verified by experiments, in the experiments of Vrij and others, who have observed the structure factor for the spherical colloidal particles with size ranging from 20 to 200 nm. In the real sense, the idealized hard sphere fluid can be realized much accurately and probed more easily with colloids than with its atomic realization argon [1].

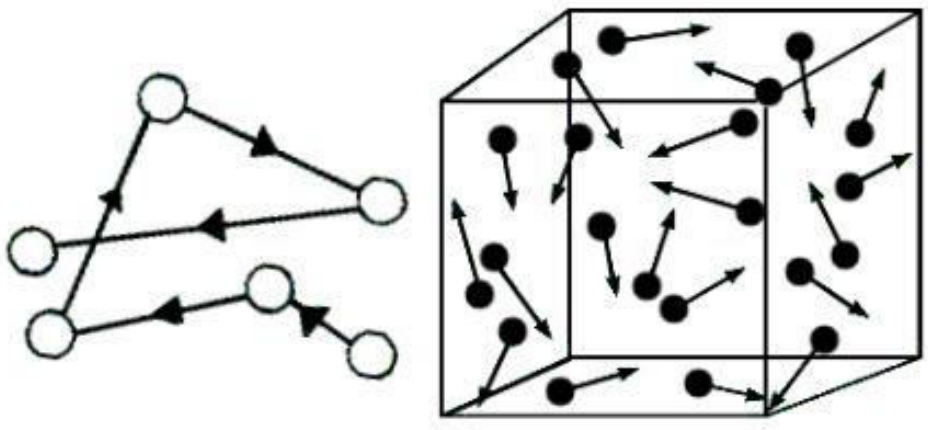

Figure-1 (Brownian motion)

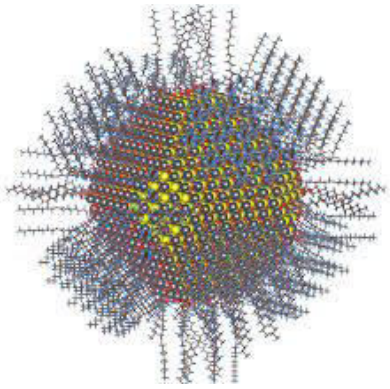

Figure-2 (Nanofluid particles)

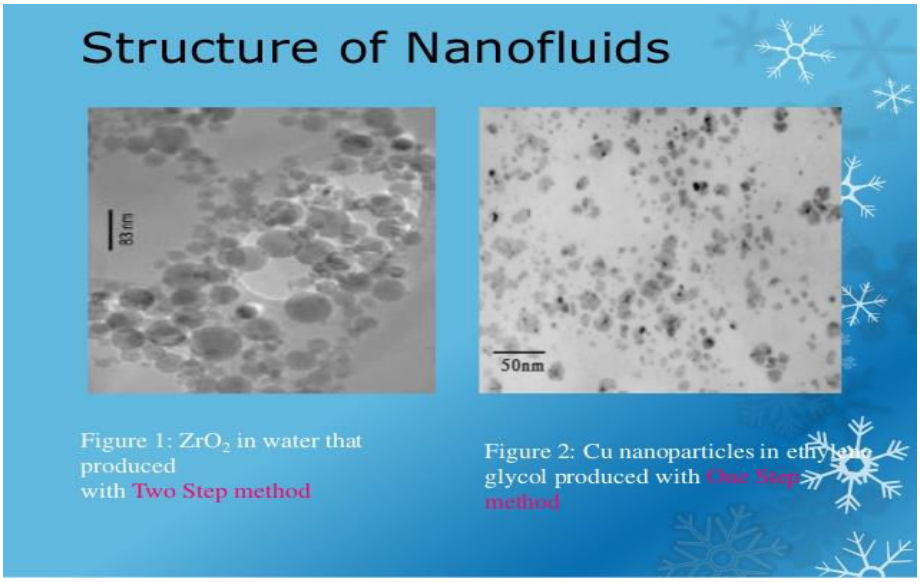

Figure-3 (Structure of nanofluids)

So that we have seen that the two particles fall fast when falling close to one other and along their line of centers. However, all the analysis up to now has been carried out ignoring Brownian effects. When examining the dilute suspensions of colloidal spheres in some liquid or water, we notice that each particle moves about with the continuous but random zigzag motion. We can think about these particles as being constantly bombarded by the random impacts of molecules of liquid. The resulting motion of colloids is known as Brownian motion [8], which sees them diffuse relative to each other. So in order to interpret this diffusive spreading, it can be much useful to model their behavior by using the random walks. This includes allowing each particle to take steps δx in any direction along each axis every time steps δt. The motions in each of these directions are statistically independent as colloids on colliding with water molecules will lose the initial velocity. The particles will move independently from each other such that the walk will be unbiased.

The nanofluids are the new class of fluids engineered by the dispersing nanometer-sized materials i.e., nanofibers, nanoparticles, nanotubes, nanosheet, nanorods, or droplets in the base fluids. In other words, nanofluids are nanoscale colloidal suspensions that containing solid nanomaterials. They are normally two-phase systems with one phase i.e., the solid phase in another phase i.e., the liquid phase. For the two-phase system, there are some new issues that one has to face. One of the most important

issues is the stability matter of nanofluids and it remains a great challenge to get desired stability of nanofluids.

The more emphasis for nanofluids research lies in the wide range of several applications. Although some review articles involving the progress of nanofluid investigation were published in past several years, most of the reviews are concerned on theoretical and experimental studies of the convective heat transfer or the thermophysical properties of the nanofluids. The purpose of the present paper will focuses on the stability mechanisms and preparation methods, especially the new application trends for nanofluids and the thermal conductivity of nanofluids. We will try to analyses some issues that need to be solved for the future research based on the review on these aspects of the nanofluids.

The nanofluids would be prepared by suspending solid particles with the size of less than 100 nanometers inside a basefluid. The terms synthesis and Characterization are mostly used in the literature that describing the preparation phase of the nanofluids. In general terms, it can be said that the nanofluids contains nanometer sized solid fibers, particles, tubes or rods suspended in different basefluids [11]. By taking together with the basefluids and nanoparticles, some additives are utilized to increase stability of nanofluids and to improve the dispersion behavior of them. The nanoparticles of $Al_2 O_3$ and basefluid water exploited in synthesis would be tabulated from different sources.

2. Thermal Conductivity

In general, two production methods of preparation and dispersion, called one-step method and two-step method exist. Moreover, the key to significant increment of thermal conductivity of nanofluids is synthesis, within which non-agglomerated nanoparticle are suspended in the basefluid [5]. In the single-step method, preparing nanoparticles and dispersing inside basefluid occurs simultaneously. In two-step method, nanoparticles are processed and made by some techniques first and then dispersed them into the basefluid. Most nanofluids including oxide nanoparticles are generated by the means of the two-step method, but for the metallic nanoparticles or particles with high thermal conductivity one-step method is used preferably. For instance, Hong prepared Fe/ethylene glycol nanofluid by taking advantage of the two-step method. In this case, the synthesis of Fe nanoparticles have been performed by the chemical vapor condensation process and then, it was dispersed in the basefluid.

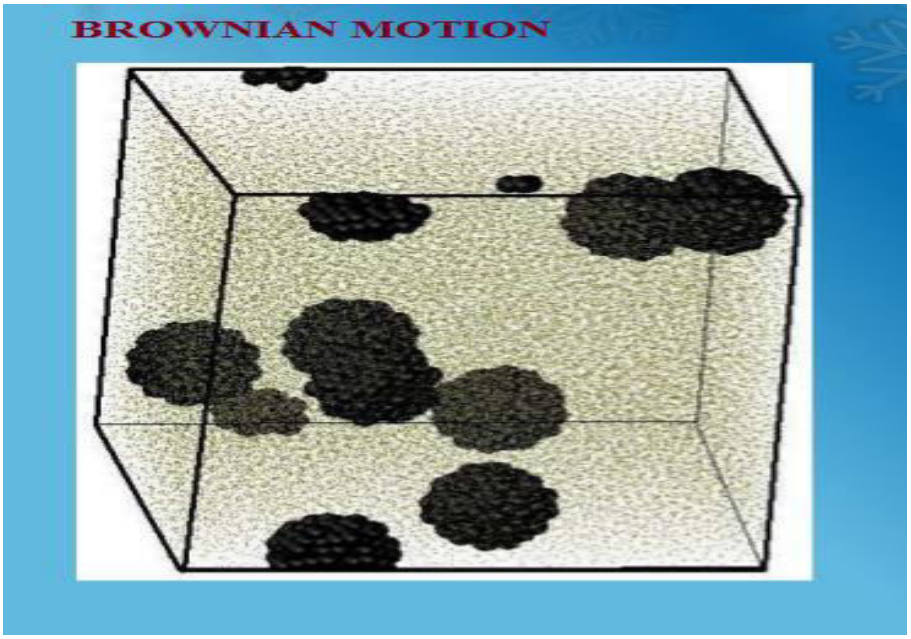

Figure-4 (Brownian motion of nanofluids) [8]

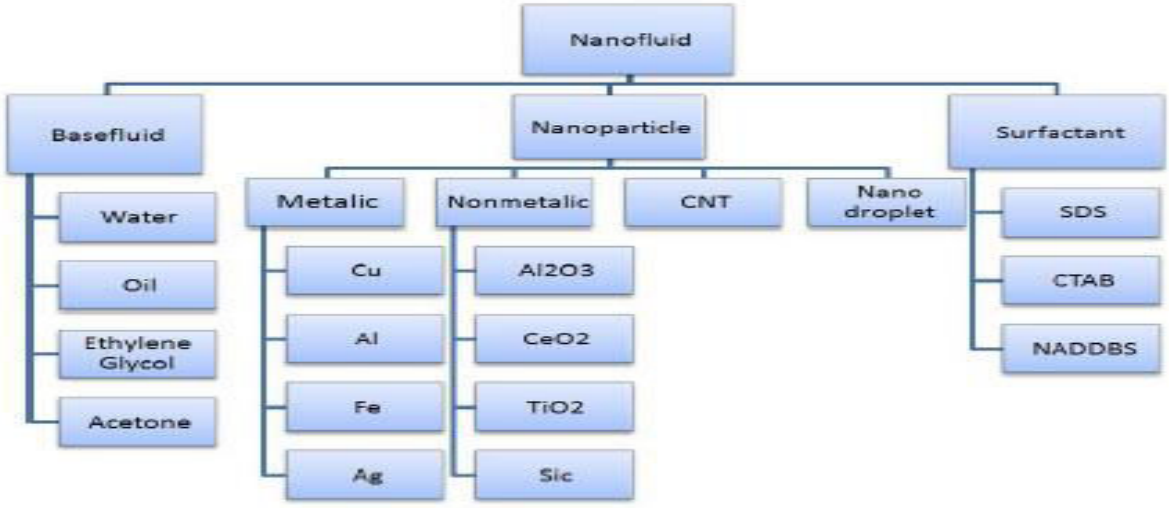

Figure-5 (Analytical chart of nanofluids)

The Thermo physical properties of the nanofluids are also much essential to analyze their heat transfer behavior. It is much important in control for the perspectives of industrial and energy saving. There is a wide industrial interest in the nanofluids. The nanoparticles have great potential to improve their thermal transport properties compared to conventional particles fluids suspension, micrometer and millimetre sized particles. In the last few years, the nanofluids have gained a significant attention due to their enhanced thermal properties. The experimental studies show that the thermal conductivity of nanofluids depends on the different factors like as material of particle, volume fraction of particle, size of particle, material of base fluid, particle shape and temperature. The amount and types of additives and the acidity of the nanofluid were shown to be much effective in thermal conductivity enhancement. The transport behavior of the nanofluid: dynamic thermal conductivity and viscosity are not only dependent on volume fraction of nanoparticle but also highly dependent on other parameters such as particle size, shape, surfactant, mixture combinations and slip mechanisms etc. The analysis shows that the thermal conductivity and viscosity both increases by use of nanofluid compared to base the fluid. So far the various experimental and theoretical studies have been conducted and a lot of correlations have been proposed for the thermal conductivity and the dynamic viscosity of the nanofluids. However, no uniform correlations have been established due to lack of common understanding on mechanism of the nanofluid.

The thermal properties of liquids play an important decisive role in heating as well as cooling applications in the industrial processes. The Thermal conductivity of the liquid is an important physical property which decides its heat transferring performance. The conventional heat transfer fluids have the poor thermal conductivity that makes them inadequate for the ultra high cooling applications. The various scientists have tried to enhance the inherently poor thermal conductivity of these heat transfer fluids by using the solid additives following the classical effective medium theory (Maxwell, 1873) for effective properties of the mixtures. The fine tuning of dimensions of these solid suspensions to millimeter and micrometer ranges for getting better heat transfer performance have failed due to drawbacks such as still particle sedimentation, low thermal conductivity, particle clogging, corrosion of components of machines, excessive pressure drop etc. The downscaling of particle sizes continued in search for new types of fluid suspensions having enhanced thermal properties and also heat transfer performance. All physical mechanisms have a critical scale below that the properties of the material changes. Now the modern nanotechnology offers chemical and

physical routes to prepare nanostructured materials or nanometer sized particles engineered on the molecular or atomic scales with enhanced thermo-physical properties compared to their respective bulk forms. Choi (1995) and other researchers (Masuda *et al.,* 1993; Lee *et al.,* 1999) have observed that it is possible to break the limits of the conventional solid particle suspensions by considering the definition of nanoparticle fluid suspensions. These nanoparticle fluid suspensions are said as nanofluids, obtained by dispersing the nanometer sized particles in the conventional base fluid like oil, ethylene glycol, water etc. The nanoparticles of materials like metallic oxides (CuO, Al2O3), nitride ceramics (AlN, SiN), carbide ceramics (TiC, SiC), metals (Ag, Cu, Au), semiconductors (SiC, TiO2), single, double or multi walled carbon nanotubes (DWCNT, SWCNT, MWCNT), alloyed nanoparticles (Al70Cu30) etc. have been used for preparation of the nanofluids. These nanofluids have been found to give an enhanced thermal conductivity (Eastman *et al.,* 2001; Choi *et al.,* 2001; Shyam *et al.,* 2008) as well as improved heat transfer performance (Artus, 1996; Xuan *et al.,* 2003; Yu *et al.,* 2003; Vassalo *et al.,* 2004) at the low concentrations of nanoparticles. Even at the very low volume fractions (< 1/10 %) of suspended particles, attractive enhancement up to the limit of 40% in the thermal conductivity has been reported on these nanotechnology based fluids (Wang *et al.,* 1999) and the enhancement percentage is observed to increase with temperature (Das *et al.,* 2003) and also concentration of the nanoparticles (Shyam *et al.,* 2008). The effective thermal conductivity of these nanofluids are expressed as a normalized thermal conductivity value obtained by dividing the overall thermal conductivity of nanofluid by the base fluid thermal conductivity or sometimes as a percentage of the effective value with respect to base fluid value [7].

In the present analysis, there is emphasis on the concentration of the stationary fluids. Then to provide an estimate for contribution of the Brownian motion induced nanoscale fluid flow to the thermal conductivity, let us assume that the entire volume of the fluid diffuses together with nanoparticles and that the velocity of fluid is the same as that of the velocity of the particles. On considering these assumptions, that overestimate the actual magnitude of fluid velocity field, a well known kinetic theory formula gives Brownian motion induced contribution to thermal conductivity, κ_B, as given:

$$\kappa_B = D_B c_p, \tag{1}$$

Where c_p is the heat capacity of the fluid per unit volume at the constant pressure, and D_B is the diffusivity of the nanoparticles. One should note that due to the much higher volume of the fluid at the low particle volume fraction, the particles themselves carry much less heat than the fluid moving together with the particles. So, we can neglect the direct contribution of particle Brownian motion to the thermal transport. The thermal conductivity of base fluid, κ_F can be also written in the form of eq. (1) as:

$$\kappa_F = D_T c_p, \tag{2}$$

where D_T is the thermal diffusivity of the fluid defined as:

$$D_T = \kappa_F / c_p.$$

The ratio of κ_B to κ_F can be evaluated by combining the equations (1) and (2), as follows:

$$\kappa_B / \kappa_F = D_B / D_T, \tag{3}$$

i.e., the ratio of the Brownian motion contribution to thermal conductivity to the thermal conductivity of the base fluid is given by the ratio of nanoparticle diffusivity to the fluid thermal diffusivity [8].

Wide ranges of the experimental and theoretical analysis were conducted in literature to model thermal conductivity of the nanofluids. The existing results were normally based on the concept of the effective thermal conductivity of a two component mixture. The Maxwell (1881) model was the first models that proposed for solid and liquid mixture with relatively large particles. It was based on solution of heat conduction equation through a stationary random suspension of spheres. The effective thermal conductivity is given by the equation as follows [6]:

$$k_{eff} = \{k_p+2k_{bf}+2\phi(k_p-k_{bf})\}\ k_{bf} / \{k_p+2k_{bf}-\phi(k_p-k_{bf})\} \quad (4)$$

Where k_p is the thermal conductivity of the particles, k_{eff} is the effective thermal conductivity of the nanofluid, k_{bf} is base fluid thermal conductivity, and ϕ is volume fraction of the suspended particles. The suitable trend in the experimental studies is that the thermal conductivity of nanofluids increases with decreasing the particle size. This trend is theoretically supported by two mechanisms of the thermal conductivity enhancement; the Brownian motion of nanoparticles and liquid layering around nanoparticles (Ozerinc et al, 2010) [5]. However, there is also a suitable amount of contradictory data in some analyses that indicate decreasing thermal conductivity with decreasing the particle size. The different results illustrated neither agreement about mechanisms for heat transfer enhancement nor a unified possible explanation related to the large discrepancies in the results even for same base fluid and nanoparticles size. There are various models available so for in context to the measurement of the effective thermal conductivity of nanofluids (Wang and Mujumdar, 2007) but there exists a large number of deviations between them. In the present time, there are no experimental or theoretical results available in this context to give and predicts accurately about the thermal conductivity of the nanofluids [3]. Some Nanofluids with their thermal conductivity increase in nanofluid thermal conductivity over base fluid thermal conductivity and synthesis procedure used as reported in some analyses are shown in the table-1. [4]

Table -1.

Particle Type	Base Fluid	Particle Volume Fraction (%)	Particle Size (nm)	Maximum Enhancement (%)	Temp.	Reference
Al_2O_3	Water	1.30-4.30	13	32.4	≥31.85ºC	Masuda et al. [9]
Al_2O_3	Water	1.00-4.30	38.4	10	Room temp.	Lee et al. [10]
Al_2O_3	Water	1.00-5.00	38.4	18	Room temp.	Lee et al. [10]
Al_2O_3	Water	3.00-5.50	28	16	Room temp.	Wang et al. [12]
Al_2O_3	Water	5.00	60.4	23	Room temp.	Xie et al. [14], [15]
Al_2O_3	Water	1.00-4.00	38.4	24	Room temp.	Das et al. [13]
Al_2O_3	Water	2.00-10.00	36	29	27.5ºC-34.7ºC	Li et al. [11]

3. Conclusion

We have analyze a kinetic theory argument and also the results of molecular dynamics simulations, both leading to the conclusion that the thermal conductivity of a nanofluid with well dispersed nanoparticles is well described by the effective medium theory and does not show any significant enhancements due to their effects associated with Brownian motion induced hydrodynamic effects.

Our conclusions are in agreement with results of various experiments on thermal conductivity of suspension of well dispersed metal nanoparticles, and suggest that other effects, such as particle clustering, are responsible for large thermal conductivity increases observed in some "experiments".

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