Role of Brownian motion and Thermophoresis in the improvement of thermal conductivity of nanofluids – A precise review

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Abstract

The thermophysical properties such as dynamic viscosity, thermal conductivity, specific heat, etc., of a nanofluids, having the uniform suspension of solid particles of nanosized and based fluid as a component, depends on the various parameters. The primary reason to use nanofluids is the improvement in the thermal conductivity of the working fluid in the heat transfer processes. Different parameters affect the variation in thermal conductivity, such as Brownian motion, nanolayer, thermophoresis, size and concentration of nanoparticles. The present study provides a very precise review on the theoretical models predicting the improvement in the thermal conductivity of the working fluid due to the suspension of solid nanoparticles as a function of the Brownian motion and thermophoresis mechanisms. It follows that the Brownian motion contributes in the improvement of the thermal conductivity of nanofluid, while a very small effect of thermophoresis was found with the observation that thermophoresis effect was not a function of the nanoparticle size.

Keywords: *Nanofluid, thermal conductivity, Brownian motion, thermophoresis.*

INTRODUCTION

The advancement in the area of nanotechnology motivated Choi (1995) to use the nano-sized solid particles instead of micron sized solid particles and found an improvement in the thermal conductivity without the sedimentation or clogging of application area. After his contribution, many researches organized to explore the importance of nanofluids in the heat transfer processes and observed the rise in the thermal conductivity. Puliti et al. (2011) reported that the thermal conductivity of nanofluids is affected by various variables such as material, size, shape, concentration, temperature, dispersion in base fluid, stability, and clustering of nanoparticles along with the pH variation, chemical additives and surfactant. To explore the effect of nanoparticles on the thermal conductivity of base fluids, a numerous theoretical and experimental investigations have been organized. These investigations were attentive to determine the dependency of thermal conductivity on the thermal and physical properties of nanoparticles.

Numerous investigations are discussed in the literature to evaluate the thermal conductivity of suspension, but still some controversy is existed on some issues such as suitability or adequacy of classical models. The theoretical approaches considered only the thermal conductivity of nanoparticle, shape and concentration of nanoparticles with the temperature to estimate the thermal conductivity of nanofluids. Kumar et al. (2015) categorized the proposed models to estimate the thermal conductivity of suspension, such as classical models, modelling approaches, extension of conduction models, mixed convection, and based on nano-convection due to the random movement of nanoparticles. Further, the thermal conductivity of nanofluid is defined as the amalgamation of static thermal conductivity and dynamic thermal conductivity. In static thermal conductivity, the effect of nanoparticle and electric double layer, an ordered layer of liquid surrounded the nanoparticle, are investigated, whereas the variation in thermal conductivity as an effect of nanoparticles motion due to the convection, comes under the dynamic part of thermal conductivity. Puliti et al. (2011) conducted a review on the properties of nanofluids and found that four mechanisms: Brownian motion, nanolayer, aggregation and radiative heat transfer are responsible for the improvement in the thermal conductivity.

EFFECT OF BROWNIAN MOTION

In 1827, Robert Brown, a Scottish biologist, notified the zigzag motion of pollen grains in water but did not recognise the reason behind the motion. In 1906, Einstein predicted a relation between the Brownian motion and size of suspended spherical solid particle based on the kinetic theory and calculated the diffusion coefficient for the spherical particle. The Brownian motion can be defined as stochastic movements of small solid particles suspended in the base fluid where the solid particles colloid with each other, transfer the momentum, and resulted in the chaotic and non-directed movements.

Jang and Choi (2004) investigated the role of Brownian motion on the thermal conductivity of nanofluids by taking the four modes of energy transport in account for nanofluids. These modes consisted the collision between the molecules of base fluid, thermal diffusion in nanoparticles in base fluid, particle – particle collision due to Brownian motion and interaction between the nanoparticles and base fluid molecules due to thermal diffusion. The effect of collision between the nanoparticles due to Brownian motion on the thermal conductivity of nanofluids was very small than the other modes, hence it was neglected, and a model was proposed based on the remaining three modes to estimate the thermal conductivity of nanofluids, as given in equation 1.

$$k_{nf} = k_{bf}(1-\phi) + k_p\phi + 3C_1\frac{d_{bf}}{d_p}k_{bf}Re_{d_p}^2 Pr\phi \qquad (1)$$

Where C_1 is proportional constant, *Re*is Reynolds number, *Pr* is Prandtl number. The Reynolds number can be defined as

$$Re_{d_p} = \frac{Vd_p}{\nu} = \frac{\rho k_B T}{3\pi\mu^2 d_p l_{bf}} \qquad (2)$$

Where l_{bf} is the mean free path for the water molecule.

The thermal conductivity of suspension was found to be increased with the particle concentration and particle's thermal conductivity while increment was higher for the base fluids of lower thermal conductivity. Xiao et al. (2013) proposed an analytical model to predict the thermal conductivity of nanofluids by considering the fractal distribution of nanoparticles in base fluid, as given by equation 3.

$$k_{nf} = \frac{k_{bf}[k_p - 2\phi(k_{bf} - k_p) + 2k_{bf}]}{k_p + \phi(k_{bf} - k_p) + 2k_{bf}} + \frac{Cd_{bf}k_{bf}\left[\frac{3}{\propto}\sqrt{\frac{2k_BT}{\pi\rho_p}}\frac{\left(K^{\frac{1}{2}-d_f}-1\right)d_f^{1/8}}{2d_f-1} + \frac{\left(K^{1-d_f}-1\right)\left(4-d_f\right)^{1/8}d_{np,av}^{1/2}}{d_f-1}\right]}{Pr\left(1-K^{2-d_f}\right)\left(4-d_f\right)^{3/8}\left(2-d_f\right)^{-1}d_f^{-1/4}d_{np,av}^{3/2}} \quad (3)$$

Where C is a constant relevant to the thermal boundary layer and equal to 236, K is a constant, equal to 10^{-3}, d_f is fractal dimension of nanoparticles, $d_{np,av}$ is average diameter of nanoparticles, α is thermal diffusion coefficient, ρ_p is density of nanoparticle, d_{bf} is equivalent diameter of base fluid molecule. The first and second terms of the right side in equation 1 are the thermal conductivity due to stationary nanoparticles dispersed in base fluid and by heat convection due to the Brownian motion of nanoparticles, respectively. Based on the equation 3, Xiao et al. (2013) found a reduction in the thermal conductivity due to increased particle size. The large particles lead in a decreased Brownian motion and less convection due to nanoparticles occurred. The significance of Brownian motions on the improvement in the thermal conductivity of nanofluids was only found for nanoparticles smaller than the 16 nm diameter. Another observation was found that the thermal conductivity increased with the temperature as a decrease in the viscosity of nanofluid and resulted in the enhanced Brownian motion of nanoparticles, and consequently, the convection due to nanoparticles is increased. The results observed by Xiao et al. (2013) were similar to the Jang and Choi (2004), like the thermal conductivity of nanofluid is increased with the temperature and the increment was higher for the smaller particles than the larger.

Prasher et al. (2006) reported a theoretical model based on the convection-conduction, known as multi-sphere Brownian model based on the Brownian motion to predict the thermal conductivity. The effect of conduction of nanoparticles, thermal resistance (R_b) between the nanoparticle and base fluid, and convection contribution of nanoparticles on the thermal conductivity of nanofluid was included in the proposed model, given in equation 4,

$$\frac{k_{nf}}{k_{bf}} = (1 + ARe^m Pr^{0.333}\phi)\left(\frac{[k_p(1+2\alpha)+2k_m]+2\phi[k_p(1-\alpha)-k_m]}{[k_p(1+2\alpha)+2k_m]-\phi[k_p(1-\alpha)-k_m]}\right) \quad (4)$$

Where A and m are constants, A is independent of the fluid type, whereas m is a function of fluid type, and for water-based nanofluids, equal to 4×10^4 and 2.5 % ± 15%, respectively. The thermal conductivity of matrix is denoted by k_m, and nanoparticle Biot number is denoted by α, which is given as

$$\alpha = \frac{2R_b k_m}{d_{np}} \quad (5)$$

The primary reason of enhanced thermal conductivity of nanofluid was found as the Brownian motion of nanoparticles induced convection. The increase in temperature and particle concentration enhanced the thermal conductivity of nanofluids.

Gupta and Kumar (2007) conducted a study to determine the interparticle potential based on the stern length and interaction of the nanoparticle and base fluid. About 6 % enhancement in the thermal conductivity of nanofluid was reported only due to Brownian motion of nanoparticles without taking the thermal diffusion into account. This effect of Brownian motion is limited by the volume concentration for the particular particle diameter and become constant beyond the particle size (≥ 10 nm). The impact of Brownian motion was also investigated by the Koo and Kleinstreuer (2005) and found that the effect of Brownian motion decreases with the particle size and particle concentration. At low particle concentration (ϕ < 0.5 vol. %), the enhancement in thermal conductivity was observed independent of the particle interactions, while contradictory behaviour was reported at higher particle concentration (ϕ > 1.0 vol. %). Murshed and Castro (2011) formulated the contribution of Brownian motion in thermal conductivity of nanofluid by considering the static and dynamic mechanisms and proposed a model as given in equation 6.

$$k_{nf} = \left\{\frac{(k_p-k_{nl})\phi\left(\left(1+\frac{h}{r}\right)^3-1\right)k_{nl}\left[2\left(1+\frac{h}{2r}\right)^3-\left(1+\frac{h}{r}\right)^3+1\right]+(k_p+2k_{nl})\left(1+\frac{h}{2r}\right)^3\left[\phi\left(\left(1+\frac{h}{r}\right)^3-1\right)\left(1+\frac{h}{r}\right)^3(k_{nl}-k_f)+k_f\right]}{\left(1+\frac{h}{2r}\right)^3(k_p+2k_{nl})-(k_p-k_{nl})\phi\left(\left(1+\frac{h}{r}\right)^3-1\right)\left[\left(1+\frac{h}{2r}\right)^3+\left(1+\frac{h}{r}\right)^3-1\right]}\right\} + \left\{0.4465\rho_n C_{p_n} r\phi\sqrt{\frac{3k_BT\left(1-1.5\left(1+\frac{h}{r}\right)^3\phi\right)}{2\pi\rho_n\left(1+\frac{h}{r}\right)^3 r^3}}\right\} \quad (6)$$

The first term in the equation 6 is contribution of static mechanisms including the nanolayer, particle concentration and thermal conductivity of nanoparticle, nanolayer and base fluid, similar to given by Leong et al. (2006), and second term shows the influence of dynamic mechanisms such as Brownian motion. It was observed that the static mechanisms caused the enhancement of the thermal conductivity primarily while the contribution of Brownian motion was effective only for smaller particle size and low particle concentration. Mehta et al. (2011) modified the Maxwell model by assuming that the thermal conductivity of nanofluids depends on the micro-convection heat transfer due to the Brownian motion and thermal conductivity of nanoparticles and observed an enhancement in the thermal conductivity of nanofluid by increasing the nanoparticle size and concentration. Paul et al. (2011) also reported the role of Brownian motion in the enhancement of thermal conductivity of nanofluids. As an enhancement of 100 % in thermal conductivity was observed at high temperature of 70 °C but reduction was found by increasing the size of nanoparticles.

EFFECT OF THERMOPHORESIS

The nanoparticles, dispersed in the base fluid, tend to move from hot region to cold region and the velocity of movement depends on the temperature gradient. This behaviour of nanoparticles is known as thermophoresis and it occurs due to striking of base fluid molecules on the nanoparticles in the hot region with very high velocity than that of cold temperature region. The molecules of base fluid from both the region, hot and cold, strike the nanoparticles, but due to higher force applied by the hot region molecules, excited by the higher temperature, the nanoparticle is forced to move towards the cold region and heat convection from hot to cold region takes place. Thermophoresis is a non-equilibrium transport mechanism due to temperature gradient which is driving force of thermophoresis. Koo and Kleinstreuer (2005) compared the effect of thermophoresis with the Brownian motion and osmophoresis and formulated the contribution of thermophoresis effect in the thermal conductivity of nanofluids, as given by equation 7.

$$k_{TP} = \frac{1}{6\pi}\frac{\phi k_b}{\mu_{bf}}\frac{3k_{bf}}{k_p+2k_{bf}}\left(1\times 10^5\rho_{bf}c_{p_{bf}}\right)\Delta T \quad (7)$$

Here, ΔT denotes the temperature gradient in the base fluid. The improvement in the thermal conductivity of nanofluids due to thermophoresis was independent of the size of nanoparticles and impact of thermophoresis on thermal conductivity was less than the Brownian motion, but more than the osmophoresis. Aminfar et al. (2010) also confirmed that the effect of thermophoresis on the thermal conductivity was less than the Brownian motion of nanoparticles. A Lagrangian – Eulerian approach was applied to investigate the effect of Brownian motion and thermophoresis on the thermal conductivity of nanofluids and concluded that the velocity of nanoparticles was observed more at the wall region than that of centre due to thermophoresis and the velocity was decreased with the particle size. Further, the effect of thermophoresis on the micro-convection was observed very low than the Brownian motion.

CONCLUSIONS

Various mechanism affects the thermal conductivity of working fluid due to suspension of nanoparticles, such as nanolayer, Brownian motion, particle size and concentration, thermophoresis, etc. In the present review, primarily, the two mechanism have been discussed. Based on the review of the literature, the effect of Brownian motion and thermophoresis on the thermal conductivity of nanofluid can be summarized as:

- The Brownian motion depends particle size and temperature, as it is slow for the large size of nanoparticles and higher for small size. With the temperature, the Brownian motion of nanoparticles is increased.
- The increased size of nanoparticles resulted in the decrease of thermal conductivity due to decreased Brownian motion which caused less convection due to nanoparticles.
- Thermal conductivity improved with the temperature due to decrease in the viscosity of nanofluid and enhanced Brownian motion of nanoparticles.
- The effect of Brownian motion on the thermal conductivity was found significant when the average diameter of nanoparticles is smaller than the 16 nm and for the low particle concentration.
- The improvement in the thermal conductivity due to suspension of nanoparticles due to thermophoresis was independent of the size of nanoparticles.

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