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Impact of thermophoresis on nanoparticle distribution in nanofluids

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ABSTRACT: *This research attempts to study the effects of particle migration on concentration distribution of the water-TiO2 nanofluid inside a circular tube. The scale analysis shows that thermophoresis can have an essential role on particle migration and consequently, on concentration distribution. Therefore, the concentration distribution of particles is obtained by considering the effects of thermophoresis, non-uniform shear rate, Brownian diffusion, and viscosity gradient. The results reveal that as the particles become lar- ger, the concentration distribution becomes more non-uniform. Meanwhile, thermophoresis intensifies non-uniformity of concentration distribution and its effect is more noticeable at higher mean concentrations.*

KEYWORDS: *Nanofluids Nanoparticles Thermophoresis Particle Distribution Scale analysis*

A nanofluid is a dilute suspension of solid nanoparticles (1–100 nm) [1–5]. Over the past decade, many experimental and numerical studies have been conducted on nanofluids. Adding solid nanoparticles into a base fluid increases thermal conductivity and therefore, improves other thermal characteristics of base fluid. However, many studies have proven that the improvement rate of nanofluid thermal characteristics like convective heat transfer is higher than the thermal conductivity increment [6,7]. It means that other factors are effective on this case as well. Xuan and Roetzel [8] used from the concept of "thermal dispersion" to describe this observation for the first time. Xuan and Li [6] claimed that dispersion makes temperature distribution more uniform and consequently, increases heat transfer between the fluid and solid surface.

Beside dispersion, particle migration can also have a significant effect on concentration distribution and nanofluid characteristics. Nonetheless, very few studies have been conducted in this regard. Ding and Wen [9] evaluated the particle migration in nanofluid flow through a tube. The authors considered three factors, namely, non-uniform shear rate, viscosity gradient, and Brownian motion to determine particle distribution, while they overlooked the effect of thermophoresis. Malvandi et al. [10] investigated thermal performance of hydromagnetic alumina-water nanofluid inside a vertical microannular tube considering different modes of nanoparticle migration. It was revealed that increasing the slip velocity and magnetic field strength intensify the thermal performance, whereas increasing the ratio of inner wall to the outer wall radius, volume fraction, and heat flux ratio decrease it.

In the present study, it is firstly proved via scale analysis that thermophoresis also plays an important role in particle distribution and then, concentration distribution is obtained considering thermophoresis along with the effects of other three factors mentioned above. In the surveys that have considered thermophoresis, simulations have been performed by two-phase approaches which need a large volume of calculations. The main novelty of the present work, however, is that unlike studies conducted in this field, the effect of thermophoresis is considered together with other factors simultaneously by solving a differential equation. Moreover, the significance of this term is estimated by means of scale analysis.

Particle fluxes caused by viscosity gradient, non-uniform shear rate, and Brownian diffusion are evaluated using equations below [9,11]:

$$J_{\mathbf{I}} ¼ -K_{\mathbf{I}} c u^2 \left(\frac{d_p^2}{\mathbf{I}} \right)! \frac{d\mathbf{I}}{du} \frac{du}{dr} \qquad ð1Þ$$

$$J_c ¼ -K_c d_p^2 \left(u^2 \frac{dc}{dr} þ uc \frac{du}{dr} \right) \qquad ð2Þ$$

$$J_B ¼ -D_B \frac{du}{dr} \qquad ð3Þ$$

where $J_{\mathbf{I}}$, J_c and J_B represent the particle fluxes due to viscosity gradient, non-uniform shear rate and Brownian motion, respectively. Moreover, $K_{\mathbf{I}}$ and K_c are constants, while c, u, 1, and d_p represent the shear rate, concentration, dynamic viscosity, and particle diameter, respectively. The parameter D_B presents the Brownian diffusion coefficient obtained by:

$$D_B ¼ \frac{k_B T}{3 p \mathbf{l} d_p} \qquad ð4Þ$$

where k_B denotes the Boltzmann constant and T is the temperature.

Furthermore, particle flux due to thermophoresis is obtained through the following equation [12]:

$$J_T ¼ -D_T \frac{dT{=}dr}{T} \qquad ð5Þ$$

where D_T is the thermophoretic diffusion coefficient that can be calculated using the following equation:

$$D_T ¼ b \frac{\mathbf{l}}{q} u \qquad ð6Þ$$

where q represents density and b is evaluated by Eq. (7).

$$b ¼ 0{:}26 \frac{k}{2k þ k_p} \qquad ð7Þ$$

where subscript p refers to particle and k denotes the thermal conductivity.In the following, the order of magnitude analysis is used to determine the importance of thermophoresis and its scale is calculated compared to that of Brownian diffusion.By use of the scale analysis, the relevant terms are as below based on Eqs. (3) and (5):

$$\text{Brownian diffusion} : D_B \frac{Du}{d_{tube}} \qquad ð8Þ$$

$$J ¼ J_{\mathbf{I}} þ J_c þ J_B þ J_T \qquad ð11Þ$$

With the integration of Eq. (10) and the use of symmetry boundary condition at the tube center, we have:

$$J ¼ J_{\mathbf{I}} þ J_B þ J_c þ J_T ¼ 0 \qquad ð12Þ$$

Substituting Eqs. (1) to (3) and (5) in Eq. (12), we obtain:

$$K_{\mathbf{I}} c u^2 \left(\frac{d_p^2}{\mathbf{I}} \right)! \frac{d\mathbf{I}}{du} \frac{du}{dr} þ K_c d_p^2 \left(u^2 \frac{dc}{dr} þ uc \frac{du}{dr} \right) þ D_B \frac{du}{dr}$$

$$þ D_T \frac{dT{=}dr}{T} ¼ 0 \qquad ð13Þ$$

Eq. (13) is solved in order to determine concentration distribution, in which assuming nanofluid as a Newtonian fluid, we have:

$$c_{-} ¼ \frac{1}{2\mathbf{I}} \frac{dP}{dx} r \qquad ð14Þ$$

where P denotes the pressure.

In order to solve Eq. (13), thermal conductivity and viscosity models must be determined. The experimental model proposed by Duangthongsuk and Wongwises [14] is used for thermal conductivity. Moreover, the temperature- and concentration-dependent model presented in our previous study [15] is used for viscosity (Eq. (15)). These models have been developed for water-TiO_2 nanofluid.

$$\mathbf{I} ¼ 0{:}009093894\ T^{-0:721707} ðu þ 1Þ^{0:258153} \qquad ð15Þ$$

Thermophoresis : $D_T \frac{\mathrm{D}T}{Td_{tube}}$ ð9Þ

where the required scales are as follows:

$\mathrm{u} \sim 10^{-2}; \mathrm{Du} \sim 10^{-2}; T \sim 10^2; \mathrm{D}T \sim 10; d_{tube} \sim 10^{-3}; k_p \sim 10;$

$k \sim 1; \mathrm{l} \sim 10^{-3}; \mathrm{q} \sim 10^3; k_B \sim 10^{-23}; d_p \sim 10^{-8}$

Considering the scales above, the scales of Brownian diffusion coefficient and thermophoresis diffusion coefficient are obtained via Eqs. (4) and (6) as below:

$D_B \sim 10^{-11}$ and $D_T \sim 10^{-10}$

Therefore, according to Eqs. (8) and (9), orders of Brownian diffusion and thermophoresis will be 10^{-10} and 10^{-8}, respectively. It is found that thermophoresis can have stronger effects on particles compared to that of Brownian diffusion and thus, its effect should not be overlooked. Hence, the current study considers particle fluxes caused by all the four mentioned factors to find particle distribution. Malvandi and Ganji [13] have also evaluated the effects of Brownian diffusion and thermophoresis on particle migration by use of two-component, four-equation Buongiorno model.

It should be noted that for evaluation above, the scale of d_p has been assumed 10^{-8} and according to Eq. (4), change of particle size modifies significance of Brownian motion in comparison with that of thermophoresis.

For nanofluid flow within a tube that is steady-state and fully developed, mass balance for the particle phase gives:

$J þ r \frac{dJ}{dr}$ ¼ 0 ð10Þ

where r represents the radial coordinate and J is the total flux of particles in r direction.

In the above equation, the particle phase is considered as continuous. As stated before, the total flux of particle migration is caused by four factors:

To solve Eq. (13), a boundary condition is needed and achieved by:

u_m ¼ $\frac{\mathrm{R}\ \mathrm{u}ðrÞ dA}{\mathrm{R}\ dA}$ ð16Þ

where u_m represents the mean concentration.By solving Eq. (13), the nanoparticle distribution is obtained for nanofluid flow inside the tube.

Fig. 1 shows nanoparticle concentration distribution for different particle sizes at mean concentration of 1.5%. As seen, as the particles become larger, the concentration becomes more non-uniform. Non-uniform shear rate leads to the migration of particles toward the central regions of the tube. On the other hand, the Brownian force acts upon the particles against the concentration gradient direction, that is, these two factors act in the opposite direction to each other. According to Eqs. (2)–(4) by the particle enlargement, the Brownian force reduces while the shear rate effect increases. Thus at a given mean concentration, a higher con- centration is created in central regions for larger particles.

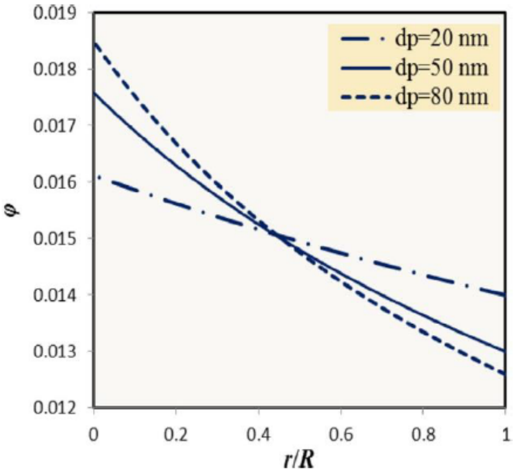
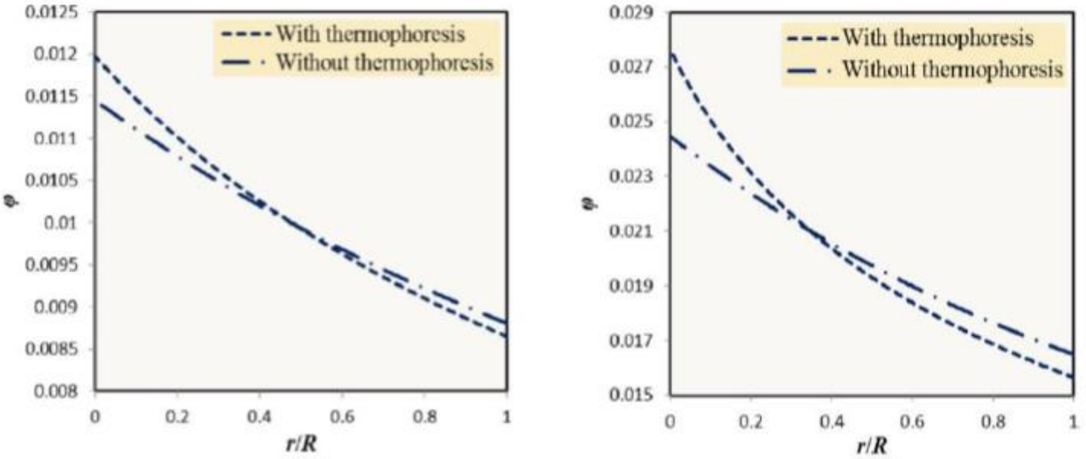


Fig. 1. Nanoparticle concentration distribution for different particle sizes at mean concentration of 1.5%.



(a) (b)

Fig. 2. Particle distribution in the cases of with and without thermophoresis for d_p = 80 nm at: a) u_m = 1%, b) u_m = 2%.

Fig. 2 shows the effect of thermophoresis on the particle distri- bution at two different mean concentrations for dp = 80 nm. As can be observed, when the effect of thermophoresis is overlooked (i.e. by eliminating the last term in Eq. (13)), the concentration distri- bution becomes more uniform. The reason is that thermophoretic force exerts on the particles in the opposite direction of the tem- perature gradient. The direction of temperature gradient is from the center of the tube toward the wall. Thus, thermophoresis makes the particles migrate toward the center of the tube. In addition, It is noticed in this figure that at higher concentration (Fig. 2b), thermophoresis is more effective and consequently, when thermophoresis is overlooked, more difference occurs in the concentration distribution, such that by neglecting thermophoresis, the maximum value of concentration at mean concentration of 1% decreases about 4.4% while it decreases about 11.5% at mean concentration of 2%.

The results of this contribution indicate that thermophoresis has a relatively significant effect on particle distribution. Although this study examines the effect of thermophoresis on nanoparticle migration in nanofluids, more studies are needed to be conducted in this area in the future.

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