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# Effects of temperature-dependent thermophysical properties on nanoparticle migration at mixed convection of nanofluids in vertical microchannels

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ABSTRACT

The current paper investigates the effects of temperature-dependent thermophysical properties on nanoparticle migration at the mixed convective heat transfer of nanofluids inside microchannels in the presence of heat generation/absorption. The chief motivations of this study are to examine different modes of nanoparticle migration induced by asymmetric heating and to evaluate how temperature dependency influences the thermophysical properties of nanofluids. To those ends, the modified, two-component heterogeneous Buongiorno's model is employed for nanoparticle-fluid suspension, which takes into account nanoparticle slip velocity relative to the base fluid originating from thermophoretic diffusion—that is, a force driven by the temperature gradient—and Brownian diffusion, or a force driven by the nanoparticle concentration gradient. Due to surface roughness within the solid–fluid interface in microchannels, a slip condition is employed at the wall surfaces to assess the non-equilibrium region near the interface. Once the fluid flow is fully developed, governing equations including continuity, momentum, energy, and nanoparticle volume fraction are simplified to ordinary differential equations and solved numerically. The results are obtained with and without consideration of the dependency of thermophysical properties upon temperature. Results indicate that neglecting the temperature dependency of thermophysical properties does not significantly influence the flow fields and heat transfer behavior of nanofluids, but changes the relative magnitudes. Moreover, unlike temperature-dependent buoyancy force, concentration-dependent one exerts considerable effects upon flow fields and nanoparticle migration. Furthermore, one-sided heating enhances the heat transfer rate anomalously, especially for larger nanoparticles.


## 1. Introduction

Colloidal suspensions of nanoparticles in base fluid, called nanofluids, possess novel properties, which make them suitable for many industrial applications [1] like pharmaceutical processes (drug delivery), surfactant and coating, cooling in heat exchangers, fuel cells, hybrid-powered engines, solar PV, and microelectromechanical systems (MEMs). These novel properties are the greater specific surface area, more stable colloidal suspension, lower pumping power for a specific heat transfer rate, reduced clogging compared to regular cooling colloids, and the ability to tune the thermophysical properties of suspensions by changing the nanoparticle materials and physical conditions, volume fraction of particles, particle size, and their shape.

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### 1.1. Theoretical modeling of nanofluids

To predict the behavior of nanofluids in convective heat transfer, various theoretical models have been proposed. The models try to respond to the three important observations from the experiments: a) abnormal increase in thermal conductivity with respect to the base fluid [2,3]; b) abnormal increase in viscosity relative to the base fluid [4,5]; and c) abnormal single-phase heat transfer coefficient with respect to the base fluid [6]. In 2006, Buongiorno [7] proposed a two-component (solid and fluid) four-equation (continuity, momentum, energy, and nanoparticle flux) non-homogeneous equilibrium model to illuminate the experimental findings. In the Buongiorno model, nanoparticle fluxes are considered in accordance with the seven slip mechanisms: inertia, fluid drainage, Brownian diffusion (or Brownian motion), thermophoresis (or thermophoretic diffusion), Magnus effect, diffusiophoresis, and gravity. Buongiorno claimed that the thermophoresis and Brownian diffusion are the crucial slip

**Nomenclature**

| | |
|---|---|
| $c_p$ | specific heat ($m^2/s^2K$) |
| $d_{bf}$ | equivalent diameter of base fluid (m) |
| $d_p$ | nanoparticle diameter (m) |
| $D_h$ | Hydrodynamic diameter (m) |
| $D_B$ | Brownian diffusion coefficient |
| $D_T$ | thermophoresis diffusion coefficient |
| $h$ | heat transfer coefficient ($W/m^2.K$) |
| $H$ | half of height of the channel (m) |
| $k$ | thermal conductivity (W/m.K) |
| $k_{BO}$ | Boltzmann constant ($=1.3806488 \times 10^{-23}\, m^2kg/s^2K$) |
| $M$ | Molecular weight of base fluid (kg) |
| $N$ | slip velocity factor |
| $N_A$ | Avogadro number |
| $Nu$ | Nusselt number |
| $N_{BT}$ | ratio of the Brownian to thermophoretic diffusivities |
| $Nr$ | mixed convection parameter |
| $p$ | pressure (Pa) |
| $q_w$ | surface heat flux ($W/m^2$) |
| Re | nanoparticle Reynolds number |
| $T$ | temperature (K) |
| $u$ | axial velocity (m/s) |
| $x,\ y$ | coordinate system |

*Greek symbols*

| | |
|---|---|
| $\phi$ | nanoparticle volume fraction |
| $\gamma$ | ratio of wall and fluid temperature difference to absolute temperature |
| $\eta$ | transverse direction |
| $\mu$ | dynamic viscosity (kg/m.s) |
| $\rho$ | density ($kg/m^3$) |
| $\lambda$ | slip parameter |
| $\varepsilon$ | heat flux ratio parameter |

*Subscripts*

| | |
|---|---|
| $B$ | bulk mean |
| $bf$ | base fluid |
| $fr$ | freezing point of base fluid |
| $p$ | nanoparticle |
| $wr$ | condition at the right wall |
| $wl$ | condition at the left wall |
| 0 | condition at ambient temperature (293 K) |

*Superscripts*

| | |
|---|---|
| * | dimensionless variable |

mechanisms in nanofluids and the other slip mechanisms can be ignored. Many researchers then studied convective heat transfer in nanofluids, after taking Buongiorno's model into consideration in different geometries—for instance, Sheremet et al. [8], Karimipour et al. [9], Yadav et al. [10], Garoosi et al. [11], and Kuznetsov and Nield [12]. Theoretical investigation on the effect of nanofluids has been systematically reported and well documented, which can be found in the open literature [13–27].

### 1.2. Nanoparticle migration effects

In 2013, Yang et al. [28,29] modified the Buongiorno's model to consider the impact of nanoparticle volume fraction on nanofluids thermophysical properties. This model does not ignore the dependency of thermophysical properties of nanofluids (including thermal conductivity and viscosity) to nanoparticles concentration. In other words, non-uniformity of the thermophysical properties has been considered. Later, Malvandi et al. [30], employed the modified Buongiorno model to assess the mutual effect of buoyancy and nanoparticle transport on the mixed convective heat transfer of nanofluids in a vertical annular channel. Then, Malvandi and Ganji [31] investigated the impacts of nanoparticle migration as well as asymmetric heating at the walls on forced convective heat transfer of magnetohydrodynamic alumina/water nanofluid in microchannels. Hedayati and Domairry [32,33] investigated the effects of nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. In the above mentioned studies, it was shown that the direction and intensity of nanoparticle migration are able to tune thermophysical properties of nanofluids to improve thermal performance of heat exchange equipment. Next, more attentions are directed toward the impact of nanoparticle migration on the thermal performance [34]. Similarly, the effects of nanoparticle migration on film boiling and condensation are studied [35–38]. The popularity of nanoparticle migration modeling can be gauged from the numerous published literatures such as [39–45].

### 1.3. Motivation and Novelty

The study of the flow with internal heat generation/absorption in nanofluids is of special interest and has several practical applications in manufacturing processes. The impact of heat generation/absorption on thermal convection is significant where there is a high temperature difference between the surface and the ambient fluid. Possible heat generation also alters the temperature distribution; for instance, the most conspicuously practical applications include the particle deposition rate in nuclear reactors, electronic chips and semiconductor wafers. In order to have a conceivable view about implementing this physical problem with the use of experimental techniques, it can be mentioned that the applied nanofluid can be provided by Electrical Explosion of Wire technique, and the nanofluid flowing inside the microchannel can be heated by an electrical heating coil wrapped around it. In this paper, an analysis is devoted to the laminar fully developed mixed convection of alumina/water nanofluid inside a vertical microchannel which is subjected to a constant volumetric internal heating. This can be accomplished, for example, by external radiation as well as viscous dissipation, or by a neutron flux in a lithium blanket that occurs in fusion reactors. The nanoparticle volume fraction distribution is obtained considering the nanoparticle fluxes originating from the Brownian diffusion and thermophoresis. As the thermophoresis is the key mechanism of the nanoparticle migration, different temperature gradients are imposed by different wall heat fluxes in which $q''_{wl}$ and $q''_{wr}$ belong to the left and right wall surfaces respectively. Because of low dimensional structures in microchannels, a linear slip condition is considered at the surfaces, which appropriately represents the non-equilibrium region near the fluid/solid interface. To improve the novelty of the paper, the effects of temperature dependency of thermophysical properties have been investigated. In order to do so, all the results are obtained with and without taking into account the dependency of nanofluids thermophysical properties to the temperature. The impacts of heat generations/absorptions, asymmetric heating, temperature-dependent thermophysical properties and different modes of nanoparticle migration on convective transport of nanofluids are of our particular interest.

## 2. Problem Description and Governing Equations

Consider a laminar steady two-dimensional fully developed flow of alumina/water nanofluid through a vertical microchannel along with a thermal asymmetry ($\varepsilon = q''_{wl}/q''_{wr}$) at the wall boundaries in the presence of a heat source/sink which is oriented along the gravitational direction. The physical model is depicted in Fig. 1, where the Cartesian coordinate x and y were aligned parallel and perpendicular to surfaces respectively. From the numerical solutions conducted by Koo and Kleinstreuer [46]