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Original Research Paper

Fully developed mixed convection of nanofluids in microtubes at constant wall temperature: Anomalous heat transfer rate and thermal performance

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ABSTRACT

This is a theoretical investigation on fully developed mixed convective flow of nanofluids inside microtubes subjected to a constant wall temperature (CWT). The modified Buongiorno model is used for the nanofluids which fully accounts for the distribution of nanoparticles concentration on thermophysical properties. The effect of nanoparticles migration originating from the nano-scale diffusivities including thermophoretic diffusion (temperature-gradient driven force) and Brownian diffusion (concentration-gradient driven force) on the thermophysical characteristics of nanofluids has been considered. A Navier's slip condition is considered at the wall to model the non-equilibrium region at the fluid-solid interface in micro-scale channels. A scale analysis is performed to estimate the relative significance of the pertaining parameters that should be included in the governing equations. The effects of pertinent parameters including the ratio of Brownian motion to thermophoresis (N_{BT}), slip parameter (λ), mixed convective parameter (Nr), and bulk mean nanoparticle volume fraction (ϕ_B) on the flow and thermal fields are investigated. The figure of merit (FoM) is used to measure the thermal performance of equipment and finding the optimum thermal condition. It is shown that increasing the buoyancy force would enhance the heat transfer rate, especially for the larger nanoparticles. Also, larger nanoparticles enhance the thermal performance based on a required heat transfer rate with the lowest penalty in the pressure drop.

1. Introduction

Nanofluids (colloidal suspensions of nanoparticles in base fluid) possess novel properties including 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 adjust the thermophysical properties of suspensions by changing the nanoparticle materials and physical conditions [1], volume fraction of particles, particles size, and their shape. These novel characteristics make nanofluids suitable for several industrial applications such as pharmaceutical processes (drug delivery), surfactant and coating, cooling in heat exchangers, fuel cells, hybrid-powered engines, solar PV, and microelectromechanical systems (MEMs).

Several theoretical models have been introduced so far to calculate the behavior of nanofluids on convective heat transfer. The proposed models, however, depend on certain inputs from experimental observations. Each model acquiring the best conformity to the experimental observations is construed as an accurate model by those researchers. In the literature, the heat transfer coefficients were determined by modeling the nanofluid as either single or two-phase flow. The most important findings from the experiments are: (a) an abnormal increase in the thermal conductivity of nanofluids with respect to the regular fluid [2]; (b) an abnormal increase in the viscosity of nanofluids relative to the regular fluid [3]; and (c) an abnormal single-phase heat transfer coefficient of nanofluids with respect to the regular fluid [4]. In 2006, Buongiorno [5] proved that the single-phase model as well as the dispersion models cannot accurately follow the experimental observations. Accordingly, he proposed a two-component (solid and fluid) four-equation (continuity, momentum, energy, and

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Nomenclature

c_p	specific heat capacity (m^2/s^2 K)
d_p	nanoparticle diameter (m)
D_B	Brownian diffusion coefficient
D_T	thermophoresis diffusion coefficient
FoM	figure of merit
g	gravity (m/s^2)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
k_{BO}	Boltzmann constant ($= 1.3806488 \times 10^{-23}$ m^2 kg/s^2 K)
N	slip velocity factor
Nr	mixed convective parameter
Nu	Nusselt number
N_{BT}	ratio of the Brownian to thermophoretic diffusivities
P	pressure (Pa)
q_w	surface heat flux (W/m^2)
R_o	outer radius (m)
T	temperature (K)
u	axial velocity (m/s)
x, r	coordinate system

Greek symbols

ϕ	nanoparticle volume fraction
γ	ratio of wall and fluid temperature difference to absolute temperature
η	transverse direction
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
λ	slip parameter

Subscripts

B	bulk mean
bf	base fluid
p	nanoparticle
w	condition at the wall

Superscript

$*$	dimensionless variable

nanoparticle flux) heterogeneous equilibrium model to illuminate the experimental findings. In the Buongiorno model, nanoparticle fluxes are considered in accordance with the two important slip mechanisms: Brownian diffusion (or Brownian motion) and thermophoresis (or thermophoretic diffusion). Next, after taking Buongiorno's model into consideration in different geometries, several investigations are performed on the convective heat transfer in nanofluids; for instance, Sheremet et al. [6], Yadav and Linho [7], Sheikholeslami et al. [8,9], Sandeep and Malvandi [10], Garoosi et al. [11], and Nield and Kuznetsov [12]. Dinarvand et al. [13] probed the double-diffusive mixed convective boundary layer flow of a nanofluid near stagnation point region over a vertical surface with taking account of the Buongiorno's model. Theoretical investigation on the effect of nanofluids has been systematically reported and well documented, which can be found in the open literatures [14–19]. Moreover, many researches such as Sheremet and Pop [20–22], Sheremet et al. [23] and Bondareva et al. [24] have been carried out on convective heat transfer in nanofluids under effects of the Brownian diffusion and thermophoresis. Comprehensive review papers on the application of nanofluids are conducted by Sheikholeslami and Ganji [25], Bahiraei [26], and Salman et al. [27].

Yang et al. [28] was modified the Buongiorno model to examine the impact of nanoparticle distribution on the thermal conductivity and viscosity of nanofluids. Their proposed modified model did not ignore the dependency of thermophysical properties of nanofluids to the nanoparticles volume fraction. Their results indicated that the non-uniformity of the thermophysical properties is the reason for the anomalous heat transfer enhancement. Malvandi and Ganji [29], then, used the modified model to examine the mutual impacts of buoyancy and nanoparticle migration on the mixed convection of nanofluids in vertical annuli. Subsequently, Malvandi and Ganji [30] investigated the laminar flow and convective heat transfer of alumina/water nanofluid inside a circular microchannel in the presence of a uniform magnetic field. Their results indicated that the nanoparticles migrate from the heated walls to the core region of the microchannel and form a non-uniform nanoparticles distribution. It was further observed that for smaller nanoparticles, the nanoparticle volume fraction is more uniform and abnormal variations in the heat transfer rate vanish. Hedayati and Domairry [31] investigated the effects of the nanoparticle migration on titania/water nanofluids in horizontal and vertical channels. Recently, Malvandi and Ganji [32] took advantage of the modified Buongiorno model so as to evaluate the effects of temperature-dependent thermophysical properties on nanoparticle migration inside microchannels at the mixed convective heat transfer of nanofluids. The popularity of modeling the nanoparticle migration can be gauged from the numerous published literatures such as [33–38].

The current study is motivated by the need to examine the detailed behavior of nanoparticles movements for nanofluid flow inside circular microchannels and how they can tune the thermal performance and heat transfer rate. Recently, Malvandi and Ganji [39] demonstrated that because of thermophoresis, asymmetrically heated walls are able to tune and control the fluid flow and heat transfer characteristics of nanofluids. Moreover, the rate of heat transfer enhancement can be controlled by adjusting the heat flux at the boundaries. These observations show that thermal boundary condition is a salient factor on heat transfer characteristics of nanofluids. Consequently, in the current investigation, a constant wall temperature is prescribed at the wall, which is an important development for the modified Buongiorno model [28,29]. The fully developed governing equations of the modified Buongiorno model for the constant wall temperature are obtained for the first time and the results for the pressure drop and the heat transfer enhancement are presented versus varying pertinent parameters. Due to the low dimensional structures in microtubes, a linear slip condition is considered at the surfaces, which adequately represents the non-equilibrium region at the fluid/solid interface. To study the thermal performance, the figure of merit (FoM) is calculated to signify it. The impact of constant wall temperature at the wall on nanoparticle migration, the heat transfer rate as well as the thermal performance is of our particular interests.

2. Problem formulation

The geometry of the problem under consideration with the adapted coordinate system is demonstrated in Fig. 1. To give a more physical outlook of the problem, the distributions of velocity and nanoparticle volume fraction are schematically illustrated. The cylindrical coordinates x and r were aligned parallel and perpendicular to the wall respectively. The slip velocity is considered at

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