Journal of Molecular Liquids 209 (2015) 531–538

Contents lists available at ScienceDirect

Journal of Molecular Liquids

journal homepage: www.elsevier.com/locate/molliq

Effect of particle migration on flow and heat transfer characteristics of magnetic nanoparticle suspensions

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A R T I C L E I N F O

Article history:
Received 11 April 2015
Received in revised form 2 June 2015
Accepted 8 June 2015
Available online xxxx

Keywords:
Magnetic nanofluid
Particle migration
Turbulent flow
Heat transfer

A B S T R A C T

Flow and heat transfer characteristics of the suspensions containing Fe_3O_4 magnetic nanoparticles have been evaluated in turbulent flow regime. The effects of particle migration which lead to non-uniform concentration distribution have been considered in the simulation. For this purpose, the effects of Brownian motion, shear rate and viscosity gradient have been taken into account on diffusion of the particles. By applying the effects of particle migration, the amount of concentration at the wall vicinity will be lower than that at the tube center. Non-uniformity of the concentration distribution is more significant for the coarser particles. Meanwhile, this non-uniformity intensifies by increasing mean concentration and Reynolds number. Thermophysical properties of the suspension also demonstrate a non-uniform distribution. Nusselt number increases by raising the Reynolds number and mean concentration. The effect of concentration on Nusselt number reduces at higher Reynolds numbers. The increase of the concentration will raise the friction coefficient, which has an almost similar trend at various Reynolds numbers. The results obtained are properly consistent with the experimental results.

1. Introduction

Suspensions are one of the most important mixtures which are used in various industries. Particle migration is of significant importance in flow of suspensions. Several studies have been conducted on the mechanisms of particle migration in suspensions containing micron-sized particles. A phenomenological model for particle migration was first proposed by Leighton and Acrivos [1,2] in a shear-induced flow, which assigned the particle migration to irreversible interactions. They offered an expression for diffusion flux of particles in a simple shear flow [1]. Thereafter, Phillips et al. [3] modified this expression and transformed it into a diffusion equation to find the particle concentration. Lam et al. [4] examined particle migration in concentrated suspensions of micron-sized particles. They concluded that the concentration has the minimum value adjacent to wall and quickly increases to reach its maximum at $r/R \approx 0.8$–0.9, followed by an additional reduction toward the center of the tube. This observation was attributed to shear-thinning effect of the concentrated suspensions. The studies implemented so far show that the suspensions with spherical particles have a non-uniform concentration distribution in a non-homogeneous shear flow [1,5–9]. Some researchers have utilized Laser Doppler Anemometry (LDA) techniques in their works [10,11]. Phillips et al. [3], Abbot et al. [12] and Chow et al. [13] measured the concentration profiles for concentrated suspensions in a gap Couette device using nuclear magnetic resonance.

Unlike suspensions containing micron-sized particles, a few studies have evaluated particle migration in suspensions containing nanoparticles (or nanofluids). Nanoparticle-containing flows are seen in an extensive range of engineering problems. The research on nanofluids has become one of the hottest area in engineering [14]. Particularly, the nanoparticle-containing flows in pipes have numerous applications such as enhanced heat transfer in heat exchangers and cooling of electronic devices. Their marvelous enhancement in heat transfer has been the most important reason for widespread use of nanofluids in recent years. A literature review reveals that the enhanced heat transfer induced by nanofluids can be caused by the presence of nanoparticles in base fluid [15], Brownian and thermophoresis diffusions [16], increased thermal conductivity [17], energy transfer via nanoparticle dispersion [18,19] as well as molecular-level layering of the liquid at the liquid–particle interface [20].

Some controversial results are found in the literature associated with nanofluids [21]. Therefore, it is very important to understand the flow behavior and particle migration in nanofluids in order to make application of nanofluids feasible in the near future. How the nanoparticles move in nanofluid as a heat transfer medium is of great importance. Wen and Ding [22] investigated movement of the nanoparticles in laminar pressure-driven pipe flows for dilute suspensions. They demonstrated that the particle concentration near the wall is noticeably lower than that at the tube center. Buongiorno utilized a model comprised of four equations to consider the effects of particle migration in nanofluids [16].

Two different approaches have been adopted in the literature to simulate flow and heat transfer of nanofluids, namely single-phase and two-phase. The former considers nanofluid as a homogeneous fluid

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http://dx.doi.org/10.1016/j.molliq.2015.06.030
0167-7322/

Nomenclature

A	area (m^2)
c_p	specific heat (J/kg K)
D	diameter of tube (m)
D_b	Brownian diffusion coefficient (m^2/s)
d_p	diameter of nanoparticles
f	friction coefficient
h	convective heat transfer coefficient (W/m^2K)
J	total particle flux (m/s)
J_μ	particle flux due to viscosity gradient (m/s)
J_c	particle flux due to non-uniform shear rate (m/s)
J_b	particle flux due to Brownian motion (m/s)
K_c	constant
K_μ	constant
k	thermal conductivity (W/m K)
k_B	Boltzmann's constant (J/K)
L	length of tube (m)
Nu	Nusselt number
P	pressure (Pa)
Pe	Peclet number
Pr	Prandtl number
q''	wall heat flux (W/m^2)
R	radius of tube (m)
Re	Reynolds number
r	radial coordinate
T	temperature (K)
$\mathbf{v}$	velocity (m/s)
z	axial direction
Greek letters	
$\dot{\gamma}$	shear rate (1/s)
ε	rate of dissipation (m^2/s^3)
κ	turbulent kinetic energy (m^2/s^2)
μ	dynamic viscosity (kg/ms)
μ_t	eddy viscosity (kg/ms)
ρ	density (kg/m^3)
φ	volume concentration
φ_m	mean volume concentration
Subscripts	
w	wall
b	bulk

with effective properties, assuming that solid and liquid phases are at thermal equilibrium with zero relative velocity. On the other hand, the latter takes into account relevant forces and interactions between solid particles and base fluid. The implemented studies show that one may achieve results close to experimental ones by homogeneous assumption since the particles are very small [23,24]. Although the two-phase approach provides very good results [25–27], it requires a great calculation time.

Particle migration may cause non-uniformity in particle distribution for flowing nanofluids, which will in turn affect the overall heat transfer performance. When the concentration shows non-uniform distribution at a specific cross section, the effective properties will also incorporate non-uniform distributions. Therefore, application of a proper concentration distribution is crucially important in analysis of nanofluid problems, which has been overlooked in the single-phase approach. The studies which have employed the single-phase approach so far, have considered a uniform particle distribution. However, the particles can migrate under the conditions of shear and viscosity gradient [1], such that using the uniform concentration will introduce error to the results.

In order to find the concentration distribution, it is required to take into account the effective mechanisms on particle migration. Applying the effects of particle migration in the single-phase approach can lead to acceptably accurate results with lower computational volume in comparison with the two-phase approaches. The key point in the single-phase method is the use of correct effective properties in the conservation equations.

One of the methods that can be used to control the heat transfer process is to apply magnetic fields [28]. Rashidi and Keimanesh [29] applied the differential transform method (DTM) and Pad'e approximant to construct analytical approximate solutions of the heat transfer in a liquid film over an unsteady stretching surface with viscous dissipation in the presence of external magnetic field. They showed that the DTM-Pad'e method is an excellent method for solving MHD boundary-layer equations. Malvandi and Ganji [30] investigated the laminar flow and convective heat transfer of water/alumina nanofluid inside a parallel-plate channel in the presence of a uniform magnetic field. Their results indicated that nanoparticles move from the heated walls toward the core region of the channel. Moreover, it was shown that in the presence of the magnetic field, the near wall velocity gradients increase, enhancing the slip velocity and thus the heat transfer rate as well as the pressure drop.

Recently, magnetic nanofluids have been of much interest because of their unique optical, electronic, and magnetic properties, which can be changed by applying an external magnetic field [31]. Magnetic nanofluids, suspensions containing magnetic nanoparticles such as magnetite (Fe_3O_4), iron (Fe), nickel (Ni), and cobalt (Co), show both magnetic and fluid properties and have important applications in industries [32,33]. Magnetic nanofluids can be deemed as a new class of magnetic materials with a great potential for being used in different areas of heat transfer, medicine and nanotechnology. Just a few studies have been conducted on heat transfer characteristics of magnetic nanofluids. Parekh and Lee [34] noticed a 30% increase in thermal conductivity of Fe_3O_4 nanofluid at concentration of 4.7% in the temperature range of 25 to 65 °C. Yu et al. [35] investigated the kerosene based Fe_3O_4 nanofluids and oleic acid and achieved a 34% rise in thermal conductivity at concentration of 1%. Aminfar et al. [36] reported the hydrodynamics and thermal behavior of a magnetic nanofluid (kerosene and 4 vol.% Fe_3O_4) in a vertical tube under the effect of a non-uniform magnetic field using the two-phase mixture model. They concluded that the magnetic field with negative gradient acts similar to buoyancy force and augments the Nusselt number, while the magnetic field with positive gradient decreases it. Sundar et al. [37] studied the convective heat transfer coefficient and friction coefficient of water–Fe_3O_4 nanofluid experimentally. Two correlations were developed in their study based on the experimental data for the estimation of Nusselt number and friction coefficient.

The effects of particle migration have been rarely addressed in the literature for nanofluids. In the current study, the concentration distribution is obtained considering the effective factors on particle migration and then employed in numerical analysis in order to study flow and heat transfer characteristics of the water–Fe_3O_4 magnetic nanofluid. The effects of some parameters like particle concentration, Reynolds number and particle size are assessed. To the best knowledge of the author, this is the first study which evaluates the effects of particle migration on magnetic nanofluids.

2. Theory

The geometry under study is a circular tube. The investigation is carried out on the water–Fe_3O_4 nanofluid. There are three major mechanisms which cause particle migration in non-uniform shear flows:

- Shear-induced migration which causes particles to move from higher shear rate regions to lower shear rate regions;