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Two-phase mixture model for nanofluid turbulent flow and heat transfer: Effect of heterogeneous distribution of nanoparticles

Mohammad Amani [a], Pouria Amani [b], Alibakhsh Kasaeian [c], Omid Mahian [d,*], Wei-Mon Yan [e]

[a] Mechanical and Energy Engineering Department, Shahid Beheshti University, Tehran, Iran
[b] Department of Chemical Engineering, Faculty of Engineering, University of Tehran, Tehran, Iran
[c] Department of Renewable Energies Engineering, Faculty of New Sciences & Technologies, University of Tehran, Tehran, Iran
[d] Renewable Energies, Magnetism and Nanotechnology Lab., Faculty of Science, Ferdowsi University of Mashhad, Mashhad, Iran
[e] Department of Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei 10608, Taiwan

HIGHLIGHTS

- Two-phase mixture model of SiO_2/water nanofluids in turbulent flow is proposed.
- Heterogeneity of concentration due to crossed effect and Brownian motion are considered.
- Considering heterogeneous concentration gives more close results to experimental data.

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ABSTRACT

In this work, a two-phase mixture model for evaluation of flow and heat transfer performance of SiO_2/water nanofluids under turbulent flow was proposed by considering the heterogeneity of concentration due to crossed effect and the influences of shear rate, viscosity gradient, thermophoresis and Brownian motion on the diffusion of the nanoparticles. The effects of Peclet number, Reynolds number, nanoparticle size and nanofluid mean concentration on the distribution of nanoparticles have been evaluated. The values of thermal conductivity and viscosity as the main thermophysical properties of nanofluids changed across different layers of the liquid due to the heterogeneous distribution of concentration. It was observed that an increase in the Peclet number caused heterogeneity in the distribution of the properties. The achieved nanoparticle distribution has been implemented for analysis of nanofluid using two-phase mixture model. It was found that the effect of nanofluid concentration on the Nusselt number was more noticeable in lower Reynolds numbers due to the insignificant effect of flow momentum on heat transfer. The maximum of 43.9% enhancement in convection heat transfer was achieved by dispersion of 4% SiO_2 nanoparticles inside DI-water at $Re = 25{,}000$.

1. Introduction

Suspensions containing nanoparticles with a size of 1–100 nm have wide applicability in heating and cooling industries. During last decade, many researchers have evaluated the properties and influence of nanofluids on the heat transfer improvement in thermal systems, for example see Refs. (Colangelo et al., 2015; Milanese et al., 2016a, 2016b; Colangelo et al., 2016a, 2016b; Milanese et al., 2016; Iacobazzi et al., 2016; Amani et al., 2017a, 2017b, 2017c; Lomascolo et al., 2015; Cai et al., 2017). Flow-induced particle migration is an essential mechanism in suspension rheology in various engineering applications such as sequestration processes in porous media, chromatography, heat transfer, oil recovery, transport of sediments and composite materials, which can considerably enhance the heat transfer rate in nanofluids by modifying the thermophysical properties and intensifying the heterogeneity of concentration distribution. The homogeneous models presented for nanofluid do not consider all fluid-particle interactions in the hydrothermal analysis. Therefore, it is essential to model the nanofluid as a heterogeneous two-phase mixture and physically consider the particle movements to successfully predict the dynamics of nanoparticles as well as the mechanism of thermal transport in nanofluids.

* Corresponding author.
E-mail addresses: m_amani@sbu.ac.ir (M. Amani), pouria.amani@ut.ac.ir (P. Amani), akasa@ut.ac.ir (A. Kasaeian), omid.mahian@gmail.com (O. Mahian), wmyan1234@gmail.com (W.-M. Yan).

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Nomenclature

A	area (m^2)
d_p	particle diameter (m)
D_T	thermophoresis coefficient
D_B	Brownian diffusion coefficient
g	gravitational acceleration (m^2/s)
G_κ	generation of turbulence kinetic
J	total flux of particle migration (kg/m^2 s)
K_c, K_μ	phenomenological constants
k_B	Boltzmann's constant
Nu	Nusselt number
P	pressure (Pa)
Pe	Peclet number
q''	heat flux (w/m^2)
r	radial coordinate (m)
Re	Reynolds number
T	Temperature (K)
u	axial velocity (m/s)
V	velocity (m/s)
$\bar{V}$	time-averaged fluid velocity (m/s)
x	longitudinal component (m)

Greek letters

φ	nanoparticle fraction
ρ	density (kg/m^3)
μ	dynamic viscosity (Pa s)
λ	thermal conductivity (W/m K)
$\dot{\gamma}$	shear rate (1/s)
κ	turbulent kinetic energy
ε	rate of dissipation
σ_ε	effective Prandtl numbers for turbulent kinetic energy
σ_κ	effective Prandtl numbers for rate of dissipation
μ_t	eddy viscosity (Pa s)
η	thermal performance index

Subscripts

atm	atmosphere
B	thermophoresis
dr	drift
f	base fluid
m	mixture
nf	nanofluid
p	particle
S	non-homogenous shear rate
T	thermophoresis
μ	viscosity gradient

Lam et al. (2004) studied the poiseuille flow of shear-induced particle migration of micron-sized particles suspended in a base fluid. They observed that the shear-thinning of base fluid could improve particle migration from the higher shear rate region toward the lower shear rate region. Therefore, the minimum particle concentration was obtained adjacent to tube surface and rapidly increased up to radius ratio of 0.8–0.9 corresponding the maximum particle concentration and starts to decline to the center of the tube. Chen et al. (2004) investigated the shear-induced particle migration in a concentrated suspension using a phenomenological diffusive flux model. They revealed that particle migration plays a pivotal role to determine the flow pattern of concentrated suspensions.

Nanofluids flowing through the tubes lead to increase the heat transfer in conventional heat exchangers and heating/cooling units. This significant improvement of heat transfer is the reason of great usage of the nanofluids in the last decade. By reviewing the published studies, it is revealed that molecular-level layering of the liquid at the particle-liquid interface (Keblinski et al., 2002), energy transfer by nanoparticle dispersion (Xuan and Roetzel, 2000; Xuan and Li, 2003), increased thermal conductivity (Kasaeian et al., 2015; Raja et al., 2016) as well as Brownian motion and thermophoresis diffusion (Yang et al., 2016) have been introduced as possible reasons behind the heat transfer improvement of nanofluids. A few studies have been conducted on the effect of nanoparticle migration on heat transfer characteristics of nanofluids. Here, some of these studies are reviewed briefly. Wen and Ding (2004) studied the nanoparticle migration in laminar flow in a tube and observed that the nanoparticle concentration is smaller near the tube surface in comparison with the center of the tube. Bahiraei and Hosseinalipour (2013) studied the influence of particle migration on TiO_2 nanoparticle distribution and laminar convection heat transfer considering thermophoresis in a tube by using dispersion model. Their results showed that thermophoresis played a substantial role in the particle migration. Thermophoresis caused the velocity profile flatter and the concentration more non-uniform. Moreover, greater convection heat transfer coefficient was achieved by considering thermophoresis in all Reynolds numbers in their study. Later, Bahiraei (2016) presented a comprehensive review of investigations conducted on particle migration in nanofluids including Eulerian-Lagrangian, molecular dynamics, and Buongiorno methods. The author concluded that the results of different research groups are inconsistent.

There are two different approaches in the literature for modeling the flow and heat transfer of nanofluid i.e. single-phase and two-phase methods. In single-phase method, nanofluids are assumed as homogeneous fluids considering zero relative velocity and thermal equilibrium of liquid and solid phases. The numerical analysis using single-phase method is implemented by considering uniform particle distribution and the effective thermal conductivity, density, and viscosity of nanofluid. Some of the investigations show that the results of homogeneous assumption for nanofluids are very close to the experimental data since the nanoparticles are very tiny (Keshavarz Moraveji and Hejazian, 2012). On the other hand, some studies have implemented the two-phase method for modeling of nanofluid flow such as two-phase Euler-Lagrange model and mixture model. The former method considers the base fluid and nanoparticles as a continuous and dispersed phase, respectively. In this approach, the interaction between nanoparticles and base fluid and related forces are taken into account. The substantial issue in the mixture model is that just one setoff velocity component is solved for mixture momentum equation. In this model, the interaction between the primary and secondary phase occurs through drag, turbulence and reduction in momentum. Kakaç and Pramuanjaroenkij (2016a, 2016b) and Vanaki et al. (2016) summarized the numerical studies applying both single-phase and two-phase approaches to study the performance of nanofluids. Keshavarz Moraveji and Hejazian (2012) analyzed the turbulent forced convective heat transfer of Al_2O_3/water nanofluids in a tube using two-phase Euler-Lagrange and mixture models comparatively. According to their analysis, mixture model was more accurate than the other approach. Siavashi and Jamali (2016) conducted a numerical analysis of TiO_2/water nanofluid through annuli using two-phase mixture model in turbulent flow