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A two-phase numerical study of buoyancy-driven convection of alumina–water nanofluids in differentially-heated horizontal annuli

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ABSTRACT

A two-phase mixture model is used to study buoyancy-driven convection in differentially-heated horizontal annuli filled with alumina–water nanofluids having temperature-dependent properties, in the hypothesis that Brownian diffusion and thermophoresis are the primary slip mechanisms between solid and liquid phases. A computational code based on the SIMPLE-C algorithm is used to solve the system of the mass, momentum and energy transfer governing equations. Numerical simulations are performed using the diameter of the suspended nanoparticles and their average concentration, as well as the radii of both concentric cylinders and their temperatures, as independent variables. It is found that the thermal performance of the nanofluid increases with increasing the nanoparticle concentration up to an optimal particle loading at which the heat transfer performance has a peak. The impact of the nanoparticle dispersion on the thermal performance increases as the nanoparticle size and the radius of the inner cylinder decrease, and the radius ratio, the temperature of the cooled cylinder and the temperature difference increase. The optimal particle loading increases as the radius of the inner cylinder decreases, and the nanoparticle size, the temperature of the cooled cylinder and the temperature difference increase, being practically independent of the radius ratio. Based on the results obtained, a set of correlations is developed.

1. Introduction

Buoyancy-induced heat transfer and fluid flow in differentially-heated horizontal annuli is of great importance in several engineering applications, e.g., heat exchangers, solar collectors, thermal storage systems, and cooling of electronic devices. Among the wide number of studies performed in this area, it seems worth mentioning those executed in the late seventies by Kuhen and Goldstein [1–3]. For a review of selected works published thereafter, reference can be made to the compilation proposed by Xu et al. [4]. In recent times, a renovated interest in this topic has spurred from the possible replacement of traditional heat transfer fluids, such as water, ethylene glycol and mineral oils, with nanofluids, i.e., colloidal suspensions of solid nanoparticles, whose thermal performance is known to be higher than that of the corresponding pure base liquid.

The studies readily available in the literature on this subject were carried out numerically by Abu-Nada and co-workers [5–7], Arefmanesh et al. [8], Parvin et al. [9], Sheikholeslami and colleagues [10–12], and Yu et al. [13]. A summary of these papers is presented in Table 1. First of all, it is apparent that any listed work is based on the homogeneous or single-phase approach, in which nanofluids are treated as pure fluids. Furthermore, in all the cited studies the physical properties are assumed to be constant, except for the density variation in the buoyancy force term, which is calculated through the Boussinesq approximation. Another observation deemed to be mentioned is that in many papers the effective thermal conductivity and dynamic viscosity of the nanofluid are calculated by the Maxwell–Garnett model [14] and the Brinkman equation [15], respectively, which can lead to erroneous results, that is the case of Refs. [5,9–12]. In fact, unless the nanofluid is at ambient temperature, the Maxwell–Garnett model [14] tends to underpredict the increased thermal conductivity of the suspension, as e.g. shown in Das et al. [21], Li and Peterson [22], and Yu et al. [23]. Similarly, the nanofluid dynamic viscosity is notably underestimated by the Brinkman equation [15], as e.g. demonstrated by Chen et al. [24] and Chevalier et al. [25]. Misleading conclusions may also derive from the evaluation of the effective properties either by using correlations well outside their ranges of validity or by relying on experimental data that are in contrast with the main body of the literature results. The former case is represented by Ref. [8], in which the effective thermal conductivity and dynamic viscosity up to a 5% volume fraction of the suspended nanoparticles are calculated using a pair of correlations proposed by He et al. [18], whose range of validity is 0–1.2%. The

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Nomenclature

c	specific heat at constant pressure, J/(kg K)
D_B	Brownian diffusion coefficient, m^2/s
D_i	diameter of the inner cylinder, m
D_T	thermophoretic diffusion coefficient, m^2/s
d_f	equivalent diameter of a base fluid molecule, m
d_p	nanoparticle diameter, m
E	heat transfer enhancement
$\mathbf{g}$	gravity vector, m/s^2
h	average coefficient of convection, $W/(m^2 K)$
$\mathbf{I}$	unit tensor
$\mathbf{J}_p$	nanoparticle diffusion mass flux, $kg/(m^2 s)$
k	thermal conductivity, W/(m K)
k_b	Boltzmann constant = 1.38066×10^{-23} J/K
L	gap width, m
Le	Lewis number
M	molecular weight of the base fluid, g/mol
m	nanoparticle mass fraction
N	Avogadro number = 6.022×10^{23} mol^{-1}
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Q	heat transfer rate, W
q	heat flux, W/m^2
r	radial coordinate, m
R_i	radius of the inner cylinder, m
R_o	radius of the outer cylinder, m
Ra	Rayleigh number
Re_p	nanoparticle Reynolds number
Sh	Sherwood number
T	temperature, K
t	time, s
t_D	time required for a nanoparticle to move by a distance equal to its diameter, s
U	radial velocity component, m/s
u_p	nanoparticle Brownian velocity, m/s
$\mathbf{V}$	velocity vector, m/s
V	tangential velocity component, m/s

Greek symbols

δ	radius ratio
θ	angular coordinate, deg
φ	nanoparticle volume fraction
μ	dynamic viscosity, kg/(m s)
ρ	mass density, kg/m^3
$\boldsymbol{\tau}$	stress tensor, $kg/(m\ s^2)$

Subscripts

av	average
c	cooled cylinder, at the temperature of the cooled cylinder
eq	equivalent
f	base fluid
fr	freezing point of the base fluid
h	heated cylinder, at the temperature of the heated cylinder
max	maximum value
min	minimum value
n	nanofluid
opt	optimal value
S	solutal
s	solid phase
T	thermal

latter case is that of Refs. [6,7], wherein the effective dynamic viscosity is calculated through correlations based on the raw experimental data of Nguyen et al. [17], which appear to be overestimated. In fact, the effective dynamic viscosities measured for Al_2O_3 (d_p = 47 nm) + H_2O were higher than those measured for Al_2O_3 (d_p = 36 nm) + H_2O, that is in contrast with most published results, according to which the effective dynamic viscosity is inversely proportional to the particle size, as e. g. found by Chevalier et al. [25], and Prasher et al. [26]. On the other hand, since the data relative to d_p = 36 nm are in substantial good agreement with the results obtained by Chevalier and co-workers for d_p = 35 - nm, the data reported for d_p = 47 nm are presumably overestimated. Also the values of the dynamic viscosity of CuO (d_p = 29 nm) + H_2O detected by Nguyen and colleagues are larger than those available for water-based nanofluids with suspended nanoparticles having a diameter similar to 29 nm, such as those reported by Masuda et al. [27] for d_p = 27 nm, Pak and Cho [28] for d_p = 27 nm, and Wang et al. [29] for d_p = 28 nm. Moreover, in Ref. [7] the evaluation of the thermal conductivity of CuO + H_2O using the experimental correlation obtained for Al_2O_3 + H_2O by Chon

Table 1
Summary of the numerical studies performed on natural convection of nanofluids in differentially-heated horizontal annuli.

Year	Author(s)	Model	Properties	Nanofluid	Volume fraction φ (%)	k_n (eqn/data)	μ_n (eqn/data)	Heat transfer vs. φ	Note
2008	Abu-Nada [5]	Single-phase	Constant	Cu + H_2O Ag + H_2O Al_2O_3 + H_2O TiO_2 + H_2O	0–10	Maxwell–Garnett [14]	Brinkman [15]	Increases	
2009	Abu-Nada [6]	Single-phase	Constant	Al_2O_3 (d_p = 47 nm) + H_2O	0–9	Chon et al. [16]	Nguyen et al. [17]	Decreases	
2010	Abu-Nada [7]	Single-phase	Constant	CuO (d_p = 29 nm) + H_2O	0–9	Chon et al. [16]	Nguyen et al. [17]	Decreases	
2012	Arefmanesh et al. [8]	Single-phase	Constant	TiO_2 (d_p = 21 nm) + H_2O	0–9	He et al. [18]	He et al. [18]	Increases	(1)
2012	Parvin et al. [9]	Single-phase	Constant	Al_2O_3 + H_2O	0–15	Maxwell–Garnett [14] or Chon et al. [16]	Brinkman [15]	Increases	
2012	Soleimani et al. [10]	Single-phase	Constant	Cu + H_2O	0–6	Maxwell–Garnett [14]	Brinkman [15]	Increases	(2)
2012	Sheikholeslami et al. [11]	Single-phase	Constant	Ag + H_2O	0–6	Maxwell–Garnett [14]	Brinkman [15]	Increases	(3)
2012	Ashorinejad et al. [12]	Single-phase	Constant	Ag + H_2O	0–6	Maxwell–Garnett [14]	Brinkman [15]	Increases	(4)
2012	Yu et al. [13]	Single-phase	Constant	CuO (d_p = 30 nm) + H_2O	0–4	Koo and Kleistreuer [19]	Koo and Kleistreuer [20]	Increases	

Notes: (1) square annulus; (2) semi-annulus; (3) circular/square annulus with magnetic field; (4) circular annulus with magnetic field.