International Journal of Heat and Mass Transfer 88 (2015) 902–913

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Enhanced natural convection heat transfer of nanofluids in enclosures with two adjacent walls heated and the two opposite walls cooled

Massimo Corcione [a,*], Marta Cianfrini [b], Alessandro Quintino [a]

[a] DIAEE Sezione Fisica Tecnica, Sapienza Università di Roma, via Eudossiana 18, 00184 Rome, Italy
[b] DIMI – Università degli Studi Roma Tre, via della Vasca Navale 79, 00146 Rome, Italy

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 4 May 2015
Accepted 7 May 2015
Available online 25 May 2015

Keywords:
Nanofluid
Natural convection
Two-phase model
Thermophoresis
Square enclosure
Enhanced heat transfer

ABSTRACT

A two-phase mixture model is used to carry out a numerical study of buoyancy-driven convection in nanofluid-filled square enclosures heated laterally and underneath. The thermal performance of water-based nanofluids with suspended metal oxide nanoparticles having temperature-dependent properties is investigated in the hypothesis that Brownian diffusion and thermophoresis are the primary slip mechanisms between solid and liquid phases. The thermophoretic diffusion effects are taken into account through a correlation developed on the basis of wide sets of experimental heat transfer data available in the literature for different nanofluids. The idea upon which the present work is based originates from the main result of all the experimental studies conducted on natural convection of nanofluids in differentially-heated enclosures, whose common conclusion is that the addition of nanoparticles to a base liquid is substantially detrimental, due to the formation of two stagnant fluid layers near the top and bottom adiabatic walls. Therefore, if the horizontal walls are differentially heated instead of being perfectly insulated, the lack of stratification at the top and bottom of the enclosure, consequent to the development of two horizontal concentration boundary layers, may result in a heat transfer enhancement. 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 executed for three different nanofluids, using the diameter of the suspended nanoparticles and their average volume fraction, as well as the cavity width and the temperatures imposed at the walls, as independent variables. It is found that, due to the effects of the slip motion occurring between solid and liquid phases, the rate of heat transferred across the enclosure by the nanofluid is periodic and remarkably higher than that transferred by the pure base liquid. Furthermore, the heat transfer performance of the nanofluid relative to that of the pure base liquid increases with increasing the nanoparticle concentration up to an optimal particle loading at which the heat transfer rate has a smooth peak. The relative heat transfer enhancement is discovered to increase with increasing the nanofluid average temperature and the cavity width, and decreasing the nanoparticle size.

1. Introduction

Natural convection of nanofluids in enclosures has been abundantly investigated in the last decade, both experimentally and, above all, numerically.

The main finding of the experimental works is that the addition of nanoparticles to a base liquid is substantially detrimental, which is the case of the studies performed by Putra et al. [1], Wen and Ding [2,3], Nnanna [4], Chang et al. [5], Ho et al. [6], Hu et al. [7], and Hu et al. [8], using cavities differentially heated at sides.

For vertical enclosures, an interpretation of the cited heat transfer degradation was recently proposed by Aminfar and Haghgoo [9]. They found that, besides the development of two thin concentration boundary layers adjacent to the heated and cooled sides, the slip motion occurring between solid and liquid phases gives rise to the formation of two stagnant fluid layers near the top and bottom adiabatic walls, whose pronounced thickness results in a significant limitation of the heat transfer rate across the enclosure. Noticeably, the occurrence of such a marked stagnation at the top and bottom of the cavity was never pointed out before. In fact, most previous numerical works performed on this topic were based on the single-phase approach. On the other hand, the few studies based on the two-phase model typically relied on the use of the McNab-Meisen relation [10] for the calculation of the

* Corresponding author.
E-mail address: massimo.corcione@uniroma1.it (M. Corcione).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.05.028
0017-9310/

Nomenclature

c	specific heat at constant pressure, J/(kg K)
D_B	Brownian diffusion coefficient, m^2/s
D_T	thermophoretic diffusion coefficient, m^2/s
d_p	nanoparticle diameter, m
$\mathbf{g}$	gravity vector, m/s^2
$\mathbf{I}$	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^{-1}
Le	Lewis number
m	nanoparticle mass fraction
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Q	heat transfer rate, W
q	heat flux, W/m^2
Ra	Rayleigh number
S_T	thermophoresis parameter
Sh	Sherwood number
T	temperature, K
t	time, s
U	horizontal velocity component, m/s
$\mathbf{V}$	velocity vector, m/s
V	vertical velocity component, m/s
$\mathbf{V}_T$	thermophoretic velocity vector, m/s
W	width of the enclosure, m
x	horizontal Cartesian coordinate, m
y	vertical Cartesian coordinate, m

Greek symbols

φ	nanoparticle volume fraction
μ	dynamic viscosity, kg/(m s)
θ	period of oscillation, s
ρ	mass density, kg/m^3
$\boldsymbol{\tau}$	stress tensor, kg/(m s^2)

Subscripts

av	average
b	bottom wall, at the temperature of the bottom wall
c	cooled wall, at the temperature of the cooled wall
f	base fluid
h	heated wall, at the temperature of the heated wall
in	incoming
max	maximum value
min	minimum value
n	nanofluid
opt	optimal value
out	outgoing
S	solutal
s	solid phase
T	thermal
t	top wall, at the temperature of the top wall

thermophoretic velocity of the suspended nanoparticles, which implied an underestimation of the thermophoretic diffusion coefficient, as debated by Giddings et al. [11]. These are the main reasons why many authors, against any experimental evidence, concluded that the dispersion of nanoparticles into a base liquid produces almost always a heat transfer increase rather than a diminution - see, e.g., the compilation of selected papers collected by Corcione et al. [12]. Conversely, with the scope to overcome the disagreement between numerical results and experimental data, Aminfar and Haghgoo [9] adapted the value of the thermophoretic diffusion coefficient so as to fit a set of heat transfer measurements executed by Ho et al. [6] using a square cavity of side length 25 mm containing water suspensions of alumina nanoparticles with an average diameter of 33 nm and an average volume fraction of 0.01 and 0.03, which allowed them to properly account for the effects of the slip motion occurring between solid and liquid phases, and discover the mentioned stagnation occurrence.

According to what has been discussed earlier, we can assert that if the horizontal walls of the enclosure are differentially heated instead of being insulated, the lack of stratification at the top and bottom of the enclosure, consequent to the development of two horizontal concentration boundary layers, may result in an increase rather than a decrease in the heat transfer performance associated with the dispersion of a given concentration of solid nanoparticles into the base liquid.

Framed in this background, a numerical study on natural convection of nanofluids in square enclosures differentially heated at sides, and simultaneously heated at the bottom wall and cooled at the top wall, is carried out using a two-phase model based on the double-diffusive approach, in the hypothesis of temperature-dependent physical properties, assuming that Brownian diffusion and thermophoresis are the primary slip mechanisms between suspended nanoparticles and base liquid. In particular, the effects of the thermophoretic diffusion are taken into account through a specifically-developed correlation based on wide sets of experimental heat transfer data available in the literature for different nanofluids. Primary scope of the paper is to determine in what measure the thermal activity of the four boundary walls of the cavity results in an enhanced heat transfer rate when a nanofluid is used instead of the corresponding base liquid, and to discuss the main heat and momentum transfer features. Further aim of the present investigation is to evaluate the effects of the nature, size and average volume fraction of the suspended nanoparticles, as well as the effects of the cavity width and the temperatures imposed at the walls, on the nanofluid heat transfer performance relative to that of the pure base fluid.

2. Mathematical formulation

A square cavity of width W, filled with a water-based nanofluid containing metal oxide nanoparticles, is considered. The reference Cartesian coordinate system is defined so that the x axis is horizontal, while the y axis is vertical and pointing upwards in the direction opposite to gravity. The cavity is heated at one side, kept at a uniform temperature T_h, and cooled at the opposite side, kept at a uniform temperature T_c. As far as the horizontal boundary walls are concerned, the following couple of thermal configurations are considered: (a) both the bottom and top walls are adiabatic, denoted as configuration AA; and (b) the bottom wall is heated at temperature T_h and the top wall is cooled at temperature T_c, denoted as configuration HC. A sketch of the cavity is depicted in Fig. 1, where the coordinate system and the thermal states of the four boundary walls are also displayed. The buoyancy-induced flow is considered to be two-dimensional, laminar and incompressible, with negligible viscous dissipation and pressure work. It is assumed that the suspended nanoparticles and the base liquid are in local thermal equilibrium, and that Brownian diffusion and thermophoresis are the only slip mechanisms by which the nanoparticles can develop a significant relative