Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

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

Original Research Paper

Numerical analysis of conjugate natural and mixed convection heat transfer of nanofluids in a square cavity using the two-phase method

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form 15 March 2017
Accepted 10 April 2017
Available online xxxx

Keywords:
Natural convection
Mixed convection
Conjugate heat transfer
Nanofluid
Two phase model

ABSTRACT

In the present study, the problem of conjugate natural and mixed convection of nanofluid in a square cavity containing several pairs of hot and cold cylinders is visualized using non-homogenous two-phase Buongiorno's model. Such configuration is considered as a model of heat exchangers in order to prevent the fluids contained in the pipelines from freezing or condensing. Water-based nanofluids with Cu, Al_2O_3, and TiO_2 nanoparticles at different diameters ($25\ \text{nm} \leqslant d_p \leqslant 145\ \text{nm}$) are chosen for investigation. The governing equations together with the specified boundary conditions are solved numerically using the finite volume method based on the SIMPLE algorithm over a wide range of Rayleigh number ($10^4 \leqslant Ra \leqslant 10^7$), Richardson number ($10^{-2} \leqslant Ri \leqslant 10^2$) and nanoparticle volume fractions ($0 \leqslant \varphi \leqslant 5\%$). Furthermore, the effects of three types of influential factors such as: orientation of conductive wall, thermal conductivity ratio ($0.2 \leqslant K_r \leqslant 25$) and conductive obstacles on the fluid flow and heat transfer rate are also investigated. It is found that the heat transfer rate is significantly enhanced by incrementing Rayleigh number and thermal conductivity ratio. It is also observed that at all Rayleigh numbers, the total Nusselt number rises and then reduces with increasing the nanoparticle volume fractions so that there is an optimal volume fraction of the nanoparticles where the heat transfer rate within the enclosure has a maximum value. Finally, the results reveal that by increasing the thermal conductivity of the nanoparticles and Rayleigh number, distribution of solid particles becomes uniform.

1. Introduction

Over the past years, natural and mixed convection process has been investigated by various researchers due to its many important applications in engineering systems, including cooling of electronic equipment, solar collectors, thermal design of buildings and heat exchangers [1]. Heat exchangers are widely used in a variety of plant processes to transfer energy from one fluid or gas to another without mixing the two substances. There are several researches in literature made to study natural convection heat transfer in heat exchangers [2–5]. Dai et al. [2], Gap et al. [3], Garoosi et al. [4] and Wanget al. [5] studied natural convection heat transfer in an adiabatic enclosure containing a pair of hot and cold cylinders. They concluded that location of the hot and cold pipes has a significant impact on the heat transfer rate within the enclosure. Similar observations were reported by Deng [6] who investigated the effects of the location, segmentation and number of the hot and cold surfaces on the heat transfer rate in an air-filled enclosure. Nevertheless, the study of natural and mixed convection combined with conduction constitutes a challenge for researchers doing experimental and theoretical works. Conjugate heat transfer in natural and mixed convection is an important issue because it changes the boundary conditions as well as the heat transfer processes. Oztop et al. [7], Das et al. [8], Raji et al. [9] and Merrikh et al. [10] carried out a numerical analysis of conjugate natural convection in a square cavity. They concluded that, adding several conductive obstacles inside the enclosure have a significant impact on the maximum stream function and heat transfer rate at low values of Rayleigh numbers.

Today, efforts have been focused on the enhancement of thermal–hydraulic performance of heat exchangers while using a minimum energy input. Therefore, it is obvious that providing more efficient working fluid can mitigate the energy concerns significantly. With this aim, an innovative technique to enhance heat transfer rate by using nanofluid has been used widely in last decade. The term nanofluid represents the fluid in which metal

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http://dx.doi.org/10.1016/j.apt.2017.04.006
0921-8831/

Please cite this article in press as: F. Garoosi, F. Talebi, Numerical analysis of conjugate natural and mixed convection heat transfer of nanofluids in a square cavity using the two-phase method, Advanced Powder Technology (2017), http://dx.doi.org/10.1016/j.apt.2017.04.006

Nomenclature

A	surface area per unit depth $A = 2(L + W)$, m
C_p	specific heat, J kg^{-1} K^{-1}
D_B	Brownian coefficient, kg m^{-1} s^{-1}
d_f	diameter of the base fluid molecule, m
d_p	diameter of the nanoparticle, m
D_T	thermophoresis coefficient, kg m^{-1} s^{-1} K^{-1}
g	gravitational acceleration, m s^{-2}
Gr	Grashof number $(= g\beta\Delta T H^3/\nu^2)$
H	enclosure height, *m*
J_p	particle flux vector, kg m^{-2} s^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
k_b	Boltzmann's constant = 1.38066×10^{-23} J K^{-1}
K_r	thermal conductivity ratio of solid wall to pure fluid
L	length of the conductive wall
$\overline{Nu_i}$	average Nusselt number on the walls of the each heater or cooler
$\overline{Nu}_{tot}$	sum of $\overline{Nu_i}$ of all heaters or coolers
p	pressure, N m^{-2}
P	dimensionless pressure
Pr_f	Prandtl number $(= \nu_f/\alpha_f)$
Ra_f	Rayleigh number $(= g\beta_f(T_h - T_c)H^3/\alpha_f\nu_f)$
Re_B	Brownian-motion Reynolds number
Re	Reynolds number $(= U_0 H/\nu)$
Ri	Richardson number $(= Gr/Re^2)$
T	temperature, K
T_{fr}	freezing point of the base fluid, K
u, v	velocity components, m s^{-1}
u_B	Brownian velocity of the nanoparticle, m s^{-1}
U, V	dimensionless velocity components
W	length of the isothermal surface
x, y	Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	thermal expansion coefficient, K^{-1}
θ	dimensionless temperature
μ	dynamic viscosity, kg m^{-1} s^{-1}
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
φ	volume fraction of the nanoparticles (vol. nanoparticles/total vol.)
ψ	stream function $\left(= -\int_{Y_0}^{Y} U\partial Y + \psi(X, Y_0)\right)$

Subscripts

c	cold wall
f	fluid
h	hot wall
nf	nanofluid
p	solid nanoparticles
s	solid wall (conductive wall)

or metal oxide nano-sized particles (smaller than 150 nm) with high thermal conductivity (such as: Al, Ag, Au, Cu, Al_2O_3, CuO and TiO_2) are suspended in the conventional working fluids (such as: water, ethylene glycol, and oils) which have inherently low thermal conductivity as compared with solids. As a result, in recent years, a noticeable number of review papers have been provided on the thermo-physical properties of nanofluids [11,12] . A large number of research papers are available which deal with the study of natural convection heat transfer of nanofluids in simple geometry enclosures with different boundary conditions such as constant heat flux or temperature difference [13].

Generally, numerical simulation of the fluid flow, the temperature distribution and heat transfer characteristics of the nanofluid can be performed by using two different methods; single-phase (homogenous) and two phase models. In the homogenous method, it is assumed that the solid particles and the base fluid are in thermal equilibrium and have the same temperature and velocity. There are many numerical studies in this field which have been used homogeneous approach for simulation of the nanofluids [14–19]. Purusothaman et al. [20], Cho et al. [21], Sheremet et al. [22], Alsabery et al. [23] and Mahmoodi [24] presented a numerical study of natural and mixed convection heat transfer of nanofluid flow in different geometries. They used Maxwell–Garnett [25] and Brinkman [26] models to estimate the effective thermal conductivity and viscosity of the nanofluid. They showed that, by increasing the volume fraction of the nanoparticles and Rayleigh number the heat transfer rate enhances. However, the results of Corcione [27] questions the validity of these models (Maxwell–Garnett [25] and Brinkman [26] models) for simulation of the nanofluids and produces two other empirical correlations for estimating the effective thermal conductivity and dynamic viscosity of nanofluids, based on a wide variety of experimental data available in the literature. Cianfrini et al. [28], Motlagh et al. [29], Esfandiary et al. [30] and Corcione [31] examined the problem of natural convection of the nanofluids in closed enclosures using the model proposed in [27] to estimate the effective viscosity and thermal conductivity of nanofluid. Their results indicated that the thermal performance of the nanofluid enhances with increasing the nanoparticle concentration up to an optimal particle loading where the maximum heat transfer rate occurs within the enclosure. In addition, they reported that the optimal particle loading decreases as the nanoparticle size increases. In a similar work, Zerradi et al. [32,33] presented a new model for predicting the effective thermal conductivity of the nanofluid. Their results indicated that, the thermal conductivity of nanofluid is mainly due to the thermal conductivity of nanoparticles, aggregates, base fluid and the Brownian motion of the both nanoparticles and aggregates. Loulijat et al. [34] applied molecular dynamics simulations to calculate the thermal conductivity and the melting temperature of copper nanoparticle. They found that, the melting temperature of Cu nanoparticles enhances by increasing the size of the solid particles. However, comprehensive experimental studies, such as the work of Wen and Ding [35], support the idea that the slip velocity between the base fluid and particles may not be zero because their results illustrate that the distribution of solid particles is non-uniform so that the heat transfer near the heated wall is induced by pure fluid where the concentration of nanoparticles is dramatically low. Thus, the two-phase modeling can be an alternative method. In a pioneering work, Buongiorno [36] developed a non-homogeneous equilibrium model by considering the effect of the Brownian diffusion and thermophoresis as two important primary slip mechanisms in nanofluid. He found that, the effects of Brownian diffusion and thermophoresis are more pronounced for solid particles with low thermal conductivity. Furthermore, his results indicated that, thermophoresis is the main mechanism of nanoparticle migration which moves the solid particles toward the cold surface where concentration of the nanoparticles is significantly higher than the hot region. Similar observation was reported by Malvandi et al. [37–39] who investigated natural, mixed and forced convection of nanofluids in vertical and horizontal micro-channel using Buongiorno's model [36]. Pakravan et al. and [40] and Sheikhzadeh et al. [41] have performed a numerical study of natural convection

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