Powder Technology 275 (2015) 239–256

Contents lists available at ScienceDirect

Powder Technology

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

Two phase simulation of natural convection and mixed convection of the nanofluid in a square cavity

Faroogh Garoosi [a,*], Gholamhossein Bagheri [b], Mohammad Mehdi Rashidi [c,d]

[a] Department of Mechanical Engineering, University of Semnan, Semnan, Iran
[b] Section des Sciences de la Terre et de L'Environnement, Universitè de Genève, Rue des Maraîchers 13, CH-1205 Genève, Switzerland
[c] Shanghai Key Lab of Vehicle Aerodynamics and Vehicle Thermal Management Systems, Address: 4800 Cao An Rd., Jiading, Shanghai 201804, China
[d] ENN-Tongji Clean Energy Institute of advanced studies, Shanghai, China

ARTICLE INFO

Article history:
Received 20 October 2014
Received in revised form 25 November 2014
Accepted 9 February 2015
Available online 15 February 2015

Keywords:
Natural convection
Mixed convection
Nanofluid
Thermophoresis
Heater
Cooler

ABSTRACT

A numerical study is carried out concerning natural and mixed convection heat transfer of nanofluid in a two-dimensional square cavity with several pairs of heat source-sinks. Two-dimensional Navier–Stokes, energy and volume fraction equations are solved using the finite volume method. Effects of various design parameters such as external and internal heating, number of the coolers, Rayleigh number ($10^3 \leq Ra \leq 10^7$), Richardson number ($0.01 \leq Ri \leq 1000$), nanoparticle volume fraction ($0 \leq \varphi \leq 0.05$), size ($25\text{nm} \leq d_p \leq 145\text{nm}$) and type (Cu, Al_2O_3, TiO_2) on the heat transfer rate and distribution of nanoparticles are investigated. The simulation results indicate that there is an optimal volume fraction of the nanoparticles for each Rayleigh number and Richardson number at which the maximum heat transfer rate occurs. It is also observed that at low Rayleigh numbers and high Richardson numbers, the particle distribution is fairly non-uniform. Moreover, it is found that thermophoretic effects are negligible for nanoparticles with high thermal conductivity. As a result, in such conditions the use of homogeneous and single-phase models is valid at any *Ra* and *Ri*.

1. Introduction

The Buoyancy-induced convection happens in a great number of industrial applications such as indoor ventilation with radiators, cooling electrical components, cooling reactors and heat exchangers [1]. In all of these applications engineers are constantly looking for methods to improve the overall heat transfer efficiency by implementing a wide spectrum of technics, from design optimization to use of novel materials like nanofluids. In this process, numerical simulation as a relatively inexpensive research tool, has been extensively used to provide insights to the heat transfer mechanism. Since complex industrial geometries can be computationally expensive and case specific, simplified geometries like a square cavity are widely used to isolate and demonstrate effect of design parameters on the heat transfer. Work of Oztop et al. [2] can be mentioned as example of such studies, in which they numerically studied mixed convection in square cavities with two moving walls. Their results suggest that when the vertical walls move upwards in the same direction, the heat transfer decreases significantly compared to when the vertical walls move in opposite directions. In a similar work, Islam et al. [3] performed a numerical simulation on a lid-driven cavity with an isothermally heated square blockage. Their results showed that Richardson number, size and location of the heater eccentricities affect the average Nusselt number of heater. Qi-Hong Deng [4] studied laminar natural convection in a two dimensional square enclosure with two and three source–sink pairs on the vertical side walls. The obtained results showed that the heat transfer between walls of heaters and coolers, in terms of the average Nusselt number values, is one-to-one in a reversed manner. Wang et al. [5] investigated the natural convection heat transfer of a pair of hot and cold horizontal micro tubes at low Rayleigh numbers in a square cavity. They found that, by changing the location of the hot and cold tubes, the heat transfer rate varies sharply. In addition, their results show that by increasing Rayleigh number the heat transfer rate increases. Park et al. [6] performed a numerical simulation on a square cavity with a pair of hot horizontal cylinders positioned at different vertical locations. They observed that the local Nusselt numbers on the surface of the cylinders strongly depend on the gap distance between the two hot cylinders and the walls of the cavity.

The heat transfer can be greatly improved when nanofluid is used instead of pure fluids (e.g. water, oil, ethylene glycol). Nanofluids are mixtures of nano-sized solid particles (usually smaller than 150 nm) dispersed in a base fluid. In the past decade, various types of nanoparticles such as (Cu, AL_2O_3, TiO_2, Ag, Au, and Tic) have been used to increase the heat transfer coefficient. The most important characteristic of nanofluids is their high thermal conductivity relative to the pure fluids, which can be achieved even at very low volume fraction of

---

* Corresponding author. Tel.: +98 9112748341.
E-mail address: Garoosi.faroogh@yahoo.com (F. Garoosi).

http://dx.doi.org/10.1016/j.powtec.2015.02.013
0032-5910/

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, ms^{-2}
Gr	Grashof number $(= g\beta\Delta TH^3/\nu^2)$
H	enclosure height, m
J_p	Particle flux vector, kg m^{-2} s^{-1}
k	thermal conductivity, Wm^{-1} K^{-1}
k_b	Boltzmann's constant $= 1.38066 \times 10^{-23}$ JK^{-1}
$\overline{Nu}_i$	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, Nm^{-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 $(= U_0H/\nu)$
Ri	Richardson number $(= Gr/Re^2)$
T	temperature, K
T_{fr}	freezing point of the base fluid, K
u,v	velocity components, ms^{-1}
u_B	Brownian velocity of the nanoparticle, ms^{-1}
U, V	dimensionless velocity components
x,y	Cartesian coordinates, m
X, Y	dimensionless Cartesian coordinates

Greek symbols

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

Subscripts

c	cold wall
f	fluid
h	hot wall
nf	nanofluid
p	solid nanoparticles

nanoparticles. The heat transfer characteristics of nanofluids depend on the size, volume fraction, shape and thermo-physical properties of nanoparticles as well as the base fluid properties [7–10]. In general, numerical simulation of the velocity field, the temperature distribution and the heat transfer rate of nanofluids can be performed using two main approaches, namely Single-phase and Two-phase methods. The former assumes that the continuous phase and the nanoparticles are in thermal equilibrium and move with the same velocity, and has been used to simulate both natural convection [11–18] and mixed convection [19–21] in nanofluids. Corcione [11] and Garoosi et al. [12] investigated the natural convection of nanofluid at different geometries using the model proposed in [10] to estimate the effective viscosity and thermal conductivity of nanofluid. Their results show that there is an optimum volume fraction of nanoparticles, where the maximum heat transfer rate occurs. Kefayati et al. [13] and Sheikholeslami et al. [15] studied the effects of magnetic field on natural convection flow in a cavity filled with nanofluid for different geometries. They used the Brinkman [7] and Maxwell-Garnett [8] models to estimate the effective viscosity and thermal conductivity of the nanofluid. They stated that the increase in volume fraction of nanoparticle and *Ra* enhances the heat transfer rate. Sheikholeslami et al. [16] have performed a numerical study of magnetic field effects on natural convection around a horizontal circular cylinder inside a square enclosure filled with nanofluid. They found that the heat transfer rate is an increasing function of nanoparticle volume fraction as well as the Rayleigh number, while it is a decreasing function of the Hartmann number (Ha). In addition, their results indicated that for $Ha < 20$ the enhancement in average Nusselt number at $Ra = 10^4$ is greater than at other Rayleigh numbers. In a similar work, Sheikholeslami et al. [17] studied the effects of magnetic field on ferrofluid flow and heat transfer in a semi annulus enclosure. They reported that increasing Magnetic number, Rayleigh number and volume fraction of the nanoparticles lead to augmentation of the heat transfer rate but the average Nusselt number decreases with increase of Hartmann number and Radiation parameter.

Kalteh et al. [19] investigated laminar mixed convection of nanofluid in a lid-driven square cavity with a triangular heat source and found that increasing the nanoparticle diameter leads to a decrease in the heat transfer rate at any *Ri*. Talebi et al. [21] studied mixed convection of nanofluids inside the differentially heated cavity (DHC). They showed that heat transfer rate has a direct relationship with Rayleigh number and nanoparticle concentration. They also showed that at a given Reynolds number the stream function increases with increasing volume fraction of nanoparticles, in particular at the higher Rayleigh number.

However, experimental study of Wen and Ding [22] questions the validity of the single-phase assumption for nanofluids. Since the slip velocity between the base fluid and particles may not be zero, more advanced methods are developed to capture the nanofluid behavior more accurately [23–32]. In a pioneering work, Buongiorno [33] presented Brownian diffusion and thermophoresis as two important primary slip mechanisms between solid and liquid phases. He found that, with considering the effects of thermophoretic, the temperature gradient resulted in particle transport from a hot region to a cold region. Later, work of Corcione et al. [23] confirmed that the two phase mixture method of Buongiorno provides more accurate results compare to the single-phase methods. Other studies also confirm the better accuracy of model of Buongiorno with respect to experimental measurements [25,29]. Malvandi et al. [24] investigated slip flow of alumina/water nanofluid in a circular microchannel. They found that nanoparticles move from the hot wall towards the core region where fluid temperature is lower than elsewhere and result in a non-uniform nanoparticle distribution. More recently, Sheikholeslami et al. [26] studied three dimensional nanofluid flow and heat transfer in a rotating system in the presence of a magnetic field using Buongiorno's model. Their results indicated that heat transfer rate has a direct relationship with Reynolds number while it has a reverse relationship with thermophoretic parameter and Brownian parameter. They also showed that the concentration boundary layer thickness decreases with increase of thermophoretic and Brownian parameter. Sheikholeslami and Ganji [31] analyzed two phase modeling of nanofluid in a rotating system with permeable sheet. Their results indicated that thickness of the concentration boundary layer decreases with the increase of thermophoretic parameter and Brownian parameter. Sheikholeslami et al. [32] investigated the effects of thermophoresis and Brownian motion on the heat transfer rate of the nanofluid under magnetic field. They observed that