Applied Mathematics and Computation 254 (2015) 183–203

Contents lists available at ScienceDirect

Applied Mathematics and Computation

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

Numerical simulation of natural convection of the nanofluid in heat exchangers using a Buongiorno model

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ARTICLE INFO

Keywords:
Natural convection
Nanofluid
Heat exchanger
Heater
Cooler
Buongiorno model

ABSTRACT

A numerical study is carried out concerning natural convection heat transfer of nanofluid in a two-dimensional square cavity containing several pairs of heater and coolers (HACs). Walls of the cavity are insulated and several pairs of heater and coolers (HACs) with isothermal walls of T_h and T_c ($T_h > T_c$) are placed inside the cavity. Two-dimensional Navier–Stokes, energy and volume fraction equations are solved using finite volume discretization method. The effects of various design parameters on the heat transfer rate and distribution of nanoparticles such as Rayleigh number ($10^4 \leqslant Ra \leqslant 10^7$), volume fraction ($0 \leqslant \varphi \leqslant 0.05$) and size of nanoparticles ($25\ \text{nm} \leqslant d_p \leqslant 145\ \text{nm}$), type of the nanoparticles (Cu, Al_2O_3 and TiO_2), nanofluid average temperature ($294\ \text{K} \leqslant T_{ave} \leqslant 324\ \text{K}$), number of the cooler, location of the heater and arrangement of the HAC are investigated. The simulation results are indicated that, HACs location has the most significant influence on the heat transfer rate. It is also found that at low Rayleigh numbers, the particle distribution is fairly non-uniform while at high *Ra*, particle distribution remains almost uniform. Moreover, it is found that there is an optimal volume fraction of the nano-particles at each Rayleigh number in which the maximum heat transfer rate can be obtained.

1. Introduction

Many industrial and environmental processes are involved with heat transfer due to natural convection through a medium fluid. Indoor ventilation with radiators, cooling of electrical components, solar energy collection and heat exchangers are just a few examples of such systems [1]. From energy-saving point of view, improvement of heat transfer in any application of natural convection is a primary and crucial topic. Several investigations have been carried out on natural convection [2–6]. Bilgen [2] investigated laminar natural convection in a two-dimensional square cavity with a thin fin on the hot wall. It was reported that there is an optimum fin location, which is often at the center or near center of the cavity, which minimizes the natural convection heat transfer. Deng [3] studied laminar natural convection in a two dimensional square enclosure with

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http://dx.doi.org/10.1016/j.amc.2014.12.116
0096-3003/

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}
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}
$\overline{Nu}_i$	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
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
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$(= -\int_{Y_0}^{Y} U\partial Y + \psi(X, Y_0))$

Subscripts

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

two and three source–sink pairs on the vertical side walls. The results show that the heat transfer between heaters and coolers' walls, 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. [4] 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. Islam et al. [6] investigated the mixed convection heat transfer in a lid-driven cavity with an isothermally heated square body. It was reported that the Richardson number, size and location of the heater eccentricities affect the average Nusselt number.

Nanofluid, a mixture of nano-particles dispersed in a pure fluid, has been proposed as a technique in order to enhance the heat transfer. Thermal conductivity is one of the most effective properties of a fluid in heat transfer, which could be increased by using nano-particles. In the past decade, various types of nanoparticles such as (Cu, AL_2O_3, TiO_2, Ag, Au, and Tic etc.) have been used to increase the heat transfer coefficient. The experimental studies results show that the thermal conductivity of nanofluid is changed by the variation of volume fraction, diameter of the nanoparticles, type of nanoparticles and base fluid,