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Numerical study of natural convection heat transfer in a heat exchanger filled with nanofluids

Faroogh Garoosi [a, b, *], Faraz Hoseininejad [b, 1], Mohammad Mehdi Rashidi [c, d, 2]

[a] Department of Mechanical Engineering, University of Semnan, Semnan, Iran
[b] Department of Mechanical Engineering, Aliabad Katoul Branch, Islamic Azad University, Aliabad Katoul, Iran
[c] Shanghai Key Lab of Vehicle Aerodynamics and Vehicle Thermal Management Systems, 4800 Cao An Rd., Jiading, Shanghai 201804, China
[d] ENN-Tongji Clean Energy Institute of Advanced Studies, Shanghai, China

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ABSTRACT

Natural convection of nanofluids around several pairs of hot and cold cylinders in an adiabatic enclosure is investigated numerically. Hot and cold cylinders are maintained at the different constant temperatures ($T_h > Tc$) while the walls of the enclosure are thermally insulated. A parametric study is undertaken to explore the effects of the pertinent parameters, such as; Rayleigh number, size and type of the nanoparticles, shape of the enclosure, orientation and number of the hot and cold cylinders on the fluid flow and heat transfer characteristic. The simulations show that at low *Ra*, by changing shape of the enclosure from square to triangular one, the heat transfer rate decreases. It is also found that at each *Ra*, there is an optimum volume fraction of nanoparticles (ϕ_{opt}) where the heat transfer rate within the enclosure has a maximum value. Moreover, the results of this study showed by altering orientation of the hot and cold cylinders from horizontal to vertical mode, the heat transfer rate enhances. Finally, the results indicated that, by decreasing the size of the nanoparticles, the heat transfer rate and optimal particle loading (ϕ_{opt}) enhances.

1. Introduction

Phenomena involving Buoyancy-induced convection in fluid-filled enclosures have received considerable attention because natural convection plays important roles in many engineering applications, such as; home ventilation, electronic cooling systems, solar collector, cooling reactors and heat exchangers [1]. Several studies dealing with enhancing natural convection in closed enclosures are documented in the literature [2]. In all of these applications engineers are continuously looking for ways to improve the global heat transfer rate 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 design and research tool, has been widely used in recent decades to provide close insights to the heat transfer phenomenon. Work of Qi-Hong Deng et al. [3] can be mentioned as example of such studies, in which he numerically studied natural convection in a square cavity with several pairs of heat source–sink pairs on the vertical sidewalls. He found that heat transfer relationship between heat sources and sinks, in terms of the average Nusselt number values, is one to one in a reversed manner. Bhardwaj et al. [4] have discussed the influence of wavy wall and non-uniform heating on natural convection heat transfer in a triangular enclosure. They found that, at high Rayleigh number, irreversibilities due to heat transfer and fluid friction are comparable. Park et al. [5] numerically investigated laminar natural convection in an inclined square enclosure with an inner circular cylinder. They found that by increasing the tilted angle of the cavity the averaged Nusselt number along the top and bottom walls of the cavity decreases and increases respectively. Park et al. [6,7] carried out numerical simulation of natural convection in a square cavity with several hot circular cylinders inside. They found that at low Rayleigh numbers, distribution of the isotherms and streamlines is strongly depended on the distance between the cylinders and walls of the cavity. Wang et al. [8], Gap et al. [9] and Dai et al. [10] studied laminar natural convection in a two dimensional enclosure around a pair of hot and cold horizontal micro tubes. They reported that,

* Corresponding author. Tel.:+98 9112748341.
E-mail addresses: garoosi.faroogh@yahoo.com, faroogh.garoosi@semnan.ac.ir (F. Garoosi), faraz_mahoor@yahoo.com (F. Hoseininejad), mm_rashidi@yahoo.com, mm_rashidi@tongji.edu.cn (M.M. Rashidi).
[1] Tel.:+98 9101070861.
[2] Tel.:+86 136 519 247 42.

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Nomenclature

A	surface area per unit depth $A=\pi(R_1+R_2)$, m
C_p	specific heat, $J\ kg^{-1}\ K^{-1}$
d_f	diameter of the base fluid molecule, m
d_p	diameter of the nanoparticle, m
g	Gravitational acceleration, ms^{-2}
H	enclosure height, m
$\overline{h}$	heat transfer coefficient, $Wm^{-2}K^{-1}$
k	thermal conductivity,$Wm^{-1}K^{-1}$
k_b	Boltzmann's constant $= 1.38066\times10^{-23} JK^{-1}$
$\overline{Nu}_i$	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
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

arrangement of hot and cold cylinders has a big impact on the average Nusselt number. Choi et al. [11] studied the effect of the circular cylinder's location on natural convection heat transfer in a rhombus enclosure. They reported that by changing the location of the hot cylinder from lower to upper half of the enclosure, the total Nusselt number reduces considerably.

In recent years, many researchers focused on using the nanofluids as alternative heat transfer enhancement technique. The nanofluids are a new kind of heat transfer fluid containing small quantity of nano-sized particles with higher thermal conductivity compared to the pure fluid. A comprehensive review of the thermal conductivity and effective dynamic viscosity of the nanofluids can be found in literatures [12,13]. Corcione [14], presented two empirical correlations for predicting the effective thermal conductivity and dynamic viscosity of nanofluids, based on a high number of experimental data available in the literature. There are many numerical and experimental studies in the literature that focused on heat transfer enhancement of nanofluids. Bianco et al. [15], Cho et al. [16], Bouhalleb et al. [17], Bourantas et al. [18] and Cho et al. [19] numerically studied the natural convection of the nanofluid in a circular, square and triangular enclosure. Their results showed that, the heat transfer rate enhances with increasing the volume fraction of nanoparticles. Massimo Corcione [20,21] and Ali et al. [22] investigated natural and force convection heat transfer of nanofluids in different geometries. They found that, there is an optimal volume fraction of the nanoparticles at each Rayleigh and Reynolds number in which the maximum heat transfer rate can be obtained. Kalteh et al. [23], Ebrahimian et al. [24] and Mashaei et al. [25] numerically investigated the fluid flow and heat transfer rate in a square enclosure, nuclear reactors and horizontal heat pipe, respectively. They concluded that, at all Richardson and Reynolds number, by increasing the nanoparticles diameter, the heat transfer rate decreases. Kefayati [26,27], Mejri et al. [28] and Sheikholeslami et al. [29] investigated the effect of the magnetic field on natural convection of the nanofluid in an open and closed enclosure. The results demonstrated that, the average Nusselt number increases with increase of Rayleigh number and volume fraction of nanoparticle while it decreases with augment of Hartmann number. Mostafa Mahmoodi [30] conducted a numerical simulation to investigate the problem of natural convection of the nanofluid in a square cavity with an inside heater. He found that by changing orientation of the heater from vertical to horizontal, the heat transfer rate decreases. Mostafa Mahmoodi [31] and Saidi et al. [32] investigated natural convection of *Cu*-water nanofluid in an L-shaped cavity. They found that at all Rayleigh numbers, the heat transfer rate increases when the aspect ratio of the cavity and the volume fraction of the nanofluid increase. Yue et al. [33] investigated the effects of nanoparticles size and Reynolds number on the mean Nusselt number, pumping power, and entropy generation in a manifold micro channel heat sink. They discovered that, increasing particle diameter leads to decreasing average Nusselt number, pumping power, and performance index. Zhao et al. [34] studied laminar heat transfer and flow performance of Al_2O_3–water nanofluids in a flat tube. They found that, average Nusselt number and press drop can be enhanced by increasing nanoparticle volume fraction and decreasing nanoparticle size. Similar observation were reported by Bahiraei et al. [35], Siavashi et al. [36], Huang et al. [37], Bahiraei et al. [38] and Saeedan et al. [39] who investigated the effects of nanoparticles concentration on the heat transfer rate and press drop at different geometries. Selimefendigil et al. [40], Kolsi et al. [41] and Ismael et al. [42] performed a study on natural convection heat transfer and entropy generation in nanofluid filled enclosures. Their results showed that both total Nusselt number and entropy generation increase with the increase of nanoparticle concentration.

Despite a number of theoretical, numerical and experimental studies on heat transfer performance of nanofluids in closed enclosures which have been reported in the literature, there is still a serious lack of information regarding the problem of natural convection heat transfer in heat exchangers filled with nanofluids. The main objective of the present study is to numerically explore the fundamental fluid flow and heat transfer characteristics for natural convection of the nanofluids in an adiabatic enclosure with several differentially heated circular cylinders inside. Such natural convection configuration is considered as a model of heat exchangers in order to prevent the fluids contained in the pipelines from