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Numerical modeling of natural convection in an open cavity with two vertical thin heat sources subjected to a nanofluid☆

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ABSTRACT

This paper presents a numerical study of natural convection cooling of two heat sources vertically attached to horizontal walls of a cavity. The right opening boundary is subjected to the copper–water nanofluid at constant low temperature and pressure, while the other boundaries are assumed to be adiabatic. The governing equations have been solved using the finite volume approach, using SIMPLE algorithm on the collocated arrangement. The study has been carried out for the Rayleigh number in the range $10^4 \leq Ra \leq 10^7$, and for solid volume fraction $0 \leq \varphi \leq 0.05$. In order to investigate the effect of heat source location, three different placement configurations of heat sources are considered. The effects of both Rayleigh numbers and heat source locations on the streamlines, isotherms, Nusselt number are investigated. The results indicate that the flow field and temperature distributions inside the cavity are strongly dependent on the Rayleigh numbers and the position of the heat sources. The results also indicate that the Nusselt number is an increasing function of the Rayleigh number, the distance between two heat sources, and distance from the wall. In addition it is observed that the average Nusselt number increases linearly with the increase in the solid volume fraction of nanoparticles.

1. Introduction

Natural convection in open cavities has a wide range of industrial applications and has been studied extensively in the literature [1–7]. Some applications are solar thermal receivers, energy-saving household refrigerators, and electronic cooling, etc. Most of researchers considered natural convections inside open ended enclosures in contact with pure fluid. However, there are no studies concerning the cooling process in open cavities filled by nanofluid. In recent years, nanofluids have attracted more attention for cooling in various industrial applications. Such fluids consist of suspended nanoparticles which have a better suspension stability compared to millimeter or micrometer sized ones. Use of metallic nanoparticles with high thermal conductivity will increase the effective thermal conductivity of these types of fluid remarkably. Since nanofluid consists of very small sized solid particles, therefore in low solid concentration it is reasonable to consider nanofluid as a single phase flow [8]. So, it is needed to present a brief review including cavities filled by nanofluids. A numerical study of natural convection of copper–water nanofluid in a two–dimensional enclosure was conducted by Khanafer et al. [9]. The nanofluid in the enclosure was assumed to be in single phase. It was found in any given Grashof number, heat transfer in the enclosure increased with the volumetric fraction of the copper nanoparticles in water. Ho et al. [10] presented two–dimensional numerical simulation of buoyancy-driven convection in the enclosure filled with alumina-water nanofluid. The effects of adopting different formulas for the effective viscosity and thermal conductivity have been identified. A significant difference was found in the effective dynamic viscosity enhancement calculated from considered formulas other than increment of thermal conductivity. Santra et al. [11] numerically investigated the laminar natural convection heat transfer in a differentially heated square cavity filled with copper–water nanofluid. They considered a two parameter power law model for an incompressible non-Newtonian fluid. Oztop et al. [12] investigated the natural convection heat transfer in partially heated enclosures. Their studies have been carried out for different water based nanofluids. Other researches have been conducted that simulate the natural convection heat transfer using nanofluid in the other geometrical configurations [13–18].

Literature reviews show that laminar natural convection on an open cavity with a heat source has interesting applications in cooling of electronic equipment. Jaluria [19] studied numerically the three-dimensional conjugate heat transfer in a rectangular duct with two discrete flush-mounted heat sources in the context of cooling of electronic equipments.

The present study conducts a numerical study of laminar natural convection heat transfer to copper–water nanofluid from two identical

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Nomenclature

c_p	Specific heat capacity (J/K)
Gr	Grashof number, $\beta g H^4 q''/k\upsilon^2$
g	Gravitational acceleration(m/s^2)
H	Height of cavity (m)
k	Thermal conductivity(W/mK)
k_b	Boltzmann's constant, 1.38065×10^{-23}
Nu	Nusselt number
p	Pressure(N/m^2)
P	Dimensionless pressure, $pH^2/(\rho_{nf}\alpha_f^2)$
pr	Prandtl number, υ_f/α_f
q''	Heat flux at the source(W/m^2)
Ra	Rayleigh number, $\beta g H^4 q''/k(\upsilon\alpha)$
T	Temperature(K)
u, v	Components of velocity(m/s)
U, V	Dimensionless of velocity component, ($u=uH/\alpha_f$, $\nu=\nu H/\alpha_f$)
x, y	Cartesian coordinates(m)
X, Y	Dimensionless of Cartesian coordinates (m)
W	Width of cavity (m)

Greek letters

α	Thermal diffusivity,$k/(\rho c_p)$ (m^2/s)
β	Coefficient of volume expansion(K^{-1})
ϕ	Solid volume fraction
μ	Dynamic viscosity(Pa s)
υ	Kinematics viscosity(m^2/s)
ρ	Density (kg/m^3)
θ	Dimensionless temperature

Subscript

f	Fluid
m	Average
nf	Nanofluid
o	Reference state
s	Solid
w	Wall

protruding thin heat sources in the open cavity. The right opening boundary is subjected to the cold external flow at constant temperature and pressure, while the other boundaries are assumed to be adiabatic. These two heat sources are located on the horizontal walls of the cavity, cooling with ventilation on the right boundary. Simulations are performed for various parameters such as: Rayleigh number, solid volume fraction of nanoparticles, heat source geometry and location.

2. Problem definition and mathematical formulation

The geometry considered is a two-dimensional cavity with two identical protruding thin heat sources. The physical model and coordinate system are shown in Fig. 1. The cavity is subjected to an external cold nanofluid entering into the cavity from the right opening boundary. The copper–water nanofluid communicating with the opening is kept at a constant temperature (T_C) and pressure in the entry. The other boundaries are assumed to be adiabatic. In order to investigate the effect of the heat source location, three different placement configurations of heat sources are considered (case a, b and c).

It is assumed that both the fluid phase and nanoparticles are in thermal equilibrium. The shape and size of solid particles are assumed to be uniform and the diameter of them to be equal to 100 nm. Except for the density the properties of nanoparticles and fluid are taken to be constant. Table 1 presents the thermo physical properties of water and copper at the reference temperature. It is further assumed that the Boussinesq approximation is valid for the buoyancy force.

The governing equations (continuity, momentum and energy equations) for a steady, two-dimensional laminar and incompressible flow are expressed as below:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x}+\upsilon_{nf}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y}+\upsilon_{nf}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+\frac{g}{\rho_{nf}}(T-T_\infty)\left[\phi\rho_{s,0}\beta_s+(1-\phi)\rho_{f,0}\beta_f\right] \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where$\alpha_{nf}=k_{nf}/(\rho c_p)_{nf}$.

The effective density of nanofluid at the reference temperature can be defined as:

$$\rho_{nf,0}=(1-\phi)\rho_{f,0}+\phi\rho_{s,0} \tag{5}$$

where $\rho_{nf,\,0}$,$\rho_{f,\,0}$,$\rho_{s,\,0}$and ϕ are the density of nanofluid, density of base fluid, density of nanoparticle and volume fraction of the nanoparticles, respectively.

Table 1
Thermophysical properties of water and copper.

Property	Water	Copper
c_p	4179	383
ρ	997.1	8954
k	0.6	400
β	2.1×10^{-4}	1.67×10^{-5}

Table 2
Result of grid independence examination.

Number of grids in X–Y	*Nu*
43×33	1.416552
53×43	1.378717
63×53	1.308028
73×63	1.298781
83×73	1.29134

Table 3
Comparison of results obtained in this study by [24].

Nu			
	Present	de Vahl Davis[24]	Error (%)
$Ra=10^4$	2.248	2.242	0.267
$Ra=10^5$	4.503	4.523	0.444
$Ra=10^6$	9.147	9.035	1.24