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A numerical study on natural convection in porous media-filled an inclined triangular enclosure with heat sources using nanofluid in the presence of heat generation effect

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ABSTRACT

This paper discusses the natural convection heat transfer in an inclined triangular enclosure filled with Cu-water nanofluid saturated porous medium in the presence of heat generation effect. Two symmetric heat sources are located at the bottom and left walls of the enclosure while the remaining parts are thermally insulated. The inclined wall of the enclosure is considered to be cold. The partial differential equations governing the problem are transformed to a dimensionless form and solved numerically using an implicit finite difference method. The obtained results are presented in terms of streamlines, isotherms, local Nusselt number and average Nusselt number. It is found that a good enhancement in the average Nusselt number can be obtained by an increase in the nanoparticle volume fraction. Also, an increase in the heat generation parameter leads to a decrease in the average Nusselt number.

1. Introduction

Many researchers were interested in studying the natural convective heat transfer in a fluid-saturated porous media because of its applications in thermal insulation systems, geothermal engineering, porous heat exchangers, food storage, underground disposal of nuclear waste materials, oil separation from sand by steam, electronic device cooling etc. A representative review of these applications and other heat transfer applications in porous media may be found in the recent books of Vafai [1]. Nield and Bejan [2] and Ingham and Pop [3] contributed to a wide overview of this important area in heat transfer of porous media. There are many published studies related to natural convection in rectangular porous enclosures. Moya et al. [4], Bejan [5], Prasad and Kulacki [6], Baytas and Pop [7], Beckerman et al. [8], Gross et al. [9], Lai and Kulacki [10], Monale and Lage [11], and Walker and Homsy [12] have contributed many important results for this problem.

Nanofluids have attracted a significant attention about one decade ago Choi [13]. Mahmoudi et al. [14] used the Lattice Boltzmann method (LBM) to study the natural convection in an open cavity filled with a water–Al_2O_3 nanofluid and subjected to a magnetic field in the presence of heat generation or absorption. They found that the nanoparticle effect is more important for heat generation condition ($q > 0$) than heat absorption condition ($q < 0$). Bourantas et al. [15] numerically studied the problem of natural convection of a nanofluid in a square cavity filled with a porous matrix. A numerical study was presented by Garoosi et al. [16]. discussing natural and mixed convection heat transfer of a nanofluid (Al_2O_3–water) in a laterally-heated square cavity. They observed that at low Rayleigh and high Richardson numbers, the particle distribution is fairly non-uniform while at high Rayleigh and low Richardson numbers particle distribution remains almost uniform for free and mixed convection cases, respectively. Mansour et al. [17] discussed steady natural convection cooling of a localized heat source at the bottom wall of an enclosure filled with Cu-water nanofluid for a variety of thermal boundary conditions at the sidewalls. Their results show that the increase in the solid volume fraction decreases the natural convection flow whereas it increases the rate of heat transfer.

For natural convection inside a triangular porous enclosure, Mansour et al. [18] studied numerically the problem of double-diffusive convection with sinusoidal variation of boundary conditions in the presence of a heat source or sink. They found that the

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horizontal velocity component and the average Nusselt and Sherwood numbers increase as the triangle inclination angle increases; however, further increase in the inclination angle leads to opposite behaviors. Tzeng et al. [19] presented a numerical simulation-aided parametric analysis of natural convection in a roof of triangular enclosures. Ahmed et al. [20] presented the numerical modeling of a steady, laminar natural convection flow in a triangular enclosure partially heated from below and with a cold inclined wall filled with Cu–water nanofluid having variable thermal conductivity and viscosity. They observed that there are clear enhancements in the local Nusselt number along the heat source that can be obtained by increase the solid volume fraction. The problem of double-diffusive convection in inclined finned triangular porous enclosures for various thermal and concentration boundary conditions and in the presence of heat source or sink was studied by Chamkha et al. [21]. They observed that the rates of heat and mass transfer tend to increase as the inclination angle increases, whereas a decrease in the Darcy number causes a decrease in the average Nusselt and Sherwood numbers. The problem of natural convection in porous triangular enclosures with the effects of thin fin was studied by Varol et al. [22]. The results show that the thin fin can be used as a passive control element for flow field, temperature distribution and heat transfer.

A Study of the heat transfer enhancement using nanofluids inside triangular enclosures was neglected in all the previous investigations except that of Ahmed et al. [20]. However, Ahmed et al. [20] neglected the case of inclined triangular enclosures with two symmetric heat source embedded in the left and bottom walls in the presence of heat generation/absorption effect. So, the main objective of this paper is to study the effect of the heat generation/absorption on the natural convection cooling of heat sources embedded in the left and bottom walls of triangular enclosures filled with Cu–water nanofluid saturated porous medium. The partial differential equations are solved using the finite difference method and the obtained results are presented in terms of streamlines and isotherms as well as the local and average Nusselt number.

2. Mathematical modeling

Consider steady two-dimensional laminar natural convection in an inclined triangular porous enclosure filled with Cu–water nanofluid as depicted in Fig. 1. Two symmetric heat sources are located at the bottom and left walls of the enclosure while the remaining parts are thermally insulated. The inclined wall of the enclosure is considered to be cold. The properties of the fluid are isotropic and homogeneous everywhere. Also, the enclosure is assumed to have a uniform heat source with a constant volumetric heat generation/absorption rate. The viscous, radiation, and Joule heating effects are neglected. The density is assumed to be a linear function of temperature. Also, thermo-physical properties for the base fluid and the nanoparticles are shown in Table 1. Under these assumptions, the equations for conservation of mass, momentum and energy in rectangular coordinate systems are given by:

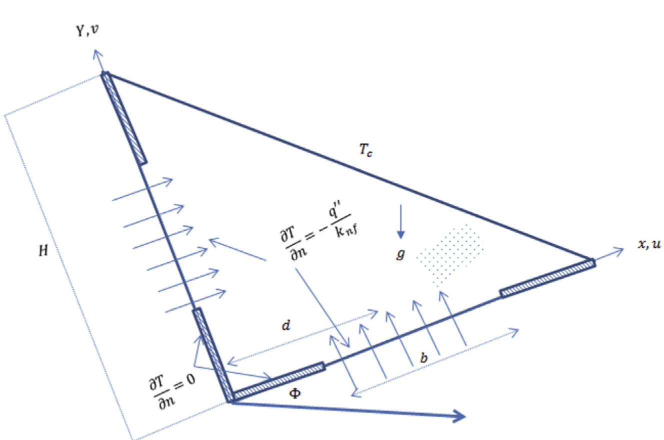

Fig. 1. Physical model and coordinate system.

Table 1
Thermo-physical properties for the base fluid and the nanoparticles.

Property	Water	Copper (Cu)
ρ	997.1	8933
C_p	4179	385
k	0.613	401
β	21×10^{-5}	1.67×10^{-5}

Table 2
Grid independency study at $Ra = 10^5$, $Da = 10^{-3}$, $B = D = 0.5$, $Q = 1$, $\Phi = \frac{\pi}{6}$, $\phi = 5\%$.

Grid size	31×31	41×41	61×61	81×81	101×101
Nu_m	6.3283	6.1371	6.2721	6.2999	6.2436

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial x} + \nu_{nf}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\sin(\Phi)g(T - T_c) - \frac{\nu_{nf}}{K}u \tag{2}$$

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -\frac{1}{\rho_{nf}}\frac{\partial p}{\partial y} + \nu_{nf}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + \frac{1}{\rho_{nf}}(\rho\beta)_{nf}\cos(\Phi)g(T - T_c) - \frac{\nu_{nf}}{K}v \tag{3}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha_{nf}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) + \frac{Q_0}{(\rho C_p)_{nf}}(T - T_c) \tag{4}$$

In Eqs. (1)–(4), x and y are Cartesian coordinates measured along the horizontal and vertical walls of the cavity respectively, u and v are the velocity components along the x- and y-axes respectively, T is the fluid temperature, p is the fluid pressure, g is the gravity acceleration, K is the permeability, Q0 is the volumetric heat generation/absorption rate, ρ is the density, ν is the kinematic viscosity, β is the thermal expansion coefficient, Φ is the inclination angle, α is the thermal diffusivity, C_P is the specific heat and nf, c refer to nanofluid and cold, respectively.

Table 3
Comparison of Nu_m at ($B = 0.4$, $D = 0.5$, $\phi = 10\%$, $Q = 0$, $\Phi = 0°$)

Ra	Ahmed et al. [20]	Present
10^3	5.450	5.450
10^4	5.475	5.475
10^5	7.204	7.204
10^6	14.014	14.014