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MHD free convection in a wavy open porous tall cavity filled with nanofluids under an effect of corner heater

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ABSTRACT

A numerical analysis of MHD natural convection in a wavy open porous tall cavity filled with a Cu–water nanofluid in the presence of an isothermal corner heater has been carried out. The cavity is cooled from the left wavy wall and heated from the right bottom corner while the bottom wall is adiabatic. Uniform magnetic field affects the heat transfer and fluid flow with an inclination angle to the axis $\bar{x}$. Mathematical model formulated using the single-phase nanofluid approach in dimensionless variables stream function, vorticity and temperature has been solved by finite difference method of the second order accuracy in a wide range of governing parameters: Rayleigh number (Ra = 100–1000), Hartmann number (Ha = 0–100), inclination angle of the magnetic field ($\gamma = 0$–π) and solid volume fraction parameter of nanoparticles (φ = 0.0–0.05). Main efforts have been focused on the effects of these parameters on the fluid flow and heat transfer inside the cavity. Numerical results have been presented in the form of streamlines, isotherms and average Nusselt numbers. It has been found heat transfer enhancement with Rayleigh number and heat transfer reduction with Hartmann number, while magnetic field inclination angle leads to non-monotonic changes of the heat transfer rate.

1. Introduction

Natural convection in different technologies finds an important place for engineering analysis. It has wide applications in engineering such as solar applications, building applications and electronic industry. The problem can be find for industrial boilers or ovens with porous materials. Also, boundaries of open or closed geometries can be non-linear. Also, the working fluid can be pure or nanofluid filled under magnetic field. In this context, a wide review has been performed by Mahdi et al. [1]. They exhibited studies on convection heat transfer and fluid flow in porous media with nanofluid.

Bilgen and Oztop [2] analyzed the natural convection in partially open inclined square cavities by using finite volume technique. They observed that inclination angle can be chosen as control parameter for flow rate and heat transfer enhancement. Arbin et al. [3] solved the double-diffusive convection problem in an open cavity and they applied heatline approach to see the heat transport way. Sheremet et al. [4] studied double-diffusive mixed convection flow in a porous open cavity filled with a nanofluid using two-phase nanofluid model. They revealed that average Nusselt number is an increasing function of the Rayleigh and Reynolds numbers, and a decreasing function of the usual Lewis number, while the average Sherwood number is an increasing function of the Reynolds and usual Lewis. Mehrez et al. [5] presented a numerical study of entropy generation and mixed convection heat transfer of Cu–water nanofluid flow in an inclined open cavity by solving governing equations via finite volume method. Their results showed that the inclination angle affects the flow field, the temperature distribution, the heat transfer mode, the heat transfer and the entropy generation rates, and the magnitude of irreversibilities in the entropy generation. Numerical simulation of natural convection in partially C-shape open ended enclosure filled with nanofluid has been performed by Bakier [6]. He found that existence of nanoparticles increases the rate of heat and mass transfer through the opening boundaries for low Rayleigh number. Sheremet et al. [7] investigated unsteady natural convection in a differentially heated wavy-walled open cavity filled with a nanofluid. The obtained results showed that an increase in the undula-

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tions number leads to a decrease in the average Nusselt number at wavy wall due to the significant heating of the wave troughs.

Effect of magnetic field on convection heat transfer is discussed by Heidary et al. [8]. They observed that the heat transfer in channels can enhance up to 75% due to the presence of nanoparticles and magnetic field in channels. Kefayati [9] solved the effect of a magnetic field on natural convection in an open enclosure which subjugated to water/alumina nanofluid using Lattice Boltzmann method (LBM). Obtained results showed that the heat transfer decreases by the increment of Hartmann number for various Rayleigh numbers and volume fractions and the magnetic field augments the effect of nanoparticles at Rayleigh number of $Ra = 10^6$ regularly. Mejri and Mahmoudi [10] examined the natural convection in an open cavity filled with a water–Al_2O_3 nanofluid and subjected to a magnetic field with a sinusoidal thermal boundary condition by using LBM. It was found that the heat transfer rate decreases with an increase in Hartmann number and increases with the rise of Rayleigh number. Bondareva et al. [11] analyzed unsteady natural convection of a water based nanofluid in a trapezoidal cavity under the influence of a uniform inclined magnetic field using the two-phase nanofluid model. It was ascertained that low Lewis and high Hartmann numbers reflect essential non-homogeneous distribution of the nanoparticles inside the cavity. Therefore the considered range of *Le* and *Ha* characterizes a competency of utilizing of the non-homogeneous model. Mahmoudi et al. [12] worked on natural convection in nanofluid filled cavity under magnetic field including heat generation/absorption boundary conditions.

Wavy walled cavities can be seen in different engineering applications such as heat exchanger, solar energy applications or buildings [13]. In this context, Cho et al. [14] presented an application on natural convection and entropy generation in a nanofluid filled cavities. Billah et al. [15] made a numerical simulation on buoyancy-driven heat and fluid flow in a nanofluid filled triangular enclosure as an application of curvilinear boundaries. They used Galerkin finite element method to solve governing equations and found that heat transfer was increased by 28% as volume fraction δ increases from 0% to 20% at $Gr = 10^5$. Other applications on wavy-walled enclosure filled with nanofluid can be found for wavy-walled porous cavity with a nanofluid presented by Sheremet et al. [16] and combined convection flow in triangular wavy chamber by Nasrin et al. [17].

Partial heater can be seen especially in electronic cooling and building heating applications [18,19]. These applications are reviewed by Oztop et al. [20]. The corner heater is a specific application to see the effects of heater dimensions on natural convection. There are many works on this application such as natural convection in inclined enclosure with a corner heater by Varol et al. [21], natural convection coupled with radiation in an inclined porous cavity by Ahmed et al. [22]. Other related paper can be found in Refs. [23–25].

The main aim of this paper is to investigate the natural convection heat transfer and fluid flow in an open nanofluid filled porous wavy cavity in the presence of corner heater and magnetic field. In the study, Cu–water nanofluid is chosen because its cost is very low and copper is common material and it can be prepared easily.

2. Basic equations

The natural convective heat transfer in a porous medium saturated with an electrically, conducting Cu–water nanofluid located in a partially open cavity with left wavy, right and bottom flat solid walls is analyzed. The considered domain of interest is presented in Fig. 1. The analyzed cavity includes isothermal left wavy wall of cold temperature and a heater of constant temperature in the right

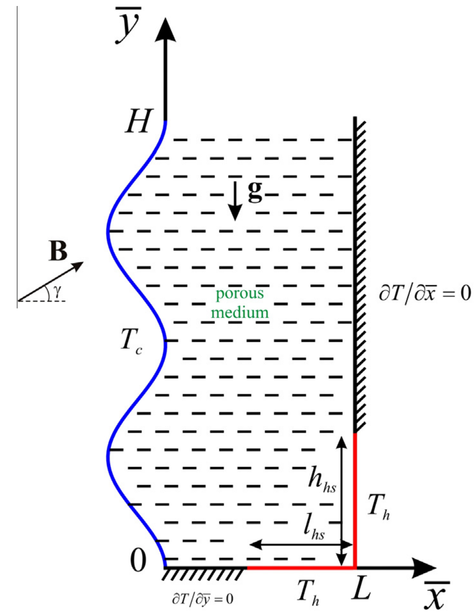

Fig. 1. Physical model and coordinate system.

bottom corner. An inclined uniform magnetic field affects natural convection inside a porous cavity. The magnetic Reynolds number is assumed to be small so that the induced magnetic field can be neglected compared to the applied magnetic field. It is worth noting that the left wavy wall and right flat wall of the open cavity are defined by the relations such as: $\bar{x}_1 = L - L[a + b\cos(2\pi\kappa\bar{y}/H)]$ is the left wavy wall; $\bar{x}_2 = L$ is the right flat wall; $\bar{\Delta} = \bar{x}_2 - \bar{x}_1 = L[a + b\cos(2\pi\kappa\bar{y}/H)]$ is the distance between the right flat and left wavy walls.

It is assumed that the nanofluid temperature is equal to the solid matrix temperature everywhere in the homogeneous and isotropic porous medium, and the local thermal equilibrium model is used. In the present study, the Darcy–Boussinesq model has been adopted in the governing equations of the problem. Taking into account these assumptions the governing equations can be written in dimensional Cartesian coordinates

$$\nabla \cdot \bar{\mathbf{V}} = 0 \tag{1}$$

$$0 = -\nabla p - \frac{\mu_{\mathrm{nf}}}{K}\bar{\mathbf{V}} - (\rho\beta)_{\mathrm{nf}}(T - T_0)\mathbf{g} + \mathbf{I} \times \mathbf{B} \tag{2}$$

$$(\bar{\mathbf{V}} \cdot \nabla T) = \alpha_{\mathrm{mnf}}\left(\frac{\partial^2 T}{\partial \bar{x}^2} + \frac{\partial^2 T}{\partial \bar{y}^2}\right) \tag{3}$$

$$\nabla \cdot \mathbf{I} = 0 \tag{4}$$

$$\mathbf{I} = \sigma_{\mathrm{nf}}(-\nabla\varsigma + \mathbf{V} \times \mathbf{B}) \tag{5}$$

where $\bar{\mathbf{V}}$ is the dimensional velocity vector, p is the pressure, T is the fluid temperature, $\mathbf{g}$ is the gravity vector, $\mathbf{B}$ is the external magnetic field vector, $\mathbf{I}$ is the electric current vector, ζ is the electric potential, μ_{nf} is the dynamic viscosity of nanofluid, α_{mnf} is the effective nanofluid thermal diffusivity saturated in porous medium, β is the coefficient of thermal expansion, σ_{nf} is the electrical conductivity of nanofluid and $-\nabla\varsigma$ is the associated electric field. As discussed by Revnic et al. [26], Eqs. (4) and (5) reduce to $\nabla^2\varsigma = 0$.

Eqs. (1)–(5) for the problem under consideration can be written, after the pressure p is eliminated by cross-differentiation, in Cartesian coordinates $\bar{x}$ and $\bar{y}$ as