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Investigation on effect of magnetic field on mixed convection heat transfer in a ventilated square cavity

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Abstract

The effect of applying the magnetic field on the mixed convection heat transfer in a ventilated square cavity filled with base fluid (water) has been investigated numerically. The upper wall of presented cavity was held at constant temperature and the bottom one was at constant heat flux. The right and left walls are adiabatic. An external flow enters the cavity through a port in left vertical wall and leaves through right one. The governing equations were discretized by a finite volume method and solved with SIMPLE algorithm. In this article, the effects of the Richardson number and Hartmann number parameters on the fluid flow and heat transfer rate have been examined. The obtained results showed that the heat transfer rate decreases with an increase of the Hartmann number.

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Keywords: Mixed convection; ventilated cavity; Hartmann number; Richardson number

1. Introduction

Magneto-Hydrodynamics (MHD) convections have various applications in engineering and industrial fields. Crystal growth in liquid, cooling of nuclear reactor, electronic package, microelectronic devices, and solar

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technology are some examples. Several studies have been done in recent decade on the effect of the magnetic field on convective heat transfer in cavities. Öztop et al. [1] investigated the effect of applying the external magnetic field on behaviour of a fluid in a cavity with two isothermal semi-circular heaters. Kandaswamy et al. [2] have done a numerical study on the magneto convection flow in a cavity with partially active vertical walls; they have assumed nine different positions of active zones for various magnitudes of the Rayleigh number (Ra) and Hartmann number (Ha). Their results showed that the mean Nusselt number decreases as the Ha and the Ra increase; also, in large magnetic field magnitude, the convection heat transfer in cavity was converted into a conduction regime. Siddiqa et al. [3] studied the effect of Hall current on the MHD natural convection flow of a viscous incompressible fluid along a semi-infinite uniformly heated vertical plate in presence of a strong cross-magnetic field with considering of a boundary layer analysis. Pirmohammadi and Ghassemi [4] investigated the effect of the magnetic field on convection heat transfer within a tilted square cavity. They found that the heat transfer mechanism and flow characteristics have affected within the cavity by the magnetic field and inclination angle. Öztop et al. [5] did a numerical investigation to study the laminar mixed convection flow in the presence of magnetic field in a lid-driven cavity that heated from a corner by heater. Saleh et al. [6] presented an investigation to study the natural convection heat transfer in a porous trapezoidal cavity with an inclined magnetic field numerically; they studied different magnitude of Ra, Ha numbers and magnetic field inclination angle; results showed that an optimum mode was obtained for the heat transfer rate. Hasa- nuzzaman ET al. [7] have done a numerical investigation on the MHD flow effect on the natural convection for a trapezoidal cavity. Al-Salem et al. [8] did a study on the effects of moving lid direction on MHD mixed convection in a square cavity.
In this article the effect of applying the magnetic field on mixed convection heat transfer in a cavity with inlet and outlet ports has studied.

2. Governing equations and problem formulation

Fig. 1 shows the studied geometry. The effect of applying the magnetic field on this geometry had studied, as a way to increase the heat transfer. Two-dimensional square cavity includes a hot bottom horizontal wall with a constant heat flux and cold upper one is considered to have constant temperature. Both left and right vertical walls are insulated. The Inlet and outlet ports are located on the bottom of the left and the top of the right side wall, respectively. The ratio of the length of inlet or outlet port to the length of the cavity is 0.1. The magnetic field is considered to apply in the positive direction of X-axis of the cavity, and its magnitude is constant and equal to B0.

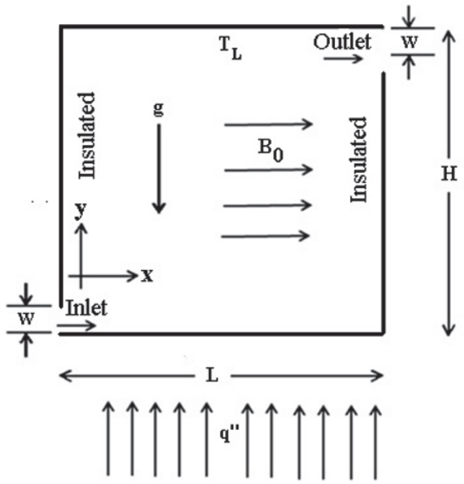

Fig. 1. Schematic of ventilated cavity.

It was assumed that the cavity is filled with 1% Cu-water nanofluid. The thermo-physical properties of nanoparticles and the water can be seen in Table 1.

Table 1. Thermo-physical properties of water and nanoparticles (Mahmoudi et al. [9])

property	Water	Cu nanoparticles
Specific heat, Cp (J/kgK)	4179	385
Thermal conductivity, K (W/mK)	0.613	400
Thermal expansion coefficient, β (1/K)	2.1×10^{-4}	1.67×10^{-5}
Density, ρ (kg/m3)	997.1	8933

The flow of this simulation was considered to be incompressible, steady, Newtonian and laminar. The viscous dissipation in the energy equation has been neglected. Also all of properties except the density are considered to be constant. The density varies according to the Boussinesq approximation.

The dimensionless variables which are used to achieve dimensionless form of the governing equations are listed as follows:

$$X=\frac{x}{L},Y=\frac{y}{L},U=\frac{u}{u_i},V=\frac{v}{u_i},\ \theta=\frac{(T-T_L)k_f}{q"L},P=\frac{p}{\rho_{nf}{u_i}^2} \tag{1}$$

The dimensionless form of the governing equations (continuity, momentum and energy equations) for laminar and steady state mixed convection fluid flow and heat transfer with the Boussinesq approximation in y-direction are as following:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{2}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\frac{\rho_f}{\rho_{nf}}\frac{1}{(1-\Phi)^{2.5}}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right) \tag{3}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\frac{1}{\mathrm{Re}}\frac{\rho_f}{\rho_{nf}}\frac{1}{(1-\Phi)^{2.5}}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)+\mathrm{Ri}\frac{\rho_f}{\rho_{nf}}\left(1-\Phi+\Phi\frac{\rho_s\beta_s}{\rho_f\beta_f}\right)\theta-\frac{\rho_f}{\rho_{nf}}\frac{\sigma_{nf}}{\sigma_f}\frac{\mathrm{Ha}^2}{\mathrm{Re}}V \tag{4}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{k_{nf}}{k_f}\frac{(\rho c_p)_f}{(\rho c_p)_{nf}}\frac{1}{\mathrm{Re\ Pr}}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{5}$$

Where the density, heat capacity, effective dynamic viscosity of the nanofluid, the effective thermal conductivity of the nanofluid and its thermal diffusivity are as following, respectively [10]:

$$\rho_{nf}=(1-\emptyset)\rho_f+\emptyset\rho_p \tag{6}$$

$$(\rho C_p)_{nf}=(1-\emptyset)(\rho C_p)_f+\emptyset(\rho C_p)_p \tag{7}$$

$$\mu_{nf}=\frac{\mu_f}{(1-\emptyset)^{2.5}} \tag{8}$$

$$\frac{k_{nf}}{k_{bf}}=\frac{(k_p+2k_f)-2\emptyset(k_f-k_p)}{(k_p+2k_f)+\emptyset(k_f-k_p)} \tag{9}$$

$$\alpha_{nf} = \frac{k_{nf}}{(\rho C_p)_{nf}} \tag{10}$$

Where Pr, Re, Ri and Ha are Prandtel number, Reynolds number, Richardson number and Hartmann number, respectively and are defined by following:

$$\mathrm{Pr} = \frac{\upsilon}{\alpha}, \quad \mathrm{Re} = \frac{u_i L}{\upsilon}, \quad \mathrm{Ri} = \frac{\mathrm{Gr}}{\mathrm{Re}^2}, \quad \mathrm{Ha} = B_0 L \sqrt{\frac{\sigma}{\mu}} \tag{11}$$

The dimensionless boundary conditions for the presented problem are specified as follows:
Inlet port:

$$u^* = 1\ , v^* = 0\ , \theta = 0 \tag{12}$$

Outlet port:

$$\frac{\partial u^*}{\partial X} = 0, \frac{\partial v^*}{\partial X} = 0, \frac{\partial \theta}{\partial x^*} = 0 \tag{13}$$

Left solid wall:

$$u^* = 0\ , v^* = 0\ , \frac{\partial \theta}{\partial x^*} = 0 \tag{14}$$

Right solid wall:

$$u^* = 0\ , v^* = 0\ , \frac{\partial \theta}{\partial x^*} = 0 \tag{15}$$

Top solid wall:

$$u^* = 0\ , v^* = 0\ , \theta = 0 \tag{16}$$

Bottom solid wall:

$$u^* = 0\ , v^* = 0\ , \frac{\partial \theta}{\partial y^*} = \frac{k_{bf}}{k_{nf}} \tag{17}$$

The local Nusselt number over the heat transfer walls was calculated by:

$$\mathrm{Nu} = \frac{hL}{k_f}, h = \frac{q_0''}{T_s - T_L}, \mathrm{Nu} = \frac{1}{\theta_s} \tag{18}$$

And the mean Nusselt number over the hot wall is:

$$Nu_m = \frac{\int Nu dn}{\int dn} \tag{19}$$

The governing equations have been discretized using the finite volume method numerically. Utilizing the SIMPLE algorithm made the velocity and pressure to be coupled in the momentum equation [11]. Whenever the difference between two successive iterations was less than 10^{-7} for every equation and every discrete control volume, the assumption of converging solution was considered. A square cavity was assumed as the solution domain. Finally a 101×101 uniform grid was selected for square cavity because it is fine enough to obtain precise results. To validating the presented numerical model, the numerical results were compared with those presented in Mehrez et al. [12].

3. Results and discussion

As mentioned in introduction, the effect of the magnetic field on the mixed convection heat transfer on the hot wall in a square ventilated cavity which is filled with incompressible base fluid, had studied. Dimensionless parameters used in the simulation were: the Rayleigh number (Ra) which was assumed to be 104, the Richardson number (Ri) that changed from 10^{-1} to 10, Prandtl number was assumed to be 6.8 (Pr=6.8) and the Hartmann number (Ha) changed between 0 to 50.

3.1. The effect of applying magnetic field on heat transfer

In this section the effect of applying magnetic field on a filled cavity by base fluid has considered. For this purpose the effect of Hartmann number change in different Richardson numbers has studied.

Figure 2 shows the effect of Hartmann number change on streamlines in Richardson number equal to 0.1. Generally the magnetic field has a tendency to affect the flows of convection, and this will lead to lower of these kinds of flows.

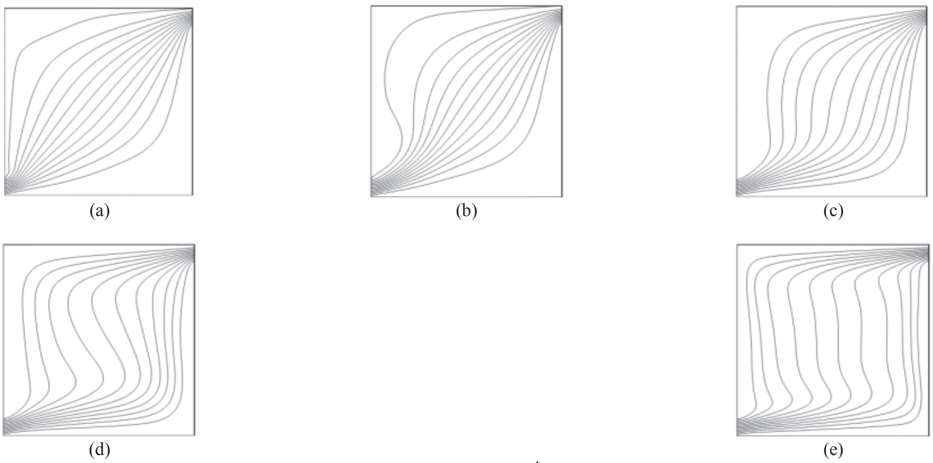

Fig. 2. The effect of applying the magnetic field on streamlines contours at Ra=10^4 and Ri=0.1a) Ha=0; b) Ha=10; c) Ha=30; d) Ha=50; e) Ha=100.

As it is illustrated in Fig. 2, without any magnetic field (Ha=0) the flow enters the cavity through inlet and then exits through outlet (Fig.2 a). But by applying magnetic field and increasing Hartmann number, it Acts like a barrier against the flow, which Leads to a better distribution of the flow inside of the cavity and finally the flow leaves through outlet. The effect of changes in Hartmann number and Richardson number on isothermal lines is illustrated in Fig. 3. As the status of the isothermal lines shows, by increasing Hartmann number that is caused by increasing of the Lorentz force, the thickness of the thermal boundary layer decreases. In the other words by increasing the Hartmann number, the centralization of the isothermal lines near the hot wall increases and the thickness of the thermal boundary layer decreases, so the temperature gradients increases.

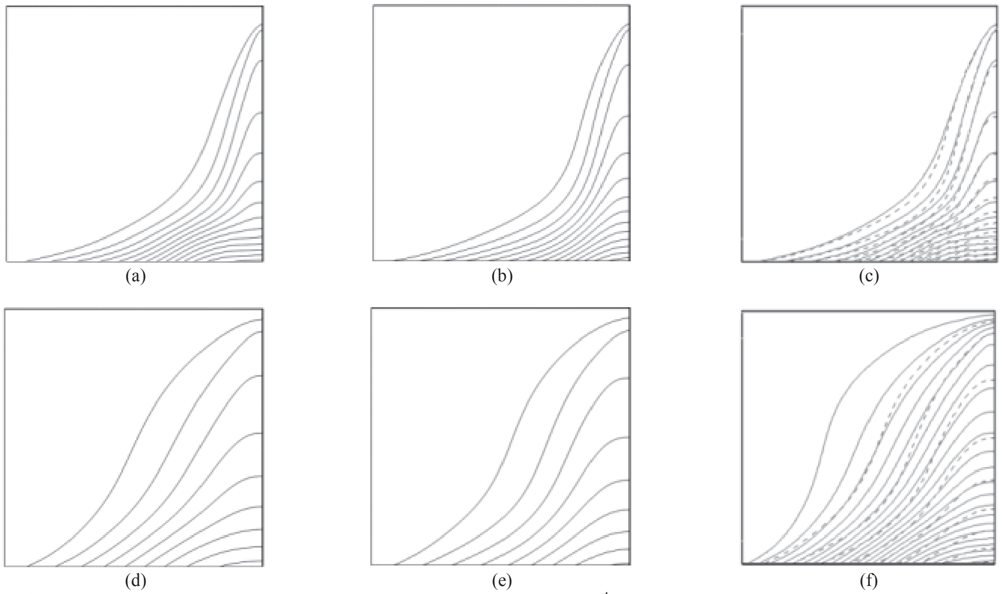

Fig. 3. The effect of applying the magnetic field on isothermal lines contours at Ra=10^4 and a)Ri=0.1and Ha=0; b)Ri=0.1anb Ha=10; c) Ri=0.1, Ha=0 (line) and Ri=0.1, Ha=10 (Dash line); d) Ri=5and Ha=0;e)Ri=5and Ha=10; f) Ri=5, Ha=0 (line) and Ri=5, Ha=10 (Dash line)

In Fig.4, dimensionless velocity and temperature profiles for section Y=0.5, with Richardson number equal to 0.1 and different Hartmann numbers are illustrated. As this figure shows, by increasing the Hartmann number caused by increasing Lorentz force, the temperature increases, which it leads to decrease in, mean Nusselt number according to relation (18).

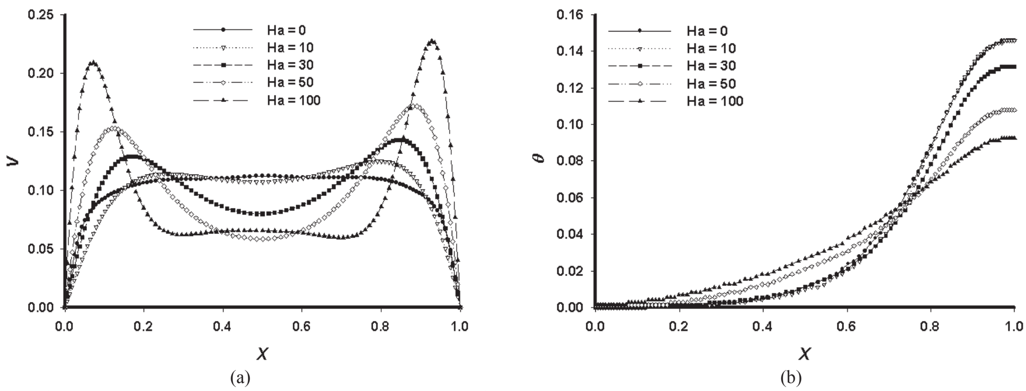

Fig. 4. The effect of variation of Hartmann number on a) dimensionless velocity profile; b) dimensionless temperature profile at Y=0.5, Ri=0.1 and Ra=10^4.

The effect of Hartmann numbers change in different Richardson numbers on the mean Nusselt number is shown in Fig. 5. As it is illustrated in this figure, by increasing the Hartmann number and Richardson number the mean Nusselt number decreases. According to momentum equation in Y direction, the Lorentz force and plunge force act in opposite directions. Hence by increasing the Richardson number which means the convection heat transfer is natural convection, As much as the magnetic field increases, the velocity of the flow decreases more, which leads to a rise in temperature and decreases heat transfer.

4. Conclusion

The results of a numerical investigation on the Magneto-Hydrodynamics (MHD) mixed convection heat transfer within a ventilated square cavity with entering and exiting port has presented in this paper. The following results were obtained from numerical simulation:

- Increasing Richardson number means decreasing Reynolds number and it causes a reduction in flow velocity which results weaker convection. On the other hand as velocity and temperature fields are coupled, by decreasing the velocity, the temperature increases. This means decreasing in Nusselt number according to relation (18).
- By increasing Hartmann number that is caused by increasing of the Lorentz force, the thickness of the thermal boundary layer decreases. In the other words by increasing the Hartmann number the centralization of the isothermal lines near the hot wall increases and the thickness of the thermal boundary layer decreases, so the temperature of the hot wall increases and causes the decrease in average Nusselt number.

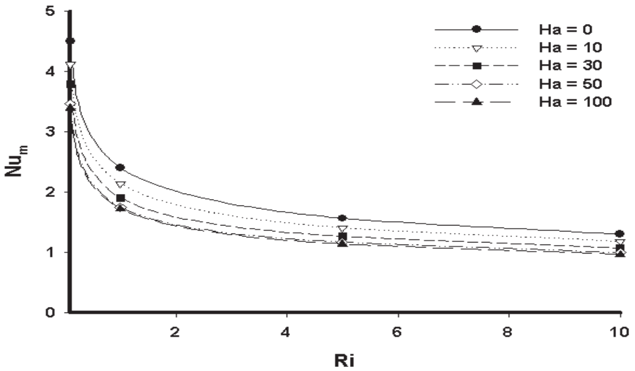

Fig. 5.the effect of variation of magnetic field at different Richardson numbers on the mean Nusselt number at Ra=10^4 and Ri=0.1.

Acknowledgements

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