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Heat and Fluid Flow Characteristics of Natural convection with Magnetic Field Effects in a Porous Cavity

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ABSTRACT
Simulation of natural convection in a Cu-water filled porous cavity with the magnetic field effects are studied numerically. The cavity is heated at bottom wall while the vertical boundary walls are kept at lower temperature and top wall of the cavity is adiabatic. The two-dimensional governing equation in a cartesian coordinate is represented by continuity, momentum and energy equation which is transformed into the vorticity and stream function. The finite difference technique is used to solve the equations. The flow in a cavity is represented as streamlines and isotherms for the different values of parameters Ra, Da and Ha at volume fraction $\phi = 0.1$. The heat transfer rate is altered by increase in Ra at different Da and Ha. The flow patterns and heat transfer range inside the cavity is more affected by magnetic field at Da = 100. The results obtained is compared with the one available in the literature for validation and further cases are discussed using plots.
KEYWORDS;-*Nanofluid, porous, magnetic, cavity*

I. INTRODUCTION

In the past three decades, the application of natural convection in a porous media has increased in many fields such as oil recovery process, soil pollution, geothermal extraction, food processing, chemical separation processes and in many other fluid flow and heat transfer processes [1][2]. A survey of heat transfer in nanofluid saturated porous media by the natural convection is discussed by Nield and Bejan[3].

Nanofluid in a porous cavity with magnetic field having different models and geometry is studied by Sheikholeslami et al. [4]. Balla et al. [5] have studied the free convection of magnetohydrodynamic boundary layer flow over an inclined nanofluid filled square cavity with nanofluid saturated porous medium and heat transfer. They investigate the flow and heat transfer by employing the weighted residual Galerkin's finite element method. They discuss results for various value of Rayleigh number, Magnetic parameter, and Inclined angle. Mansour et al. [6] investigated the Natural convection of MHD Cu-Al_2O_3-water hybrid nanofluid and heat transfer in a differentially heated/cooled square porous cavity by source and sink along with the entropy generation. They employ the finite difference method along with Successive-under-relaxation method. They discuss the results for Hartmann number, Darcy number, Nanofluid volume fraction, heat source/sink dimensions, heat source/sink parameter, Nusselt number etc. Khanafer and Chamkha [7] studied the effect of inclination of a cavity, porous and magnetic field on natural convective square enclosure. The study reveals that, suppression in the flow field occurs while in the presence of porous and magnetic field. Chamkha and Naser [8] also studied the double diffusive effect on natural convection in the inclined porous cavity. Kumar et al. [9] analyzed the sinusoidally heated boundary effect on the natural convective porous (using Carman-Kozeny equation) cavity with considering magnetic field effects. Chamkha et al. [10] discussed the heat transfer on phase change process of nanofluid filled cavity with heated horizontal cylinder inside. Chamkha [11] studied in detail about heat transfer effect of Hartmann number over the porous medium. Gorla and Chamkha [12] investigated the skin friction, surface heat transfer and surface mass transfer rate of nanofluid fill up in the porous media. Ratish Kumar and Krishna Moorthy [13] have studied the mixed convection in a rectangular shaped enclosure with fluid saturated porous medium having multiple injection/suction at the bottom/top walls. Desai and Vafai [14] reported an experimental and numerically simulated study of natural convection and heat transfer in an open annular cavity. Their investigation reports the results for higher Rayleigh number buoyancy driven induced-flows for the first time. Mixed convection in a porous cavity with sinusoidally heated wall is discussed by Anirban Chattopadhyay et al. [15] and they showed that increase in the amplitude ratio increases the heat transfer rate. Tanmay Basak et al. [16] numerically studied the natural convection in the square porous cavity with the various boundary conditions for different values of Prandtl, Darcy and Rayleigh number. Internal heat generation effects on natural convective rectangular porous cavity is discussed by Grosan et al. [17].

Chamkha et al. [18] investigated natural convective and magnetic field effect in the cavity (c-shaped) fill up with the nanofluid (CuO-water). The investigation quotes that, an increase in nano particle solid volume fraction increases the heat transfer rate and magnetic field signifies the opposite effect. Mohebbi et al. [19] discussed heat transfer due to the effect of location of the heated source over a cavity of c-shaped. The effect of magnetic field in a square cavity filled with the nanofluid is discussed by Ghasemi et al. [20] and concluded that increase in Hartmann decreases the heat transfer rate and increase in Rayleigh number enhances the heat transfer rate. Rudraiah et al. [21] discussed the effect of magnetic field (Hartmann number, Ha) and the surface tension in the rectangular cavity and concluded that average Nusselt number decreases with Ha and increases with Marangoni number. Earlier, Wilkes and Churchil [22] reported the nature of flow inside a cavity using finite difference method which serves as benchmark for investigation which followed later.

In the present work, the effect of natural convection in porous cavity applied filled with the nanofluid having magnetic field having hot boundary at the bottom has been reported. The heat transfer and flow fields are displayed using plots and results are discussed.

II. MATHEMATICAL FORMULATION

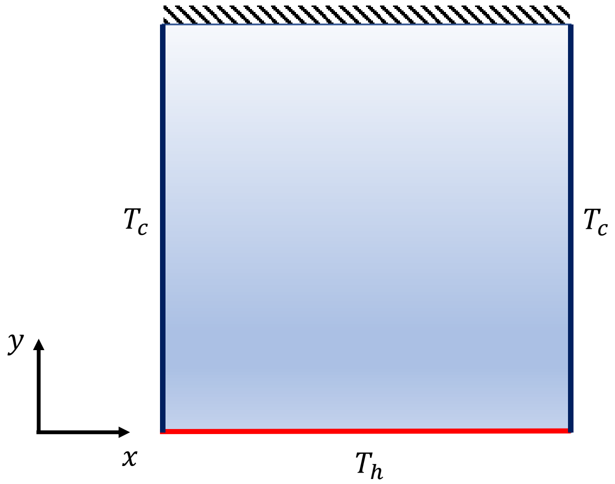

Fig. 1. Physical problem

Consider a porous square cavity of dimension, l units along the horizontal and vertical axis, x, y respectively. The horizontal and vertical velocity along the x and y direction is denoted by u, v. The left-bottom corner represents the origin of the cavity or the cartesian coordinate. The left and right face, that is at $x = 0, x = l$, of the cavity is maintained at the temperature, T_c. The bottom face, at $y = 0$, is maintained at the temperature, T_h ($T_c < T_h$). The top face, at $y = l$, is maintained adiabatically. The porous square cavity is filled with *Cu*-water (Prandtl number, $Pr = 6.2$) nanofluid. The velocity u and v are along the x and y direction in cartesian coordinate system respectively. The bottom wall is kept at higher temperature (T_h), compared with the vertical walls which are maintained at lower temperature (T_c) and the top wall is maintained adiabatically. The fluid is Newtonian having constant and incompressible properties with laminar flow. The effect of radiation and friction is ignored. The fluid is Boussinesq type. The flow through the porous media can be governed by the Carman-Koseny equation [23]. With the mentioned assumptions, the fluid flow governing equations namely the continuity, momentum and energy equations are given as follows,

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

$$\rho_n \left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right] = \mu_n \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\partial p}{\partial x} - \rho_n \frac{C_m (1-\lambda)^2}{\lambda^3} u \tag{2}$$

$$\rho_n \left[\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right] = \mu_n \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\partial p}{\partial y} - \rho_n \frac{C_m (1-\lambda)^2}{\lambda^3} v + (\rho\beta)_n g\left(T - T_{ref}\right) - \sigma_n B^2 v \tag{3}$$

$$\left(\rho c_p\right)_n \left[\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right] = k_n \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

where u, v, p, T is the dimensional velocities, pressure and temperature at x and y axis respectively. $C_m$is the porosity constant(Carman-Koseny equation constant) and liquid fraction λ. The liquid fraction is the fraction of liquid over the solid surface. The constants σ, B, g are the electrical conductivity, magnetic field intensity and gravity respectively.

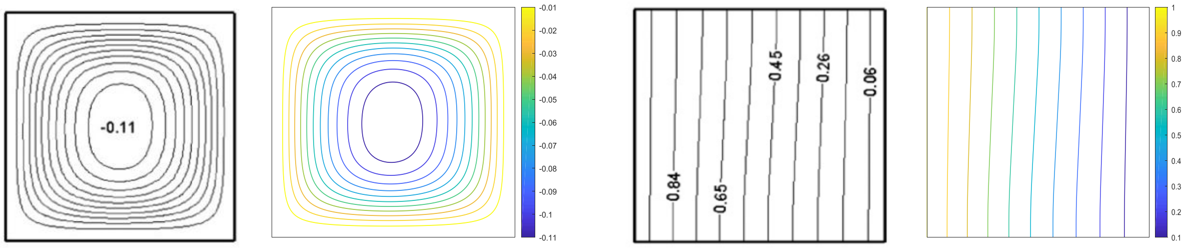

Fig. 2. Validation of present study (coloured) against Ghasemiet al. [20]($for\ the\ values\ of\ Ra = 10^3$, ϕ=0.03, Ha=30.

The thermophysical properties of nanofluids such as density, heat capacitance, coefficient of thermal expansion, viscosity and thermal conductivity are depending on the volume fraction (ϕ).

$$(\rho c_p)_n = (1-\phi)(\rho c_p)_{fl} + \phi(\rho c_p)_p, \qquad \rho_n = (1-\phi)\rho_{fl} + \phi\rho_p,$$
$$(\rho\beta)_n = (1-\phi)(\rho\beta)_{fl} + \phi(\rho\beta)_p, \qquad \mu_n = \mu_{fl}/(1-\phi)^{2.5},$$
$$k_n = k_{fl}[k_p + 2k_{fl} - 2\phi(k_{fl} - k_p)]/[k_p + 2k_{fl} - 2\phi(k_{fl} - k_p)]\ .$$

The non-dimensional form of equations (1-4) is given by,

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \qquad (5)$$

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = \frac{\mu_n}{\rho_n \alpha_{fl}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) - \frac{\partial P}{\partial X} - \rho_{fl}\frac{Pr}{Da}U \qquad (6)$$

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = \frac{\mu_n}{\rho_n \alpha_{fl}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) - \frac{\partial P}{\partial Y} - \rho_{fl}\frac{Pr}{Da}V + \frac{(\rho\beta)_n}{\rho_n \beta_{fl}}RaPr(\theta) - Ha^2\mathrm{Pr}(V) \qquad (7)$$

$$\frac{\partial \theta}{\partial \tau} + U\frac{\partial \theta}{\partial X} + V\frac{\partial \theta}{\partial Y} = \frac{\alpha_n}{\alpha_{fl}}\left(\frac{\partial^2 \theta}{\partial X^2} + \frac{\partial^2 \theta}{\partial Y^2}\right) \qquad (8)$$

with boundary conditions,

$$U = V = \theta = 0, at\ X = 0\ and\ X = 1, 0 \le Y \le 1.$$
$$U = V = 0, \theta = 1\ at\ Y = 0\ and\ \partial\theta/\partial Y = 0\ at\ Y = 1, 0 \le X \le 1.$$

where $X = x/l$, $Y = y/l$, $U = [ul]/\alpha_{fl}$, $V = [vl]/\alpha_{fl}$, $P = [pl^2]/[\rho_n \alpha_{fl}^2]$, $\theta = T - T_C/T_h - T_c$ are the dimensionless axis, velocities, pressure and temperature. The other dimensionless parameters $Pr = \nu_{fl}/\alpha_{fl}$, $Ra = [g\beta_{fl} l^3 (T_h - T_c)]/[\nu_{fl}\alpha_{fl}]$, $Ha = Bl\sqrt{\sigma_n/[\rho_n \nu_n]}$ and $Da = [\mu_{fl}\lambda^3]/[C_m(1-\lambda)^2 l^2]$ are the Prandtl number, Rayleigh number, Hartmann number and Darcy number respectively.

The heat transfer rate at bottom wall are denoted by Local Nusselt number (Nu) which is denoted as

$$Nu = -\frac{k_n}{k_{fl}}\left(\frac{\partial \theta}{\partial Y}\right)_{Y=0} \qquad (9)$$

	ρ	μ	c_p	α	β
Water	997.1 kg/m^3	8.9×10^{-4}Pa s	4179 J/kg K	0.6W/m K	2.1×10^{-4} k
Copper nanoparticles	8954 kg/m^3	–	383 J/kg K	400 W/m K	1.67×10^{-5}

Table 1. *Thermophysical properties.*

III. NUMERICAL SOLUTION AND VALIDATION

The dimensionless equations (5-8) with boundary conditions are converted to stream function-vorticity equation and solved using finite difference technique. The implicit finite difference method of Crank-Nicolson type along with Successive-over-relaxation method is employed to solve the discretized stream function-vorticity equation. Stream function and the isotherms are represented in Fig. 2 along with the one results obtained by Ghasemi et al. [12]. It is found that the results are in good agreement. This validates our computation. Hence, this proves that the results obtained here are authentic.

IV. RESULTS AND DISCUSSION

The flow in a cavity with the subjected boundary conditions are shown by the streamlines, isotherms and the heat transfer rate at bottom wall by Nu. The flow patterns are attained for the various values of $Ra = 10^3 \text{to} 10^6$, $Da = 10^{-2}, 10^2$ and $Ha = 0, 50$The properties of base fluid, water and the nanoparticle, copper are listed in the table. 1.

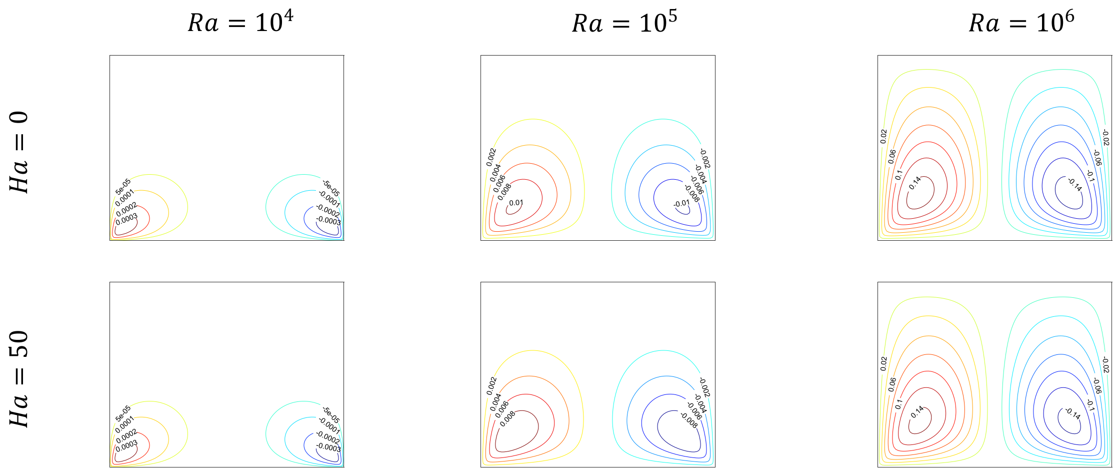

Fig. 3. Streamlines for various *Ra* and *Ha* at $Da = 10^{-2}$

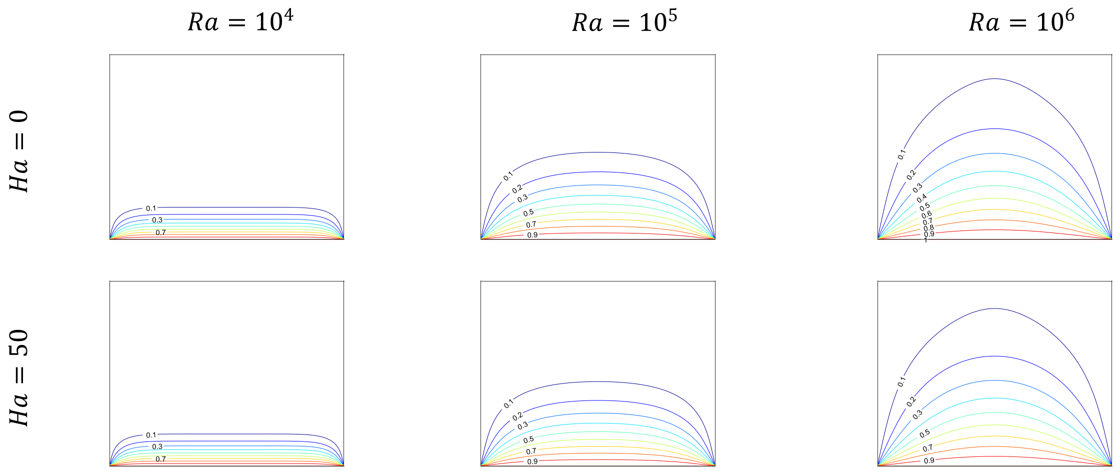

Fig. 4. Isotherms for various Ra and Ha at $Da = 10^{-2}$

From Fig. 3 and Fig. 5 describes the patterns of streamlines for different values of Rayleigh number, *Ra*, Hartmann number, *Ha* and Darcy number, *Da*. For constant *Ha*, As the *Ra* increases the streamlines gradually emerge from the corners and expand towards the centre. The spirals grow as the *Ra* increases. The spirals were distinct and they can be observed clearly for small *Da* number Fig. 3, but from Fig. 5 it can be seen that the spirals have detached from the corner and move adjacent to each other, also increasing in intensity with increase in Rayleigh number.

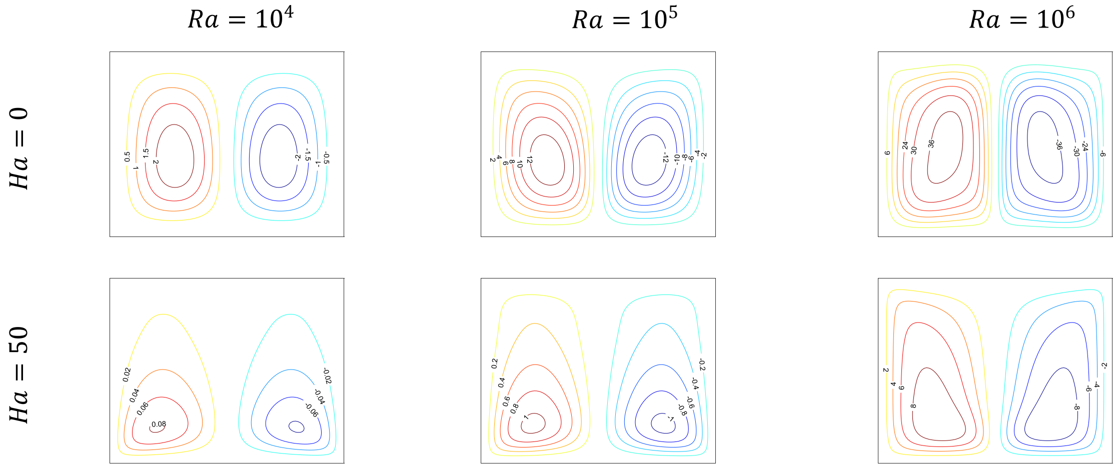

Fig. 5. Streamlines for various Ra and Ha at $Da = 10^2$

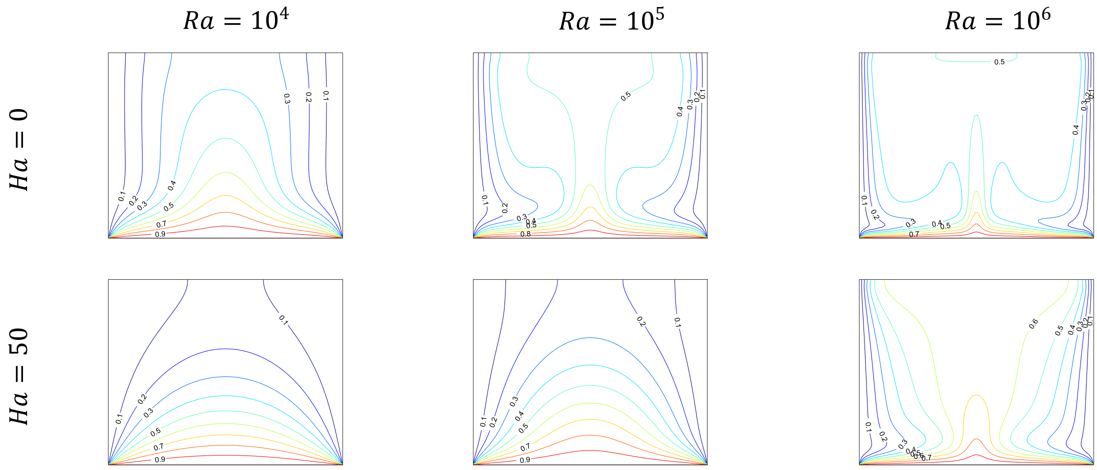

Fig. 6. Isotherms for various Ra and Ha at $Da = 10^2$

From Fig. 4 and Fig. 6 describes the patterns of isotherms for different values of Rayleigh number, *Ra*, Hartmann number, *Ha* and Darcy number, *Da*. In the case of isotherms in can be observed from these figures that the isotherm emerge from the bottom face of the cavity as the temperature at bottom is higher compared to adjacent face. This increases as the *Ra* increases. The difference is not distinct for different *Ha* for small *Da*. But it becomes distinct when the *Da* is increased to 10^2. Here the isotherms gets generated and parts away quickly for smaller *Ha* compared to larger *Ha*. This can attributed to the fact that the *Ha* subdues the flow of the fluid thereby not allowing the isotherms to part away and being small as compared to *Da* number being large. Also, as the *Ra* increases the isotherms expands towards the top face and then separates away, Fig. 5.

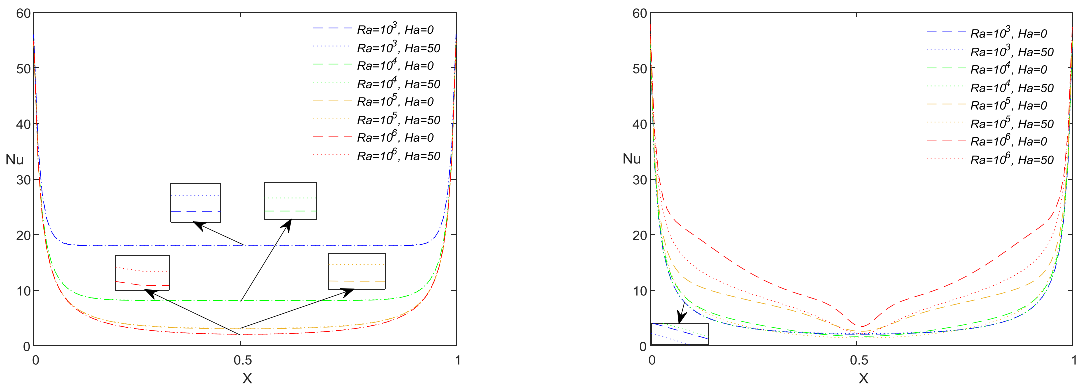

Fig. 7. Local Nusselt number at bottom wall (a) $Da = 10^{-2}$, (b) $Da = 10^2$

Fig. 7 describes the Nusselt number, Nu, for the different values of Ra and Ha. At $Da = 10^{-2}$, the increase in the Ra makes the decrease in the Nu and magnifies negatively (the difference in Nu decreases as increase in Ra). The effect of increase in Ha makes a small increase in the Nu. At $Da = 10^{2}$, the Nu is higher at the edges of bottom wall because of the discontinuity in the bottom wall temperature at edges Nu reduces towards the middle of the bottom wall. The increase in the Ra increases the Nu, the heat transfer rate is less in middle of wall as compared to other edges and increase in the Ha makes decrease in the Nu.

V. CONCLUSION

The present study exhibits the features concerning the natural convection effects in the porous cavity containing Cu-water nanofluid with the effect of magnetic field. The numerical results are shown graphically as streamlines, isotherms and local Nusselt number. The present study concludes that,

- The effect magnetic field increases when increasing in the Da.
- The magnetic field makes the suppression of the convective flow stronger on higher Da.
- An increase in magnetic field has lesser effect on lower Da.
- The increase in the Ra increases the Nu and increase in Ha decreases the heat transfer rate for higher Da.
- The increase in the Ra decreases the heat transfer rate and increase in Ha increases Nu for lower Da.

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