NATURAL CONVECTION OF WATER-CU NANOFLUID IN A POROUS CAVITY WITH TWO PAIRS OF HEAT SOURCE-SINK AND MAGNETIC EFFECT

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ABSTRACT

A numerical study of flow behaviour in a cavity due the natural convection and applied magnetic field is carried out. The heat transfer from the heated boundary and the flow patterns are derived by using the governing equations which are non-dimensionalized and solved using the FDM (Finite Difference Method). The flow patterns are visualized by streamlines and isotherms for different values of non dimensional parameters Ra, Da, ϕ, Ha . Resuction in streamline velocity occurs for increase in ϕ, Ha and with decrease in Da . The heat transfer from the source/sink from the bottom of the cavity is described using the average Nusselt number.

KEYWORDS: Porous Cavity, Natural Convection, Magnetic Field, Nanofluid, Source/Sink

Received: Jun 08, 2020; **Accepted:** Jun 28, 2020; **Published:** Sep 22, 2020; **Paper Id.:** IJMPERDJUN20201378

INTRODUCTION

Study of fluid flow through a porous matrix have an application in various fields such as crystal growth, phase change progress, manufacturing, geothermal extraction, contaminant transport, etc. (Bejan (2006); Dullien (1979); Ingham et al. (2004)). There has been lot of study of fluid flow inside an square cavity. Various physical conditions have been incorporated and investigated for flows inside square cavity.

Saeid (2005) discussed the heat and flow field due to natural convection in a porous rectangular enclosure heated partially at the bottom wall. The length of the heat source and Rayleigh number signifies the heat transfer rate. Basak et al. (2006) analysed the natural convective effect of various thermal boundaries in square cavity fill up with the porous medium. The analysis shows that heat transfer and flow circulation intensity get increased for increasing the Darcy number. Balla et al. (2017) discussed the effect of different nanoparticles in MHD free convection. Mehmood et al. (2017) examined the inclination of magnetic field on natural convection in an alumina-water filled porous cavity. Sheikholeslami (2017) did analysis on MHD natural convection in a open cavity in a porous media. some of the findings quote that, an increase in flow intensity and the shape of flow field changed for increase in the Darcy number. Gorla et al. (2017) reported the result of MHD natural convective effect in a cavity at porous media heated and cooled with the source/sink. The results reports, the magnitude of flow velocity and Nusselt number reduces for increase in the Hartmann number and solid volume fraction. Sureshkumar et al. (2018) discussed the inclination of magnetic field in a top lid driven square porous cavity filled with nanofluid. Mansour et al. (2018) analysed the effect of MHD natural convection, heated sources on both the horizontal boundaries and cooled cold sink on both the vertical boundaries in a porous cavity filled with the Al_2O_3 -water-Cu hybrid nanofluid. Abdulkadhim et al. (2018) discussed the conjugate heat transfer in a porous cavity partially heated on left wall boundary. Rashad et al. (2018) discussed the effect of magnetic field, natural convection, and location &

size of source/sink pair on the horizontal wall of the Cu-water nanofluid porouscavity. The best location and size of the source/sink is found in their study and it is noted that decrease in Nusselt number for increase in Hartmann number and solid volume fraction. Kumar et al. (2019) investigated flow field on non-uniform boundary conditions in Cu-water filled porouscavity. Vo et al. (2019) analyzed the effect of variation in shape of the nanoparticles, magnetic field, Rayleigh number, radiation parameter on nanofluid filled sinusoidal shaped cavity. Muthukumar et al. (2019) discussed inclined magnetic field effect on mixed convection porouscavity. Babazadeh et al. (2020) studied the flow behaviour of hybrid nanofluid on porouscavity due to radiation and magnetic field effect.

Yaghoubi Emami et al. (2018) discussed the inclination of cavity and location of heater configuration on Cu-water nanofluid porouscavity. Sheremet et al. (2015) investigated Tiwari and Das model of nanofluid in saturated porouscavity. Mahmoodi et al. (2015) reported various cases for heat transfer due to natural convection at locating the source, sink pair at different wall in a cavity filled up with the liquid gallium. Groşan et al. (2015) presented the free convection effect on nanofluid filled cavity by considering Brownian and thermophoretic effects. The work expresses that, nanoparticle concentration distribution is less near the heated wall than the cold one. Teamah and El-Maghlany (2012) presented heat generation, heat absorption and magnetic field effect in a nanofluid filled cavity. Aminossadati and Ghasemi (2011) discussed the flow patterns and heat transfer due to two pairs of source and sink pairs in the bottom of the cavity filled with the CuO/water nanofluid. Ghasemi et al. (2011) have studied the effect of variation of Hartmann number due to natural convection in an Al_2O_3 -water nanofluid cavity. Sathiyamoorthy and Chamkha (2010) studied the linearly heated boundary effect on natural convection and magnetic field in a cavity filled with the liquid gallium. Aminossadati and Ghasemi (2009) presented flow patterns and heat transfer of various nanofluids in partially heated bottom cavity with considering magnetic field effects. Mahmoodi et al. (2015) discussed the effect of location of source/sink on various boundaries under magnetic field. Rudraiah et al. (1995); Wilkes and Churchill (1966) have implemented the discretization and equation solving procedure for fluid flow in a cavity using the finite difference method.

PROBLEM DEFINITION

A square cavity of dimension $H \times H$ filled with the Cu-water nanofluid is shown in Figure 1. The two pairs of heat source-sink cover the entire length of the bottom wall deployed as sink and source from the origin of the cavity and remaining all the walls are insulated. The heat source (T_h) is maintained at a constant temperature higher than the heat sink (T_c). The nanofluid is assumed to be a laminar, Newtonian, incompressible with $Pr = 6.2$ and other some properties of the nanoparticle and the base fluid are listed in the Table 1. The flow is considered as negligible radiation effects and the dissipation, displacement currents and joule heating are also neglected.

Figure 1 : Physical Model

GOVERNING EQUATION

The dimensional governing equations of continuity, momentum and energy equations for the natural convection with magnetic and porous effect in the two-dimensional square cavity can be written in dimensional forms as follows

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

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

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

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \alpha_n \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) \quad (4)$$

By using the non-dimensional parameters, $X = x/H$, $Y = y/H$, $\tau = (t\alpha_f)/H^2$, $U = Hu/\alpha_f$, $V = Hv/\alpha_f$, $P = (pH^2)/(\rho_n\alpha_f^2)$, $\theta = (T - T_c)/(T_h - T_c)$, $Da = \mu_f\lambda^3/A(1-\lambda)^2H^2$, $Ra = g\beta_fH^3(T_h - T_c)/\nu_f\alpha_f$, $Pr = \nu_f/\alpha_f$, $Ha = BH\sqrt{\sigma_n/(\rho_n\nu_n)}$,

The final partial differential equations obtained from dimensional governing equations (1-4) is,

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

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

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

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

The thermophysical and transport properties of the colloid vary with the volume fraction (ϕ) of the particles. Colloid's density, heat capacities and part of the Boussinesq terms are calculated from the mixture relation:

$$\mu_n = \mu_{fl} / (1 - \phi_0)^{2.5}$$

$$\rho_n = (1 - \phi_0) \rho_{fl} + \phi_0 \rho_p$$

$$(\rho c_p)_n = (1 - \phi_0) (\rho c_p)_{fl} + \phi_0 (\rho c_p)_p$$

$$(\rho\beta)_n = (1 - \phi_0) (\rho\beta)_{fl} + \phi_0 (\rho\beta)_p$$

$$k_n = k_{fl} \left[[k_p + 2k_{fl} - 2\phi_0(k_{fl} - k_p)] / [k_p + 2k_{fl} - 2\phi_0(k_{fl} - k_p)] \right]$$

The governing equations (5-8) with the nanofluid properties are solved using the boundary conditions as,

$$\left. \begin{array}{l} \text{on vertical walls: } u = v = 0, \partial\theta/\partial X = 0 \\ \text{on top wall: } u = v = 0, \partial\theta/\partial Y = 0 \\ \text{on bottom wall: } u = v = 0, \theta = 1 \text{ (on the source)} \\ \theta = 0 \text{ (on the sink)} \end{array} \right\} \quad (9)$$

Table 1 : Properties of base fluid and particle

	Water	Cu Nanoparticles
ρ	997.1 kg/m ³	8954 kg/m ³
μ	8.9×10^{-4} Pas	—
c_p	4179 J/kgK	383 J/kgK
k	0.6 W/mK	400 W/mK
β	2.1×10^{-4} K ⁻¹	1.67×10^{-5} K ⁻¹

Heat transfer and averaged heat transfer from the boundary is pronounced as local Nusselt number and averaged Nusselt number.

$$Nu_m = -k_n / k_{fl} (\partial T / \partial Y) \quad (10)$$

$$Nu = \int_{\text{on heat sources}} Nu_m dX \quad (11)$$

Integrating the local Nusselt number along the length of the heat source gives the average Nusselt number. Therefore, the total heat transfer of a cavity from the source is the sum of the average numbers of the two heat sources.

NUMERICAL APPROACH AND VALIDATION OF WORK

The dimensionless governing equation (5-8) is transformed into the Streamfunction-Vorticity approach and discretized using the Finite Difference technique. A suitable square domain is made with equal grid spacing of 150×150 on either direction and the system is numerically modelled in FORTRAN. The solution makes use of an iterative process that is repeated till maximum residual of grid is below 10^{-5} . The present computational work is validated with the standard published results. Figure 2 presents the validation of current study (coloured) against streamlines and isotherms for a. Aminossadati and Ghasemi (2011) and b. Ghasemi et al. (2011).

Figure 2 : Validation with work by Aminossadati and Ghasemi (2011); Ghasemi et al. (2011)

RESULTS AND DISCUSSIONS

The fluid flow by streamlines and isotherms are presented for the fixed Prandtl number ($Pr = 6.2$) and various Rayleigh number ($Ra = 10^3, 10^4, 10^5$), Darcy number ($Da = 10^{-2}, 10^2$), volume fraction ($\phi = 0.01, 0.05, 0.1$) and Hartmann number ($Ha = 0, 50$).

Figure 3 shows the streamline flow patterns for $\phi = 0.01, Da = 10^{-2}, Ha = 0, 50$ and $Ra = 10^4, 10^5, 10^6$. Variation in Ra towards the right demonstrates the growth of outer two circulations and domination of middle circulation over the increment in the buoyancy driven effect. Along with the growth, circulation intensity also get stronger due to the applicable convective effect. It is noted that at the bottom of figure, reduction in the flow intensity for increase in Ha .

Similarly isotherm flow patterns for various values of Ra and Ha at $\phi = 0.01$ and $Da = 10^{-2}$ is shown in Figure 4. Temperature distribution ratio is more in the cavity for increase in the Ra . Here at lower Da , less effect is found in the Ha because of the domination of conduction over the convection.

Figure 3 : Streamlines contour for different values of Ra , Ha at $Da = 10^{-2}$ and $\phi = 0.01$

Figure 4 : Isotherms contour for different values of Ra , Ha at $Da = 10^{-2}$ and $\phi = 0.01$

Figure 5 : Streamlines contour for different values of Ra , Ha at $Da = 10^2$ and $\phi = 0.01$

Figure 6 : Isotherms contour for different values of Ra , Ha at $Da = 10^2$ and $\phi = 0.01$

An increase in fluid flow intensity is observed in case of increasing the $Da = 10^{-2}$ to $Da = 10^2$ as demonstrated in the Figure 5. The reason for increased flow rush is due to the increase in the permeability level in the cavity. In this case, multiplication of velocity intensity is occurs compared to lower Da and merging of two outer most circulation at $Ra = 10^4$. Later increase in Ra at higher Darcy number causes separation in circulation and also growth in circulation intensity. The discontinued heating in the bottom wall causes the oppositely directed middle circulation. It is observed that dominance of magnetic field is increased for $Da = 10^2$ as flow velocity get decreased for increase in Ha .

Figure 6 shows the isotherms for various values of Ra and Ha for $Da = 10^2$, $\phi = 0.01$. More temperature distribution is found as compared to the lower Da . Temperature distribution level is raised in case of increased Ra due to the raise in the behaviour of convection. The distribution of temperature is affected for increase in the Ha .

The streamlines and isotherms profile for various values of ϕ at $Da = 10^{-2}$, $Ha = 50$ and $Ra = 10^6$ is illustrated in the Figure 7. The maximum value of the streamline ($\psi = 0.16$) reduces to ($\psi = 0.1$) for the increase in the $\phi = 0.01$ to $\phi = 0.1$. The same sinerio is found for increase in Da to 10^2 as shown in Figure 8. This reduction in the flow intensity is due to the raise in viscosity as increase in the nano particle concentration. The viscosity is the responsible for the behaviour of flow resistance in the cavity.

Figure 7 : Streamlines(ψ), Isotherm (θ) contour for different values of ϕ at $Da = 10^{-2}$, $Ra = 10^6$ and $Ha = 50$

Figure 8 : Streamlines(ψ), Isotherm (θ) contour for different values of ϕ at $Da = 10^2$, $Ra = 10^6$ and $Ha = 50$

Average Nusselt number from the bottom wall of the cavity is show in the Figure 9 and Figure 10. Reduction in the Nu is observed for increase in Ra for the case of $Da = 10^{-2}$ and increase in the Nu is found in the case of $Da = 10^2$. At lower Da , the Nu decreases due to reduction in the conduction dominance over the increase in the Ra . For increase in the Da leads to increase in the permeability causes to fluid flow freely and domination of convection get significance over the higher Ra . The detailed view about the effect of solid volume fraction is shown in Figure 10. The advantage of heat transfer property of nano particle leads to increase in the Nu for increase in the ϕ , which is applicable for lower and higher Da . The resistance in heat transfer for applying the magnetic field can be reviewed increasing the Ha .

Figure 9 : Average Nusselt number(Nu) for different values of ϕ , Ra , Ha

Figure 10 : Average Nusselt number(Nu) for different values of ϕ , Ha and $Ra = 10^6$

CONCLUSIONS

In this paper, the discussion about the flow field and the heat transfer for the square porous cavity with two pairs of source/sink at the bottom of the wall. Some of the important results are,

- The effect of Ha is more significant in the case of higher Da .
- The flow velocity intensity gets increased for the higher Da and Ra .
- An increase in the solid volume fraction of nano particle causes the decrease in the flow intensity and increases Nu .
- The domination of natural convective effect is more applicable in the case of higher Da .
- An increase in the magnetic field effect (Ha) causes the reduction in the flow velocity and heat transfer rate.

ACKNOWLEDGEMENTS

The first author acknowledges the partial financial support through TEQIP-III Project, NIT Arunachal Pradesh.

The authors acknowledge the support through DST project. Sanction number : SERB ECR/2017/001007.

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