Numerical Simulation of Natural Convection of Micropolar Fluid in a Rectangular Porous Enclosure

C Sivarami Reddy, V Ramachandra Prasad, K Jayalakshmi

Abstract: ***The microploar fluid in a unsteady free convection of two dimensional rectangular porous enclosure has been examinednumerically. Thenon-dimensional coupled nonlinear partial differential equations is solved bystaggered gridbased projection method (MAC . The vertical walls of the rectangular enclosure are maintained with different temperatures while both bottom and top walls of the enclosure are considered adiabatic. The heat transfer has been studiedforinfluence of the Rayleigh number (Ra), vortex viscosity parameter (K) and Darcy parameter (Da) on fluid flow.The local Nureduces with augment of vortex viscosity parameter (K) but it enhance with rise ofDarcy number are illustrates in the results***

Keywords: Porous medium; micropolar fluid; MAC Method; Natural convection; staggered grid.

I. INTRODUCTION

The micropolar fluid theory is induced by Eringen [1] to develop the inadequacy of incompressible Navier-Stokes (N-S)equations to illustrate the right behaviour of different microstructure fluid flows such as muddy water, animal blood, chemical suspensions, colloidal fluids and lubricants [1].thesix degrees of freedomare there in the mathematical theory of micropolar fluids there is , out of six three are translation and the remaining are microrotation of microelements. Increasing interest to study convective heat transfer of micropolar flow characteristics because of it has beenseveral applications in different fields.The detailed micropolar fluid flow theory and its importance can be registered in review articles [2,3] and in the recent book [1,4].

Micro polar fluids Filled of Hsu *et al*. [5-7] have examined the thermal convection in enclosures. The help of the method collocation with cubic spline to solve the conservative equations like energy, vorticity, angular momentum, etc. The numerical computation is conducted with influenced value ranges of Gr, Re and wide rage values of parameters (material) associated with the microstructure fluid flows (i.e micropolar fluids).

Convective flows through porous media includes wide applications in several fields like science and engineering involving water resources engineering, civil engineering and mechanical, geomechanics, environmental science, bio engineering, material science, petroleum industry etc. They are examined mixed convection heat transfer within enclosure by the influence of vertical moving lids with the bottom hot wall. Basak*et al*.Chattopadhyay*et al*. [8] studied combined convection of porous enclosure with motion in vertical lids numerically. [9] reported different thermal wall boundaries of enclosure on convection in a porous enclosure. They are exhibited complex heat flow through Heatline approach for different values of governing key parameters. Sheremet*et al*. [10] with in the porous enclosure the reported finite difference numerical method based study of combined convection of Nano fluid. Their study performed on the effects of solid walls thickness, the thermal conductivity ratio, the thermophoresis parameter, the buoyancy-ratio parameter, the Brownianmotion parameter, Lewis numbers and Thermal Rayleigh number on the heat transfer and flow patterns. Natural convection of heat and mass transfer with in a square porous tilted enclosure under the effect of Soret and Dufour have been reported by Chandra Shekar*et al*. [11]. Lattice Boltzmann Method (LBM) based numerical simulation was conducted for convective of nanofluid within a porous enclosure under the effect ofnon-uniform magnetic field was considered by Sheikholeslami and Shehzad [12]. Thermo-solutal transport phenomena of porous enclosure with triangle shape was examined by Chamkha[13]. Effects ofthermal boundary condition of the enclosure wall and also concentration, aspect ratio and angles of inclinations on the flow patterns and temperature contours were analyzed. Finite difference method was adopted to seek the numerical solution. Several researchers have studied convective flows in porous medium for recent years [14-24].

From the above literature review, authors' knowledge the considered in this paper natural convection of micropolar fluid within a rectangular porous enclosure is discussed for the first time.The aim of this article is to analysis of natural convection in a rectangular porous media filled with micropolar fluid. Staggered grid based Marker and Cell Method is select to simulate this paper. Impacts of vortex viscosity parameter, Rayleigh numbers and Darcy number on convective flow in porous enclosureis examined.

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II. MATHEMATICAL FORMULATION

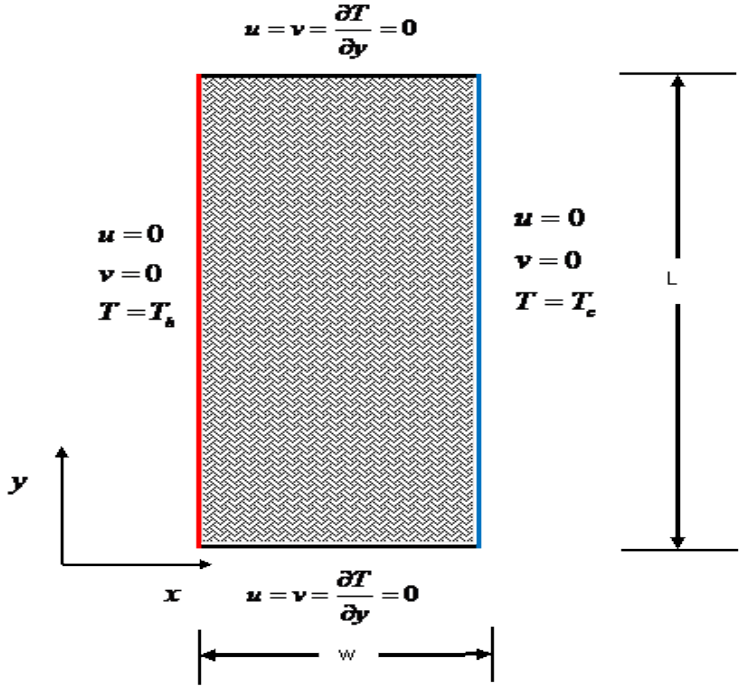


Fig. 1 Physical model and coordinate system

We consider insecure two-dimensional laminar stream of in compressible micropolarfluid of a permeable rectangular nook. The Y=0 and Y=L are the two horizontal walls which are thermally insulated when the X=0 and X=W of the vertical walls and these are maintained with different temperatures, here length of the enclosure is L and its width is W.The Brinkman extended darcy model, fluid phase for the temperature measurement and solid phase are used in this research work for thermal equilibrium rate conditions.

The cavity left wall is isothermal for boiling temperature T_h and left wall of the enclosure isothermal for cold temperature T_c. The thermo-physical chattels fluid flow is assumed to be constant except fluid density. By applying the Boussinesq approximation, the variation of density results in a body force expressed in momentum equation. Taking into account all the assumptions are mentioned as above, the mass, momentum, angular motion and energy equivalences are represented in the of form dimensional and as follows:

Equation of continuity:

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

Momentum:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+(\mu+k)\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)+k\frac{\partial \eta}{\partial y}-\frac{\mu}{\kappa}u \tag{2}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial p}{\partial y}+(\mu+k)\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)+k\frac{\partial \eta}{\partial x}-\frac{\mu}{\kappa}v+\rho g\beta\left(T-T_c\right) \tag{3}$$

Angular momentum:

$$\frac{\partial \eta}{\partial t}+u\frac{\partial \eta}{\partial x}+v\frac{\partial \eta}{\partial y}=\frac{\gamma}{\rho j}\left(\frac{\partial^2 \eta}{\partial x^2}+\frac{\partial^2 \eta}{\partial y^2}\right)-\frac{2k}{\rho j}\eta+\frac{k}{\rho}\left(\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y}\right) \tag{4}$$

Energy:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{5}$$

Where $\gamma=\left(\mu+\frac{k}{2}\right)j$,

$t=0\ u=v=T=\eta=0$ For $0\le x\le w \quad 0\le y\le l$

$t>0 \quad u=v=0,\ \dfrac{\partial T}{\partial y}=0\ \eta=-n\dfrac{\partial u}{\partial y}$ at y=0, w.

$u=v=0, T=T_h\ \eta=-n\dfrac{\partial v}{\partial x}$ at x=0

$u=v=0, T=T_c\ \eta=-n\dfrac{\partial v}{\partial x}$ at x=l

As the mentioned above mathematical expressions, n referred as constant $0\le n\le 1$. The major case n=0 indicates the micro elements strong concentration. Based on that reason illustrates the fluid particle strong concentration, moreover micro-elements of the fluid flow near the walls are impossibleto rotate. The second case, n=1/2, consiststhe diminishesof the stress tensor with anti-symmetric part and also registered a weak concentration. The third case *n*=1 is consists of the modelling of the turbulent part layer flows.

Using the following non-dimensional variables

$$\tau=\frac{t\alpha}{L^2},(X,Y)=\frac{(x,y)}{L},U=\frac{uL}{\alpha},V=\frac{vL}{\alpha},P=\frac{pL^2}{\rho\alpha^2},\theta=\frac{T-T_c}{T_h-T_c},N=\frac{\eta L^2}{\alpha}$$

$$Pr=\frac{\upsilon}{\alpha},Ra=\frac{g\beta(T-T_c)L^3Pr}{\upsilon^2},Da=\frac{\kappa}{L^2}$$

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{6}$$

$$\frac{\partial U}{\partial \tau}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+(1+K)Pr\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)+K.Pr\frac{\partial N}{\partial Y}-\frac{Pr}{Da}U \tag{7}$$

$$\frac{\partial V}{\partial \tau}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+(1+K)Pr\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-KPr\frac{\partial N}{\partial X}-\frac{Pr}{Da}V+Ra.Pr\theta \tag{8}$$

$$\frac{\partial N}{\partial \tau}+U\frac{\partial N}{\partial X}+V\frac{\partial N}{\partial Y}=\left(1+\frac{K}{2}\right)Pr\left(\frac{\partial^2 N}{\partial X^2}+\frac{\partial^2 N}{\partial Y^2}\right)-2KPrN+KPr\left(\frac{\partial V}{\partial X}-\frac{\partial U}{\partial Y}\right) \tag{9}$$

$$\frac{\partial \theta}{\partial \tau}+U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2} \tag{10}$$

With the following wall boundaries are

$\tau=0\ U=V=\theta=N=0$

For $0\le Y\le 1\ \ 0\le X\le 1$

$\tau>0 \quad U=V=0,\ \dfrac{\partial \theta}{\partial Y}=0\ N=-n\dfrac{\partial U}{\partial Y}$ at Y=0, L.

$U=V=0, \theta=1\ N=-n\dfrac{\partial V}{\partial X}$ at X=0

$U=V=0, \theta=0\ N=-n\dfrac{\partial V}{\partial X}$ at X=W

The stream function ψ evaluated with dimensionless velocity profiles *U* and *V* is represented formthe motion of flow. The worthy relationship between the velocity components and stream function ψ are

$$U=\frac{\partial \psi}{\partial Y} \text{ and } V=-\frac{\partial \psi}{\partial X}$$

The rate of hot wall heat transfer is measured by the below equation

$$Nu=-\left.\frac{\partial \theta}{\partial X}\right|_{X=0,1}$$

III. SOLUTION OF THE PROBLEM

Present computational problem governing dimensionless nonlinear differential equations (7)-(10) and the corresponding boundary conditions of enclosure walls are solved by numerically. To approximate the convective terms in momentum, angular momentum and conservation energy with the difference scheme ofsecond order accuracy is used. The diffusion terms are approximated using central differences minuet difference scheme. *X*-momentum and *Y*-momentum equations are discretized as mentioned above without pressure term then we obtained intermediate velocity profiles. Successive Overrelaxation (SOR) Method is usedto find Pressure from Poisson equation while the pressure Poisson equation (PPE).

The final velocity profiles are obtained from the well known method Projection method. Uniform fine grid in the direction of *X* and *Y* were considered.formomentum, angular momentum and energy equations then the time integration is terminated when the reaches the steady state explicit time integration is applied.

The steady state was considered to have been reached at when the changes in *U*, *V*, θ and N satisfy the equation:

$$\frac{\sum\left|\zeta^{n+1}-\zeta^{n}\right|}{\sum\left|\zeta^{n+1}\right|}=10^{-6}$$

Where ζ stands for velocity, angular velocity and temperature at iteration n.

Code validation

To test the house computational MATLAB code ofMarker and Cell (MAC) algorithm with Mahapatra *et al.*[25]. Mahapatra *et al.*[25] reports thatThe effect of buoyancy ratio on thermosolutal convection of a driven enclosure.The computed results of present house computational code and the results of Mahapatra *et al.*[25] are comparedand are presented in Fig2. This comparison registered worthy agreement for case uniformly heated and uniformly concentrated with *N*=50, $\Pr=0.7$ and $Ra=10^3$. Control-volume method and the comparison gives good agreement. This lends confidence into the worthy accuracy of the present numerical code used to get the Mahapatra *et al*. [25] computed numerical results.

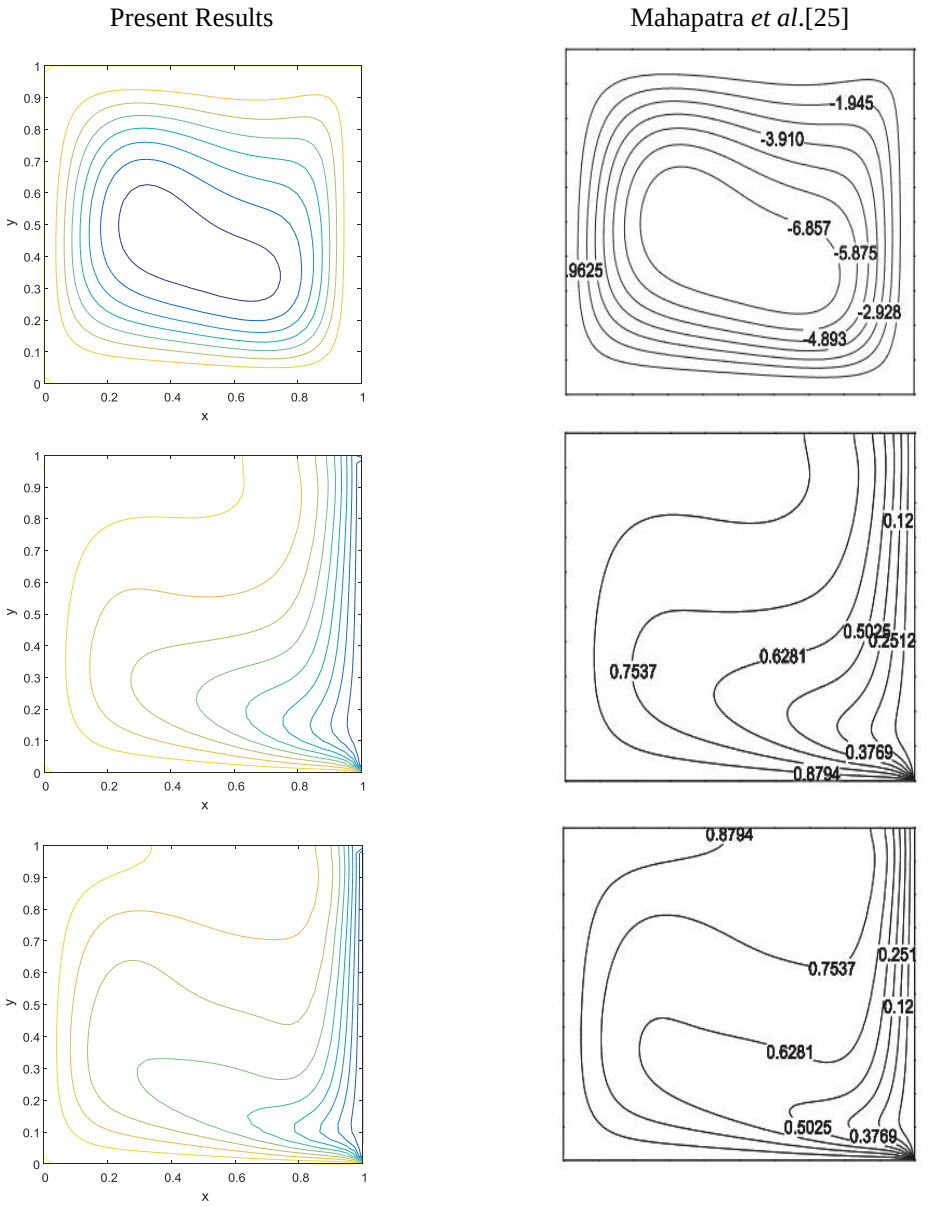


Fig. 2 Comparision of the Streamlines, Isotherms and Isoconcentrations for uniformly heated and uniformly concentrated left and bottom walls with *N*=50, Pr=0.7 and *Ra*=10^3

IV. RESULTS AND DISCUSSION

In the present investigation, fluid saturated porous medium with micropolar fluid on opposing temperature gradients have been examined by numerically fills the characteristics fluid particles and temperature distribution due to natural convection in a rectangular cavity. The computation is carried out for wide range of governing parameters like Rayleigh number (Ra=10^3-10^6), Vortex viscosity parameter (k=0-3) and Darcy number (Da=10^{-4}-10^{-1}). In this computations we consider working fluid Prandtl number take as Pr=0.71. The streamlinepatterns and isotherms distributions and micro-rotation are depicted for various values of governing parameters. The heat flowrate examined hot wall with Nusseltnumber of local and average respectively.

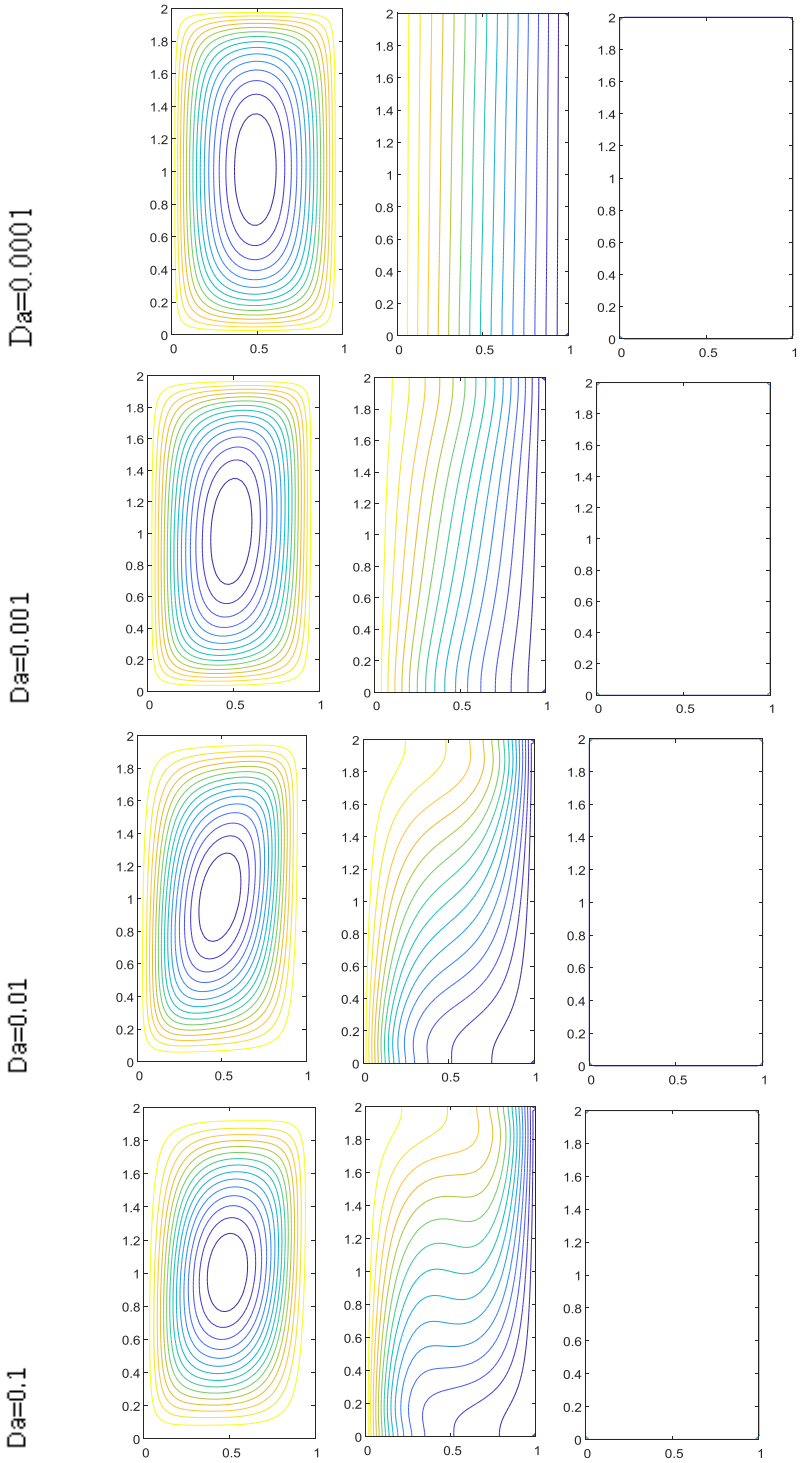


Fig. 3 Steady state patterns of streamlines, isotherms and microrotation for K=0, Pr=0.71, Ra=10^4

Fig. 3 shows the isotherms and flow pattern for various values of Da with Ra=10^4 and K=0. We expect thatthe fluid flow particles rises up to the down cold wall and falls vertical hot wall. The mechanism generates a mono enlarged vertical elliptical cell with clockwise rotation inside the rectangular enclosure.While, their the corresponding isotherm plots in Fig. 3 it shows thatthe reduce in the *Da* leads to a fall in longitudinal andtransverse temperature gradient in the domain due to gradual change in the orientation and theconvective forces strength. In tune to the variations of verticalelliptical circulation patterns to clockwise orientation circulation patterns, thetemperature readjust the resulting isotherms patterns get vertical to parallel wall of the rectangular enclosure.

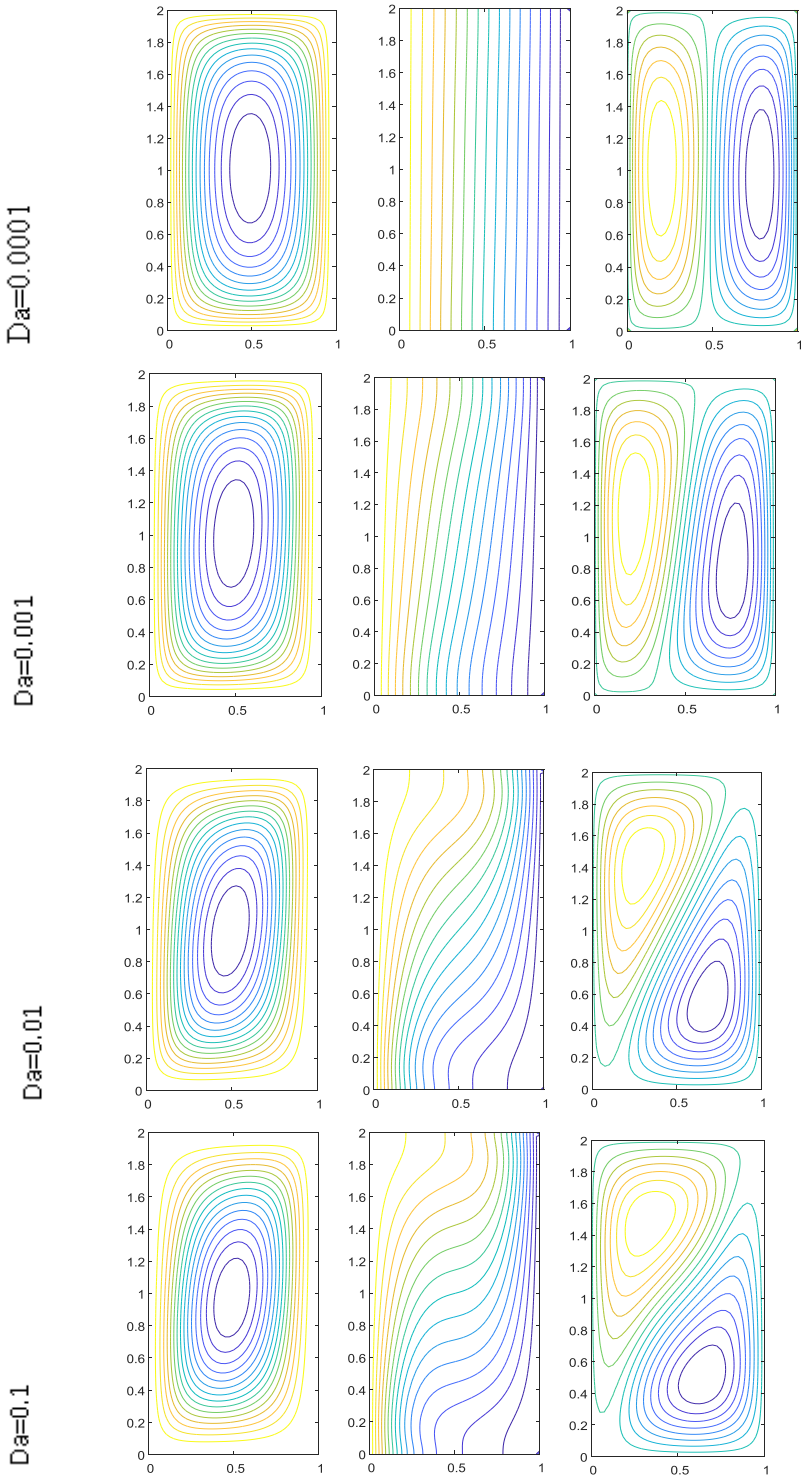


Fig. 4 Steady state patterns of streamlines, isotherms and microrotation for K=1, Pr=0.71, Ra=10^4

Fig. 4 demonstrates the streamlines, isotherms and micro-rotation for various values of Da ($Da=10^{-4}$-10^{-1}) with fixed $Ra=10^4$ and $K=1$. From the flow patterns, it is found that a mono enlarged vertical elliptical convective cell is developed inside the rectangular enclosure for low value of Da=0.0001. Weaker temperature gradients in entire enclosure due to conduction andisotherms are parallel to the side walls at Da=0.0001. Moreover, the Micro-rotationseen that two counter rotating vertical enlarged cells are formednear the side walls of the enclosure at low Da=0.0001.Increasing in Darcy number leads to significant changes are noticed in the streamline patterns, isotherms and micro-rotation. The streamlines reveal the flow patterns within an enclosure for various values of Darcy number. The fluid flow is almost circulated in vertical elliptical shape in all values of Darcy number. The isotherm patterns owe in changing of distribution of temperature contours within the rectangular cavity for varying Darcy parameter.The temperature contours are stretched towards to the cold (top portion) wall and hot wall (bottom portion) with increasing of Darcy parameter Da. Moreover, the micro-rotation is rotates in circular shape in the low temperature portion of the enclosure.

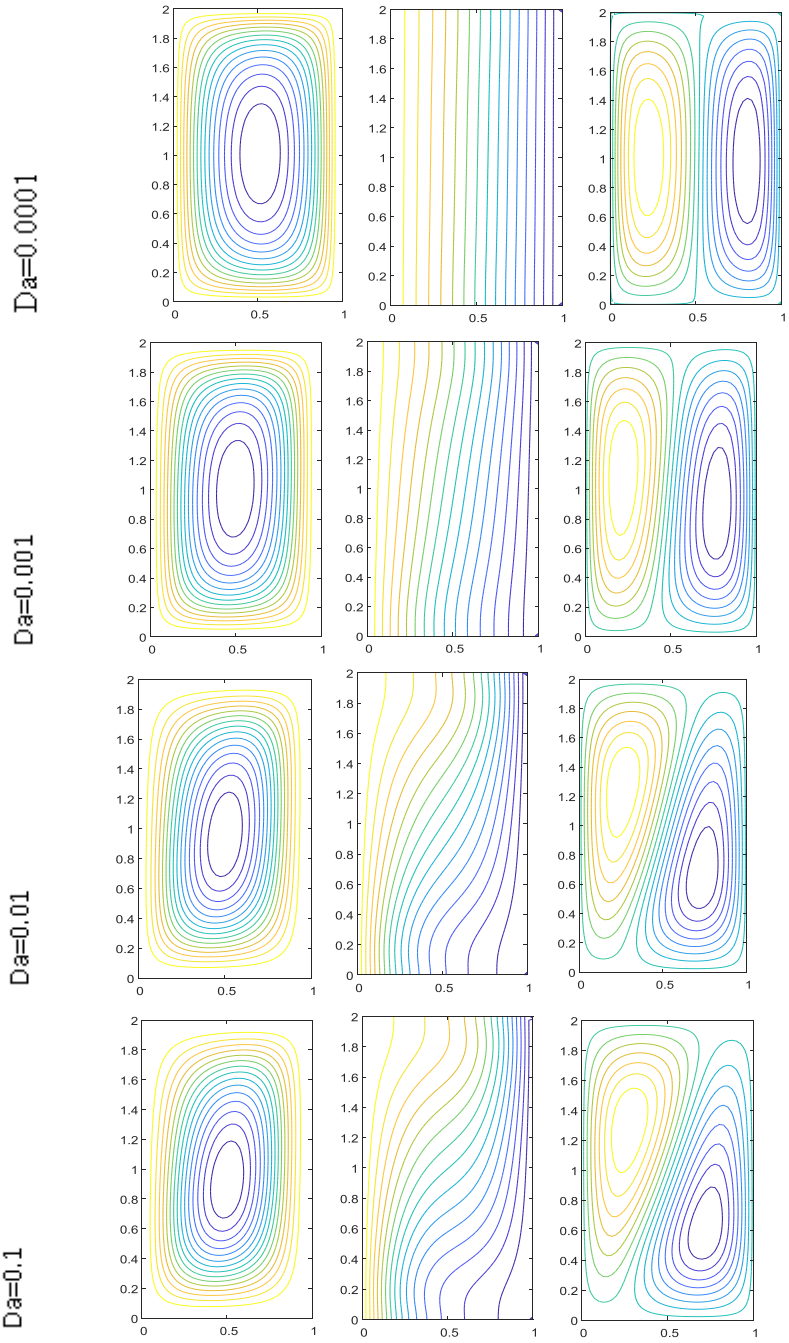


Fig. 5 Stream lines forSteady state patterns, isotherms and microrotationforK=3, Pr=0.71, Ra=10^4

Fig. 5 illustrates the streamlines, isotherms and micro-rotation for different values of *Da* ($Da=10^{-4}$-10^{-1}) with fixed $Ra=10^4$ and $K=3$.Regardless of Darcy number the clockwise vertical elliptical mono enlarged circulation is developed within the enclosure. Notably the regardless of Darcy number two micro-rotation eddies are formed within the boundary but the micro-rotation cells gradually shifted from diagonal elliptical shape to vertically elliptical shape with increasing of Darcy number parameter. The isotherms display different behaviors as Darcy number changes.

For the cases of Da=0.0001 and Da=0.001, where conduction dominates the flow regime, the temperature contours are occupied whole enclosure tend to be parallel of vertical walls. For increasing of Darcy number Da, the fluid flow become more strengthen and hence the stronger thermal boundary layer developed along the side walls.This is affected the augment of buoyancy force.Moreover, the isotherms are clustered heavily in the top region of the cold wall as well as down region of the hot wall which reveals that the steep temperature gradients arise there.

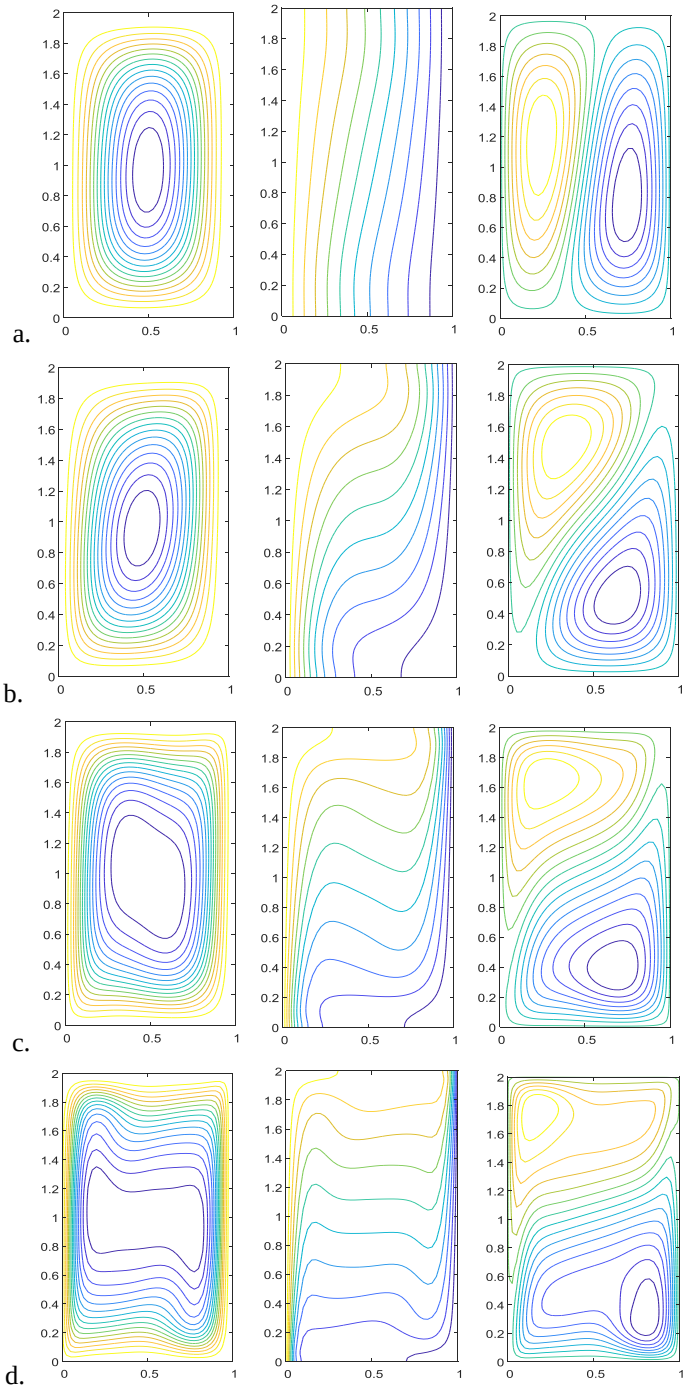
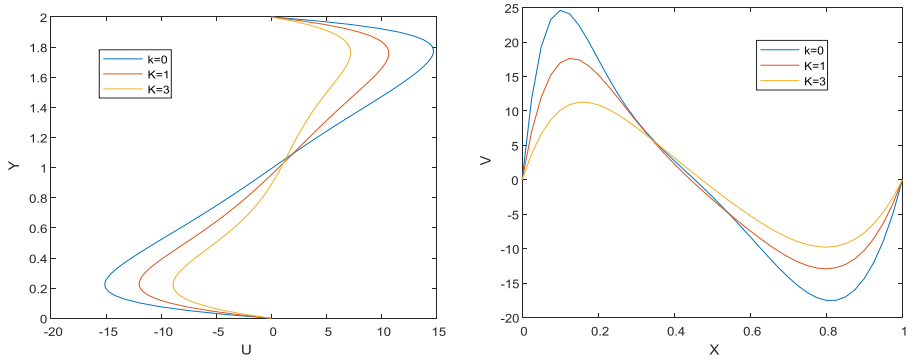


Fig. 6 Steady state patterns of streamlines, isotherms and microrotation forK=1, Pr=0.71, Da=0.1 (a) $Ra=10^3$ (b) $Ra=10^4$ (c)$Ra=10^5$ (d)$Ra=10^6$

Fig.6 consists of The influence of the Rayleigh number on streamlines isotherms and micro-rotations for *k*=1and *Da*=0.1**.** We expected, the fluid rised up neat the hot wall and descend alongthe coldwall, which forming a mono enlarged vertical elliptical circulation with clockwise rotation inside the rectangular region. The conduction mechanism is observed for lower Rayleigh number (Ra=10^3), which is reveals from the temperature contours. Due to dominant influence of stabilizing the buoyancy effect. When Ra= 10^3, the elliptic shaped cell is generated at central region, while the Rayleigh number Ra increases its shapechanges gradually. The vertical elliptical convective cell is shifted to horizontal when increasing of Rayleigh number Ra from 10^3-10^6 which can be seen from the streamline contour. The clustered isotherms are observed at bottem corner of hot wall and top corner of cold wall except *Ra*=10^3.The steeper thermal gradient increase at side walls with increasing of Rayleigh number Ra from 10^5-10^6 while the streamlines are parallel to the horizontal walls in the middle of core regime at *Ra* = 10^6. The micro-rotations countsgradually changes registered with increasing of Rayleigh number while the micro-rotation circulations are formed at low temperature regions. The two vertical symmetric micro-rotation circulation are observed at some Rayleigh number *Ra*=10^3 which is caused due to conduction. Moreover, the micro-rotations circulates are moves to cold temperature regions when enhancing of Rayleigh number with in the enclosure.



a b

Fig. 7 Central line velocity for Pr=0.71, Ra=10^4, Da=0.1 (a) *U*-velocity (b) *V*-velocity

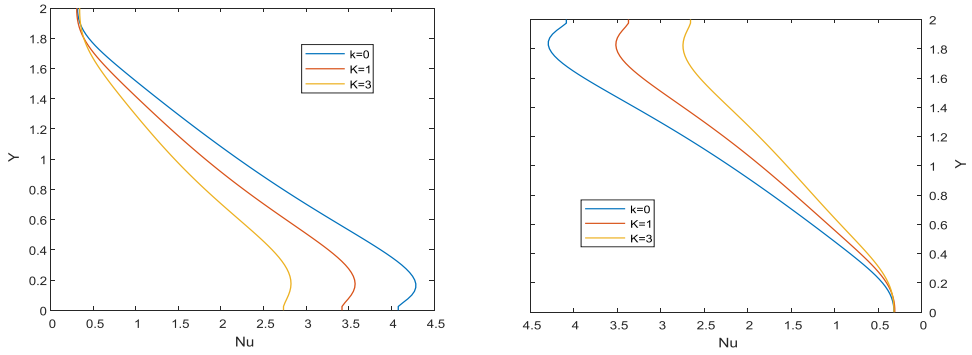


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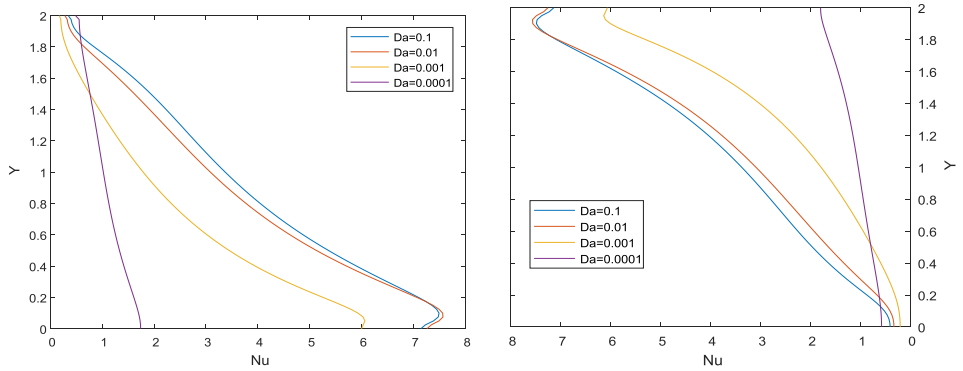
Fig. 8 Local Nusselt number for Pr=0.71, Ra=10^4, Da=0.1 (a) Hot wall (b) cold wall



a b

Fig. 9 Local Nusselt number for K=1,Ra=10^5,Pr=0.71 (a) Hot wall (b) cold wall

The variation of mid-section velocity profiles and local Nusselt numberfor Pr=0.71, Ra=10^4, Da=0.1with different values of vortex viscosity parameter are shown in Fig. 7 and Fig.8.It is noticed that the augment of vortexviscosity parameter leads to reduce the mid-section velocity profilesmean whilethe rate of heat transfer.Moreover, the flow intensity is affected strongly by thevortex viscosity parameter.forvarious values of Darcy parameter $Da$for K=1, Ra=10^5,Pr=0.71 is depicted in Fig. 9(a) and Fig. 9(b) The variation of local Nuof hot and cold walls. For various values of Darcy parameter $Da$for K=1, Ra=10^5, Pr=0.71 is depicted in Fig. 9(a) andFig. 9(b). Which describes, the local Nusselt number reduces intensely when increasing in Da from 0.0001 to 0.1. It is interestingto note that the regardless of Darcy number Da local Nusselt number increases more at top portion of the cold wall and the opposite mechanism is exhibited for hot wall.

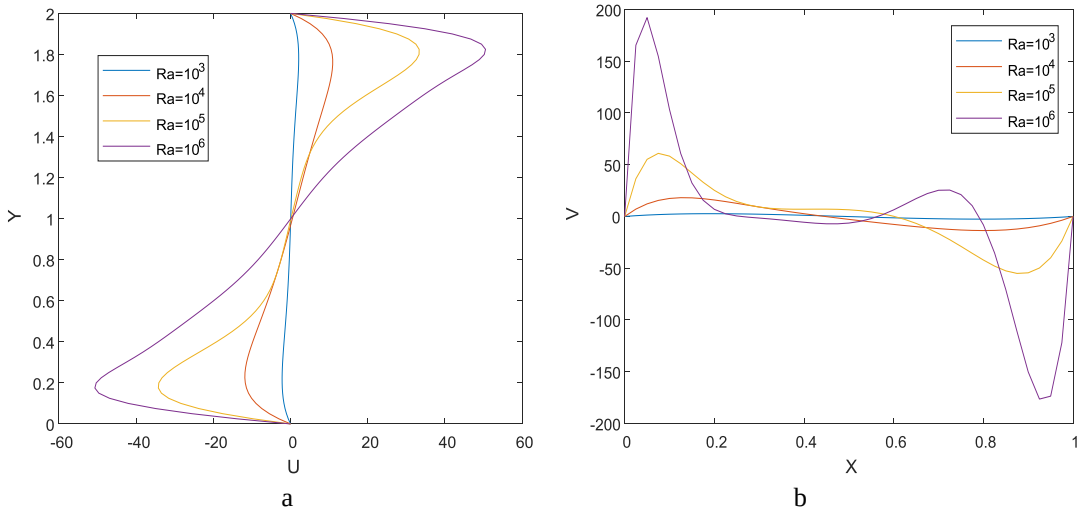


Fig. 10 Central line velocity profiles for Pr=0.71, K=1, Da=0.1 (a) U-velocity (b) V-velocity

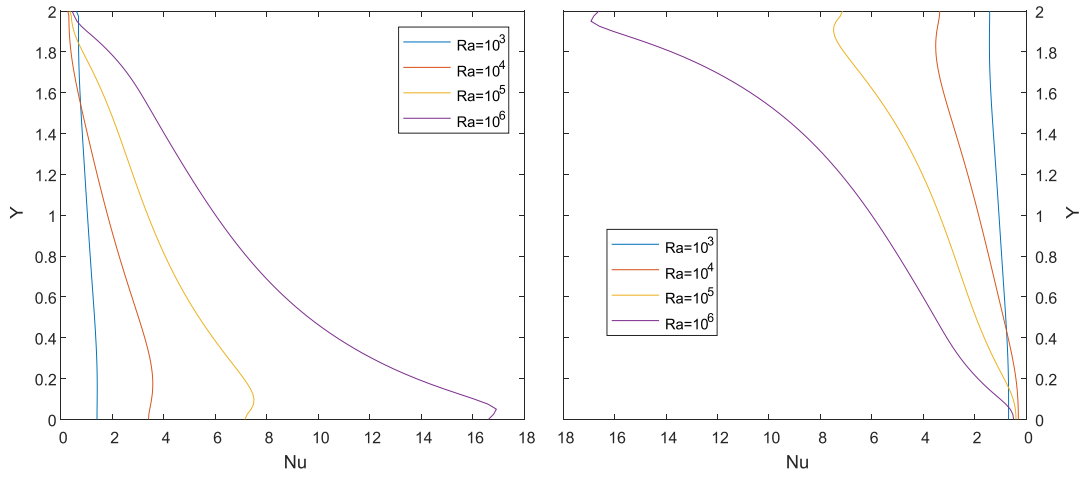


Fig. 11 Local Nusselt number for Pr=0.71, K=1, Da=0.1(a) Hot wall (b) cold wall

From Fig. 10(a) and (b) illustrate the Central line velocity profiles vertical and horizontal respectively for Pr=0.71, K=1, Da=0.1. for both horizontal and vertical It is observed that raising the Rayleigh number leads to enhancement in midsection velocity.Clearly the buoyancy force not only de-accelerates the convectivevelocities but also change its directionality.Fig. 11(a) and (b) exhibits the local Nusselt numberof hot and cold walls for various Rayleigh numbers with Pr=0.71, K=1, Da=0.1. the hot and cold wall is increased with an increase of the Rayleigh number for The local Nusselt number. However, the local Nusselt number is increases more at the bottom part of the hot wall and also top portion of the cold wall.

V. CONCLUSION

In this paper, to solve the present investigation partial governing differential equations Projection method based MAC algorithm is used.Convective heat transfer of micropolar fluids in a rectangular enclosure filled with porous medium is studied numerically. The roll of wide range of values of Rayleighnumber Ra, vortex viscosity K, Darcy number Daon flow field, the micro-rotation and the rate of heat transfer are discussed through graphically. The following conclusions are obtained.

- The regardless of Rayleigh number, with decreasing in the Darcy parameter, heat transfer rate is suppressed.
- For wide range of*K*, the augment of Ra the fluid flow rate and temperature distribution are enhanced. While the heat transfers rate and flow rate are reduced when increasing of vortex viscosity parameter K.
- The computed results (isotherms and streamlines) reveal that, vortex viscosity parameter K plays a important role the on enhancement of heat transfer. Higher heat transfer rate is notice when the absence of vortex viscosity parameter K (Newtonian fluid).
- When the vortex viscosity parameter K is increased, a significant reduction in the heat transfer and flow rate is registered for all governing parameters.
- When the Darcy number Da is increased, a significant enhancement in heat transfer and flow rate is registered for all governing parameters.

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