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Research Article

Numerical Study of Natural Convection Flow in a Square Porous Enclosure Filled with Casson Viscoelastic Fluid

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Abstract: The present simulation, a numerical investigation of natural convection of Casson viscoelastic fluid in a porous square enclosure has been reported. Darcy-Boussinesq approximation mathematical model has been considered. The enclosure has been uniformly heated from the left wall and uniformly cooled from right side wall. The developed partial differential equations of the present computational domain are employed by using stream function approach along with finite difference scheme. The house-computational numerical algorithm has been validated against with the previous work and the computational results have been registered a good correlation. All the important results as shown by streamlines, isotherms, and local Nusselt numbers, the impact of Casson fluid parameter (β), Rayleigh number (Ra) is examined. It has been observed that with the increase in Casson fluid parameter (β), the buoyancy induced fluid circulation and convection effect decreases inside the enclosure. For each Rayleigh number, there correspond a critical Casson fluid parameter (β), for which the heat transfer inside the enclosure takes place solely by conduction mode. It has been also observed that at high Casson viscoelastic fluid the effect of increase in Rayleigh number on average Nusselt number is lesser compared to the effect of increasing Rayleigh number at low Casson viscoelastic fluid.

***Keywords*:** square cavity, laminar flow, non-newtonian (casson) fluid, finite difference method, convective flow, porous medium

MSC: 80M20

Nomenclature

g	Gravitational acceleration (m/s^2)
L	Length of the square cavity (m)
p	Dimensional pressure (Pa)
P	Dimensionless pressure
Ra	Rayleigh number

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T	Temperature (K)
θ	Dimensionless temperature
u, v	Velocity components (m/s)
U, V	Dimensionless velocity components
x, y	Cartesian co-ordinates (m)
X, Y	Dimensionless Cartesian components

Greek symbols

ρ	Density of Casson fluid (kg/m^3)
α	Thermal diffusivity (m^2/s)
μ	Dynamic viscosity (kg/ms)
υ	Kinematic viscosity
β	Casson fluid parameter
γ	Casson rheological fluid parameter
τ	Shear stress (and dimensionless time)
$\dot{\gamma}$	Shear rate
$\pi = e_{ij}e_{ij}$	
e_{ij}	$(i, j)^{th}$ component of the deformation rate
π	The product of the component of deformation rate
π_c	Critical value
μ_B	Plastic dynamic viscosity of the non-Newtonian fluid
p_y	Yield stress of the fluid

Subscripts

c	Cold
h	Hot/Heat

1. Introduction

Medicine, energy systems, chemical process engineering, and geoscience continue to find extensive applications for transport in porous media. Permeable materials receive heat transfer, both convective and fluid, in many applications, such as solar absorber collectors, solar collectors [1], foam processing [2], geothermal power [3], borehole heat exchangers [4], heat transfer devices [5, 6], biomechanics [7], gastric bio-transport [8], bio-fuel cells [9] and industrial filtration [10]. Various modeling approaches and enclosures filled with porous media have been used to study natural convection flows by engineers. As a result of yield stress, Viscoplastic fluids exhibit a complex transition between solid-like and fluid-like behavior. Insufficient stress, i.e., less than yield stress, causes the material to cease flowing and behave as a solid. Above the yield stress, it behaves like shear-thinning fluid flow. Further, the Casson model is often used in medicine as a method to simulate blood rheology.

Dogonch et al. [11] considered a concentric circular semi enclosure to study the free convective flow of magnetic nanofluid with an influence of Brownian motion and thermal conductivity by control volume method. In spite of study on several parameters such as Darcy number, magnetic number number, Rayleigh number and inclined magnetic field a direct relationship of convective flow was identified with Darcy number and Rayleigh number, an inverse relationship found with an inclination angle and Hartmann number. Sivasankaran et al. [12] adopted non-Darcy porous model for the analysis of convective flow and heat expansion of Casson viscoelastic fluid within a porous square enclosure with sinusoidal thermal radiation. By Semi-Implicit Method for Pressure-Linked Equations (SIMPLE) algorithm, results states that the high values of non-Newtonian fluid parameter under radiation generates thermal stratification phenomenon. Deterioration of heat transport for the rising thermal radiation values and improvement of heat transfer noticed for the increment of Casson parameter. Shayan et al. [13] considered a L-shaped cavity with various baffle configurations filled cu-water nanofluid for the analysis of thermal convective flow by Lattice Boltzmann Methods (LBM) approach. Enhancement of natural convection irrespective of baffle positions observed for the large values of Rayleigh numbers and length of Baffle also shown an impact in this case. Masoud et al. [14] also considered a different L-shaped enclosure filled with Al_2O_3-H_2O nanomaterial for the elaborated analysis of free convective heat transport using entropy optimization. Based on cost of the nanofluid first time they introduced economic analysis for the assessment of performance of the cavity and got good agreement with the existed results. Decrement of entropy optimize number observe for the rising values of nanoparticle concentration. Raizah et al. [15] carried out three distinct thermal conditions like conducting, hot and cold solid particles within the E-shaped enclosure partially filled with porous medium to analyze thermal nanofluid characteristic. From the results it is revealed that the thermal fluid transport strengthened within the enclosure for the condition of hot solid particles. Keramata et al. [16] took a H-shaped enclosure packed with alumina water nanofluid by installing a baffle in the enclosure for the analysis of flow and heat expansion of nanofluid. They maintained hot temperature at the top rib, low temperature at side walls and other walls of cavity are insulated. Rise of heat transmission observed for the enhancement of Rayleigh number and nano-particle volume fraction.

Isam et al. [17] analysed heat transfer characteristics by natural convection within a trapezoidal cavity consists of an adiabatic circular cylinder positioned at its center packed with Ag-water nanofluid in porous field. Results reveals that thickness of the boundary layer is inversely proportional to the heat expansion and high Rayleigh number boosts the fluid flow. Alsabery et al. [18] also considered trapezoidal cavity for the analysis of Darcian free convection but the enclosure filled with two layers (one is porous layer and second one is nanofluid layer). They filled the cavity with water-based nanofluid and the nanoparticles Ag or TiO_2 or Cu chosed for the analysis. As a result, convection is remarkably increased with the addition of Ag-water nanofluid. Dutta et al. [19] analysed MHD free convection, heat propagation and entropy generation within a Rhombus shaped cavity packed with cu-water nanofluids. The rate of entropy generation diminished for the rising values of magnetic number, Rayleigh number and inclination Angles of the cavity. Liu et al. [20] also studied free convection and entropy generation of water _Al_2O_3 nanofluid inside an inclined enclosure formed by connecting two inclined triangular cavities with the implementation of horizontal magnetic field. In this geometry half of the right walls of the cavity maintained Hot and rest of the walls kept adiabatic. As a result, decrement in Entropy generation and increment in Bejan number observed for high inclination angle.

Asgar Ali et al. [21] addressed the critical role of magnetohydrodynamics with Hall currents on a time-dependent gyrating stream of non-Newtonian Modified Hybrid Nanofluid (MHNF) with Casson fluid model past a vertically fluctuating plate with ramped motion, and Newtonian heating in a porous environment. Asgar Ali et al. [22] presented the dynamism of a non-Newtonian water-ethylene glycol mixture (vol. 60-40%) based tri-hybridized nanofluid (Cu-TiO_2-Al_2O_3/WEG) on an oblique plate with ramped motion in the attendance of Hall and ion-slip currents, Darcy's porous resistance, heat radiation, chemical reaction, Newtonian heat and mass fluxes in a magneto-rotating environment. Das et al. [23] conducted to demonstrate a time-dependent hydro-magnetic Couette flow and heat transport features inside a gyrating channel filled with a reactive second-grade hybrid NF (copper-alumina-ethylene glycol) and Darcian porous medium under multiparty impacts of Hall currents, temperature-dependent thermal conductivity, and Arrhenius chemical reaction. Asgar Ali et al. [24] examined magneto-bioconvective Darcy-Forchheimer (DF) transport of gyrotactic microbes using the Williamson nanofluid model over a flexible cylinder under the physical effects of Arrhenius activation energy, thermal radiation, triple stratifications and wall slip. A note in a mixed convection flow was presented by Meena and Pranitha [25]. Meena et al. [26], Meena et al. [27] examined mixed convection flow using Lie group scaling. We can count more relevant work of porous medium as [28-30].

The main theme of the study is to examine the behavior of convective in a fluid that has non-Newtonian properties and is contained in a square cavity. An enclosure containing a non-Newtonian fluid (i.e., Casson viscoelastic fluid) saturated with porous medium is studied using a stream function-based finite difference approach. Flow in porous medium is modeled by the Brinkman-Darcy model, a Local Thermal Equilibrium (LTE) approach. Solving the boundary value problem in stream function form is the best way to solve a non-dimensional problem. As far as the author's knowledge, this problem has not been explored previously in a square cavity despite its numerous practical applications. A visual representation is provided of the effects of the Casson viscoelastic fluid parameter β and thermal Rayleigh number (Ra) on fluid flow patterns and thermal distributions. In addition, the Nusselt number is examined on the right wall of the enclosure. It also includes grid-independent validation tests.

2. Physical and mathematical model

A schematic representation of the square shape model used in this study is shown in Figure 1. It is a two-dimensional enclosure with L as height. In this study, we will examine a two-dimensional enclosure filled with porous medium with Casson viscoelastic fluid. The schematic geometry of present numerical investigation of interested domain is depicted in Figure 1, where x and y are the coordinates of the Cartesian geometry and L is the length of the square enclosure. It is assumed that the left wall is heated and kept at high temperature T_h.

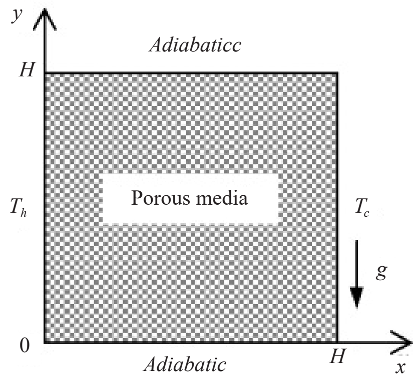


Figure 1. Schematic of problem

Let us consider a laminar incompressible non-Newtonian viscoelastic Casson fluid flow in a domain.
The Casson fluid rheological equation is expressed by following [31]

$$\tau^{\frac{1}{2}} = \tau_0^{\frac{1}{2}} + \mu\dot{\gamma}^{\frac{1}{2}}$$

$$\tau_{ij} = \begin{cases} 2\left(\mu_B + \dfrac{P_y}{\sqrt{2\pi}}\right)e_{ij}, & \pi > \pi_c \\ 2\left(\mu_B + \dfrac{P_y}{\sqrt{2\pi_c}}\right)e_{ij}, & \pi_c > \pi \end{cases} \tag{1}$$

$$P_y = \frac{\mu_B\sqrt{2\pi}}{\beta} \tag{2}$$

Casson fluid flow with the $\pi > \pi_c$, if this is the case, then we can say the following

$$\mu = \mu_B + \frac{P_y}{\sqrt{2\pi_c}} \tag{3}$$

From the equation (2) and (3), we have

$$\mu = \mu_B \left(1 + \frac{1}{\beta}\right) \tag{4}$$

The present investigation, the following assumptions are considered:

1. In a square enclosure, the horizontal walls are adiabatic and the left wall is maintained at high temperature and the other wall is kept low temperature.

2. The fluid in a square cavity is assumed as laminar incompressible non-Newtonian fluid (Casson viscoelastic fluid) in thermal equilibrium.

3. No slip flow is considered in a square enclosure and all wall are bounded with fluid and porous medium.

4. The fluid properties are isotropy and homogeneous everywhere.

5. The Local Thermal Equilibrium Model (LTEM) is considered between the fluid and porous medium.

6. The boussineq approximation, is applied and all fluid parameter are constant except fluid density where the fluid density is taken as a linear function of temperature $\rho = \rho_0[1 - \beta_T(T - T_C)]$.

Under the above discussed assumptions, the governing equations of present computations are written as follows [31-33].

$$u_x + v_y = 0 \tag{5}$$

$$u_y - v_x = -\frac{K\rho g}{\mu\left(1 + \frac{1}{\beta}\right)} \beta_T T_x \tag{6}$$

$$uT_x + vT_y = \alpha \nabla^2 T \tag{7}$$

Introducing the following dimensionless quantities are:

$$X = \frac{x}{L},\; Y = \frac{y}{L},\; U = uL/\alpha,\; V = vL/\alpha,\; \theta = \left(T - T_c\right)/\left(T_h - T_c\right) \tag{8}$$

The fluid flow field introduced stream function ψ and it is defined as follows

$$U = \frac{\partial \psi}{\partial y},\, V = -\frac{\partial \psi}{\partial x} \tag{9}$$

so, the governing equations are taken with account of stream function and equation (8) as follows

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} = -Ra.\left(\frac{1}{1 + \frac{1}{\beta}}\right)\frac{\partial \theta}{\partial x} \tag{10}$$

$$\frac{\partial \psi}{\partial Y}\frac{\partial \theta}{\partial X} - \frac{\partial \psi}{\partial X}\frac{\partial \theta}{\partial Y} = \frac{\partial^2 \psi}{\partial X^2} + \frac{\partial^2 \psi}{\partial Y^2} \tag{11}$$

Here $Ra = \frac{g\beta_T K(T_n - T_C)}{\nu\alpha}$ is the thermal Rayleigh number.

The dimensionless boundary conditions of domain of interest are [31]

$$\psi = 0,\ \theta = 0 \text{ on right wall}$$

$$\psi = 0,\ \theta = 1 \text{ on left wall} \tag{12}$$

$$\psi = 0,\ \frac{\partial\theta}{\partial Y} = 0 \text{ on } Y = 0 \text{ and } Y = 1$$

3. Numerical technique

The partial differential equations (10)-(11) of the present investigation of the domain and the corresponding boundary conditions (12) are employed by the help of finite difference method (see [32, 34-37]) with second order accuracy. The stream function Poisson equation (10) is employed from the gauss-seidel iterative method. The numerical methodology was coded in MATLAB. The developed computation algorithm is terminated when the stream function residual reaches below 10^{-8}. The house-computational code is developed in MATLAB and verified converges against the work of [38] and [39]. Table 1 depicts the comparison of mean Nusselt number Nu obtained for different Rayleigh numbers and the solid volume fraction for other authors and it gives a good agreement.

Table 1. Comparison of heat transfer rate (Nu) of Triangular enclosure

Ra	$Nu_{\_avg}$		
	[38]	[39]	Present computation
500	9.66	9.52	9.63
1,000	13.9	13.6	13.96

4. Results and discussion

Numerical simulation conducted for the Boundary Value Problem (BVP) from (10) to (13) for the subsequent governing parameters Rayleigh number (R - 100, 500, 1,000), Casson viscoelastic fluid parameter (β - 0.2, 0.5, 0.8). A remarkable specific impact noticed on these governing parameters for both heat propagation and fluid flow discussed in detail.

A substantial variation can be identified in heat propagation in porous square cavity by varying the governing parameter Rayleigh number-Ra, Figure 2 portrays streamlines as well as isotherms for Alumina-water nanofluid for various values Ra with Casson parameter β = 0.5. Regardless of distinct Ra values and mode of porous field, an anti-clockwise fine mono circulation of vortex is generated inside the square enclosure. In particular, in Figure 2(a) a single circular vortex is noticed within the cavity and respective isotherms expanded throughout the enclosure. Increment of Ra values reduces the viscous force strength that causes enhancement of buoyancy and eventually strength of eddies inside the cavity will also be upraised. As Ra increased from 100 to 1,000 (Figure 2(b), 2(c), 2(d)), the strength of the vortex gradually enlarged and its shape also changed from circular to elliptic. When Ra is increased vortices of streamline stretches horizontally with which stream function value gets increased consequently velocity profile of flow gets strengthened. For Ra = 500, the streamline contour recirculate as approximate horizontal ellipse pattern. This substantial amount of increase in stream function value shows improved convective heat transfer. When Ra = 1,000 (Figure 2(d)) a high strength is noticed in the vertex inside the cavity. With rise of Rayleigh number and strength of convective cell the convective circulation extended towards the horizontal axis, the strength of the thermal boundary layer along the right cold wall will also be increased. When Ra takes higher values as depicted in the isotherms Figure 2(c), (d) that distribution more distorted as effect of the strength of convection current related to the Ra values. Isotherm line are approximately parallel to the left vertical wall of the cavity when low values of Ra. But when Ra is increased, these lines get starts distorting which increases the longitudinal and transverse temperature/concentration gradient in the core of domain.

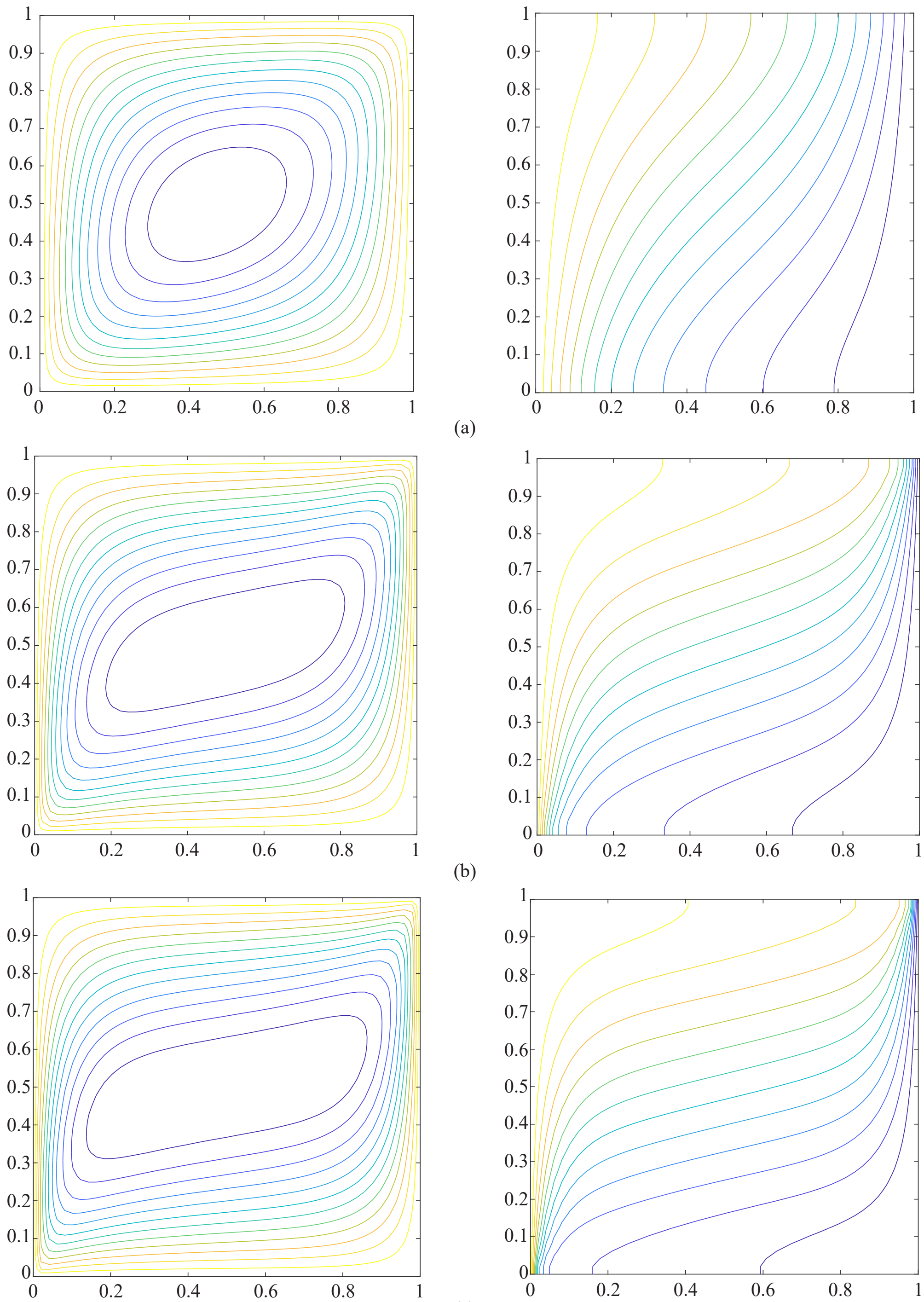


Figure 2. Streamlines and isotherms for various values Ra and β = 0.5, Ra = 100 (a), Ra = 500 (b), Ra = 1,000 (c)

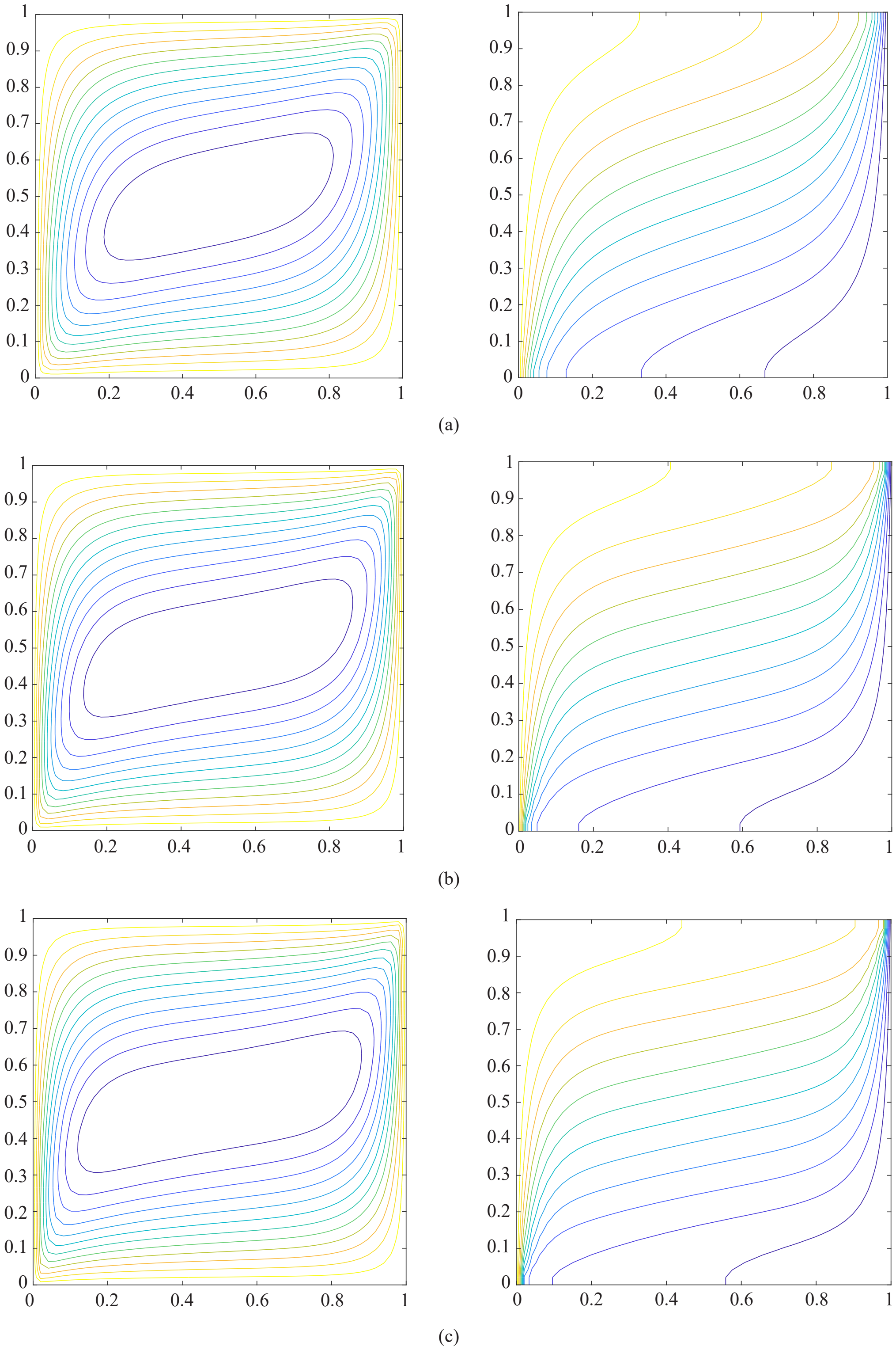
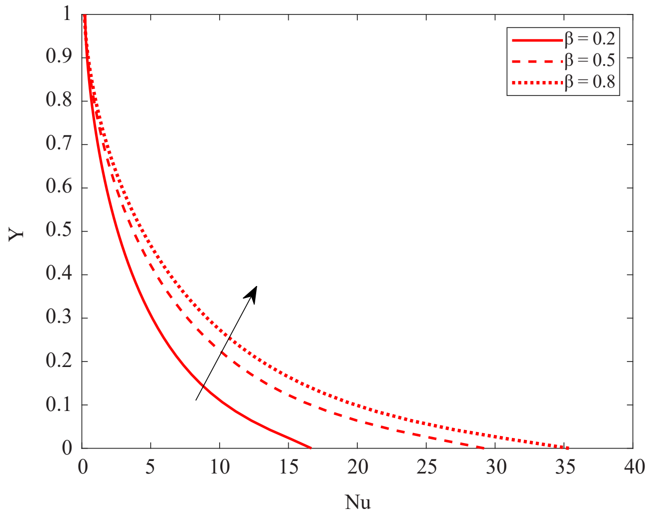


Figure 3. Streamlines and isotherms for various values β and Ra = 1,000, β = 0.2 (a), β = 0.5 (b), β = 0.8 (c)

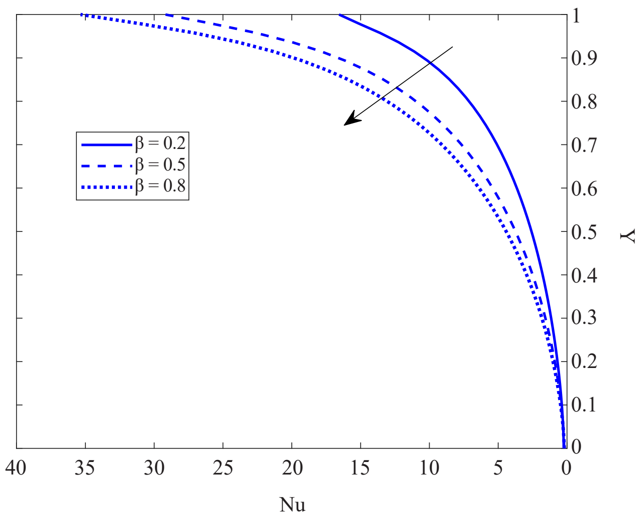
Generally convective fluid flows are directly proportional to temperature variations. At Ra = 100 (Figure 2(a)), a low-level heat propagation from hot wall to cold wall of the cavity is noticed. A significant expansion of isotherms observed towards cold wall. Rise of Rayleigh number increases the strength of heat expansion in particular at Ra = 1,000

(Figure 2(d)) the fluid particles are forcefully boosted towards right cold wall and the isotherms are steeper and high clustered near the right cold wall. A high thermal flume is noticed for the Rayleigh number Ra = 1,000, in Figure 2(d).

The flow patterns and thermal contours for distinct values of Casson viscoelastic fluid parameter at Ra = 1,000 depicted in Figure 3. A clockwise flow circulation from hot wall to cold wall is noticed within the enclosure. The incremental values of β rises the fluid flow strength accordingly the enhancement of eddies inside the cavity is noticed (see in Figure 3(a), 3(b), 3(c)). At high buoyancy force (Ra = 1,000) friction within the Casson viscoelastic fluid will be raised and the increment of β values rises the temperature field so that a considerable change in isotherms is observed. The heat flume is developed along the vertical walls, where as strongly depended on the growing values of Casson viscoelastic parameter β. The stronger thermal boundary layer is observed at higher values of β = 0.8 and which is seen in Figure 3(c).



(a) Hot wall (Left wall)



(b) Cold wall (Right wall)

Figure 4. Local nusselt number for various values β with Ra = 1,000

The thermal transport along the isothermal side walls of the porous enclosure are presented in Figure 4 and Figure

5. The impact of Viscoplastic fluid parameter (β) on heat transfer rate is shown in Figure 4. In addition, the heat transfer rate along the hot wall and cold wall are shows Figure 4(a) and Figure 4(b) respectively. Increasing of Viscoplastic fluid parameter (β) leads to growth of the thermal transport is observed due the viscosity nature is reducing. The influence of buoyancy parameter on heat transfer rate is revealed in Figure 5. In addition, the heat transfer rate along the hot wall and cold wall are displays Figure 5(a) and Figure 5(b) respectively. The Figures 4 and 5 reveals the significant heat distribution along the vertical walls and the local Nusselt numbers is a growing function of both the Casson fluid parameter (β) and Rayleigh number (Ra). From Figure 4 and 5, it is seen that raising the Rayleigh number boosts the cumulative Nusselt levels due to enhanced thermal buoyancy forces. A substantial amount of increase is noted for higher Rayleigh number whereas for it is marginal for small values of Rayleigh number.

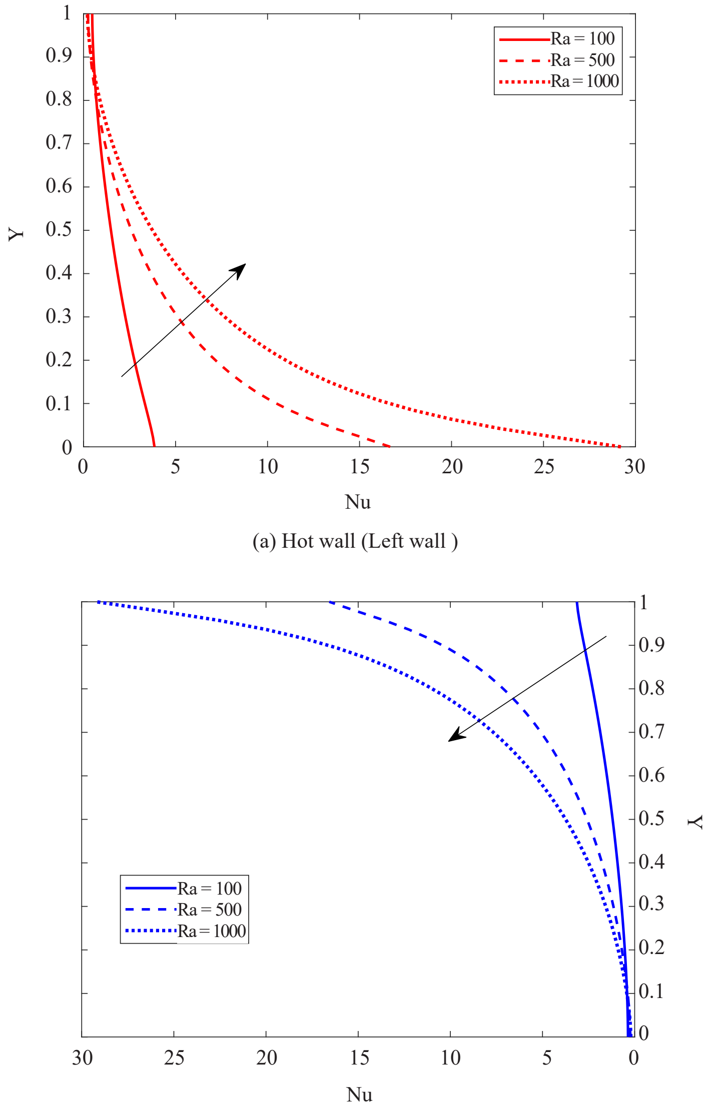


Figure 5. Local nusselt number for various values Ra and β = 0.5

5. Conclusions

The present numerical investigation, natural convective flow of Casson viscoelastic fluid in a porous enclosure is examined numerically by the help of finite difference method. The Darcy-Brinkman model of Casson fluid flow has been considered. The effect of thermal Rayleigh number (Ra), Casson fluid parameter β on convective flow and heat transfer are investigated. From the finite difference based numerical algorithm is used to find the solutions of the computational domain, it can be summarized that the thermal Rayleigh number (Ra) and Casson fluid parameter (β) can be a good control governing parameter for heat and convective flow. In addition, the heat distribution from the hot wall is an increasing function of buoyancy parameter Ra as well as Casson fluid parameter. The significance heat distribution (local Nusselt number) is observed for the impact of viscoplastic fluid parameter (β) and thermal buoyancy parameter (Ra).

The present study has examined a simple Viscoplastic model with the efficient FD numerical approach. Future enclosure simulation investigations may consider alternate non-Newtonian models e.g. micropolar liquids and efforts in this regard are currently underway.

Conflict of interest

The authors declare no conflict of interest.

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