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RESEARCH ARTICLE

Heat Transfer of A Peristaltic Electro - Osmotic Flow of A Couple Stress Fluid through an Inclined Asymmetric Channel with Effects of Thermal Radiation

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ABSTRACT

The presented article addresses the electro-osmotic peristaltic flow of a couple-stress fluid bounded in an inclined asymmetric micro-channel. The viscous dissipation, Joule heating and chemical reaction effects are employed simultaneously in the flow analysis. Heat and mass transfer have been studied under large wave length and small Reynolds number. The resulting nonlinear systems are solved numerically. The influence of various dominant physical parameters is discussed for velocity, temperature distribution, and the pumping characteristics.

Keywords: Peristaltic flow; Electro-osmotic flow; Couple stress fluid; Magnetic field; Heat transfer; Mass transfer; Inclined asymmetric micro-channel;

INTRODUCTION

Recent investigations in miniaturization and micro-fabrication have taken into assuming a lot of applications extending from organic to refrigerating of microelectronics in [1 - 9]. Many favors such as an important reduction in the utilization of required materials, ability to achieve in-vitro experiments on the continuous motion in a manner

similar to the real situation in a living biological system, being portable and vibration-free are using micro fluidic devices. Electro-osmotic transports with thermal effects of liquids in micro channels are reported in [10]. The heat transfer investigation of electro-osmotic motion in a slowly varying non-symmetric micro-channel is presented in [11]. Stokes developed the couple stress fluid model. When additives are mixed in the fluid then cohesive forces of fluid resists additive factors. This resistance creates a combined force and then a couple stress is generated in the fluid. Such fluid is known as couple stress fluid. This model is regarded as generalization of Newtonian fluid model dealing with body couples and couple stresses in fluid medium. Note that couple stress fluid has an asymmetric stress tensor. Relevant studies in this direction are given in the investigations [12 – 18]. Bio-fluids propel from one place to another place by continuous process of muscle contraction and relaxation. This process is known as peristaltic transport. The peristaltic transport phenomenon is mainly due to the neuromuscular property of any tubular smooth muscle structure. This mechanism is responsible for the transport of biological fluids in several physiological processes such as urine transport from kidney to the bladder, the movement of chyme into the gastrointestinal tract, fluids in the lymphatic vessels, bile from the gallbladder into the duodenum, the embryo transport in non-pregnant uterus, the movement of spermatozoa in the ducts efferent of the male reproductive tract, the movement of the ovum in the fallopian tube and the circulation of blood in small blood vessels are depicted in [19 – 33]. Thus the major focus of this study is to analyze the viscous dissipation, Joule heating effects on MHD electro-osmotic peristaltic flow of couple stress fluid in an inclined asymmetric micro channel. Mathematical formulation of problem is presented. The results are obtained after employing long wavelength and low Reynolds number approximation. The velocity, temperature, concentration, pressure gradient and pressure rise have been proposed for the pertinent parameters of interest.

Mathematical Formulation and analysis

We analyze the electro-osmotic peristaltic flow of an electrically conducting incompressible couple stress fluid and heat transfers through an inclined asymmetric micro-channel with charged walls under the influence of an imposed the magnetic field. The flow is assumed to be asymmetric about x' and the liquid is flowing in the x' -direction. The hydrophobic micro-channel is bounded by slowly varying walls at $y' = h_1(x')$ and $y' = h_2(x')$ respectively, in which the length of the channel (L) is assumed to be much larger than the height, i.e., $L >> (h_1 + h_2)$. Fig. 1 below depicts the schematic diagram of the problem under current study.

Electrical Potential Distribution

The basic theory of electrostatics is related to the local net electric charge density ρ_e in the diffuse layer of EDL and charge density is coupled with the potential distribution ψ' through the Poisson-Boltzmann equation for the symmetric electrolyte is given by

$$\frac{d^2\psi'(y')}{dy'^2} = \frac{2n_0 e z_v}{\varepsilon}\sinh\left(\frac{e z_v \psi'(y')}{k_B T_{av}}\right) \quad \text{... (3)}$$

where η_o represents the concentration of ions at the bulk, ε is the charge of a proton, z_v is the valence of ions, ε is the permittivity of the medium, k_B is the Boltzmann constant and T_{av} is the boundary conditions for potential function are taken as

$$\psi'(y') = \psi_1' \quad \text{at} \quad y' = h_1'(x'),$$
$$\psi'(y') = \psi_2' \quad \text{at} \quad y' = h_2'(x'), \quad \text{...(4)}$$

where ψ_1' and ψ_2' are the electric potential at the upper and lower wall respectively. Let us now introduce the following non-dimensional variables,

$$\left[\psi_O,\psi_1,\psi_2\right]=\frac{ez_v}{k_BT_{av}}\left[\psi',\psi_1',\psi_2'\right],\quad y=\frac{y'}{d_1'}\ \text{and}\ \ x=\frac{x'}{L} \tag{5}$$

The dimensionless form of Eqs. (1) - (2) and the Poisson-Boltzmann equation defined in (3) take in the following form,

$$h_1(x)=\frac{h_1'}{d_1'}=1+a\cos(2\pi x), \tag{6}$$

$$h_2(x)=\frac{h_2'}{d_1'}=-d-b\cos(2\pi x+\phi), \tag{7}$$

and

$$\frac{d^2\psi_O}{dy^2}=k^2\sinh(\psi_O), \tag{8}$$

where $a=\frac{a_1'}{d_1'}$, $b=\frac{a_2'}{d_1'}$, $d=\frac{d_2'}{d_1'}$ and $k=\frac{d_1'}{\lambda}$ is defined as the electro-osmotic parameter, λ_2 is the reciprocal of the EDL thickness and is defined by $\frac{1}{\lambda}=\left(\frac{2n_oe^2z_v^2}{\varepsilon k_BT_{av}}\right)^{\frac{1}{2}}$. Thus the electro-osmotic parameter is inversely proportional to EDL thickness λ. The dimensionless form of boundary conditions defined in (4) using the dimensionless variables (5) reduce to

$$\psi_o(y)=\psi_1 \quad \text{at} \quad y=h_1(x),$$

$$\psi_o(y)=\psi_2 \quad \text{at} \quad y=h_2(x). \tag{9}$$

We assumed that the electric potential is much smaller than the thermal potential for which the Debye-Hiickel linearization principle can be approximated as $\sinh(x)\approx x$. On the basis of this assumption, the solution of Poisson-Boltzmann equation (8) takes in the form

$$\frac{d^2\psi_o}{dy^2}=k^2\psi_o\ . \tag{10}$$

Finally, by employing the boundary conditions (9), the closed form solution of the equation (10) is given as

$$\psi_o(y)=F_1\cosh(ky)+F_2\sinh(ky)\ . \tag{11}$$

Couple Stress fluid Model

The given set of pertinent field equations governing the flow, in laboratory frame is

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{12}$$

$$\rho\left(\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}\right)=-\frac{\partial P}{\partial X}+\mu\left(\frac{\partial^2U}{\partial X^2}+\frac{\partial^2U}{\partial Y^2}\right)-\eta\left(\frac{\partial^4U}{\partial X^4}+2\frac{\partial^4U}{\partial X^2\partial Y^2}+\frac{\partial^4U}{\partial Y^4}\right)-\sigma B_0^2U-\frac{\mu}{k_o}U+$$

$$\rho g\beta_T(T-T_0)\sin\alpha+\rho_eE \tag{13}$$

$$\rho\left(\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}\right)=-\frac{\partial P}{\partial Y}+\mu\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-\eta\left(\frac{\partial^4 V}{\partial X^4}+2\frac{\partial^4 V}{\partial X^2\partial Y^2}+\frac{\partial^4 V}{\partial Y^4}\right)$$
$$-\frac{\mu}{k_o}V+\rho g\beta_T\left(T-T_0\right)\cos\alpha \quad (14)$$

$$\rho c_p\left(\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial X}+V\frac{\partial T}{\partial Y}\right)=k^*\left(\frac{\partial^2 T}{\partial X^2}+\frac{\partial^2 T}{\partial Y^2}\right)+Q_0-\frac{\partial q_r}{\partial Y}+\sigma B_0^2u^2+\sigma E^2 \quad (15)$$

where (U,V) are the velocity components in the laboratory frame, ρ is the density, P is the pressure, μ is the viscosity coefficient , η is the couple stress viscosity parameter, σ is the electric conductivity of the fluid, B_0 is the applied transverse magnetic field, k_0 is the permeability parameter, g is the acceleration due to the gravity, β_T and β_C are the coefficient of thermal and concentration expansions, T is the temperature , α is the inclination angle, c_p is the specific heat at constant pressure, k^* is the thermal conductivity , Q_0 is the dimensional heat absorption coefficient, C is the concentration in the reference to fixed frame system, D is the coefficient of mass diffusivity, K_T is the thermal diffusion ratio, T_m is the mean temperature, k_1 is the chemical reaction parameter and α is the inclination angle. The radiative heat flux in the $X-$direction is considered as negligible compared to $Y-$direction. By using Rosseland approximation for thermal radiation, the radiative heat flux q_r is specified by

$$q_r=-\frac{16\sigma^*T_o^3}{3k^*}\frac{\partial T}{\partial Y} \quad (16)$$

where σ^* and k^* are the Stefan-Boltzmann constant and the mean absorption coefficient respectively.

The coordinates and velocities in the wave frame (x,y) and the laboratory frame (X,Y) in a coordinate system moving with the wave speed c in which the boundary shape is stationary and are related by

$$x=X-ct,\ y=Y,\ u=U-c,\ v=V,\ p(x,y)=P(X,Y,t),\ \bar{T}(x,y)=T(X,Y,t) \quad (17)$$

where u,v are the velocity components, p is the pressure, T is the temperature and C is the concentration in the wave frame. Introducing the following non-dimensional quantities

$$\bar{x}=\frac{x}{\lambda},\bar{y}=\frac{y}{d_1},\bar{u}=\frac{u}{c},\bar{v}=\frac{v}{c},\ h_1=\frac{H_1}{d_1},\ h_2=\frac{H_2}{d_1},\ \bar{t}=\frac{ct}{\lambda},\ \bar{p}=\frac{d_1^2}{\lambda\mu C}p,\ \delta=\frac{d_1}{\lambda},$$

$$d=\frac{d_2}{d_1},\ a=\frac{a_1}{d_1},b=\frac{a_2}{d_1},\mathrm{Re}=\frac{\rho c d_1}{\mu},M=\sqrt{\frac{\sigma}{\mu}}B_0d_1,\ Da=\frac{k_0}{d_1^2},\ \gamma=\sqrt{\frac{\mu}{\eta}}d_1,$$

$$Gr=\frac{\rho g d_1^2\beta_T\left(T_1-T_0\right)}{\mu C},\ \bar{\psi}=\frac{\psi}{cd_1},\mathrm{Pr}=\frac{\mu c_p}{k^*},\ \theta=\frac{\bar{T}-\bar{T}_0}{\bar{T}_1-\bar{T}_0},\ \beta=\frac{Q_0d_1^2}{k^*\left(\bar{T}_1-\bar{T}_0\right)},\ Sc=\frac{\mu}{\rho D},$$

$$\gamma_1=k_1\frac{d_1^2}{\upsilon},\ Rd=\frac{16\sigma^*T_o^3}{3k^*\bar{\mu}_oc_f},C_o=\frac{\left(-\frac{d\bar{p}}{d\bar{X}}\right)d_1^2}{\mu U_{HS}} \quad (18)$$

where δ is the dimensionless wave number, Re is the Reynolds number, M is the Hartmann number, Da is the Darcy number, γ is the couple stress parameter, Gr is the local temperature Grashof number, Pr is the Prandtl number, Rd is the thermal radiation parameter, β is the heat generation parameter, γ_1 is the chemical reaction parameter, Sr is the Soret number and A is the Joule heating parameter. Using the above transformations (17) and (18) and non-dimensional quantities (19), the governing flow field equations (13) - (15), after dropping the bars, we get

The dimensional equations of the couple stress fluid are

$$\frac{\partial^4\psi}{\partial y^4}-\frac{1}{\gamma^2}\frac{\partial^6\psi}{\partial y^6}-\left(M^2+\frac{1}{Da}\right)\frac{\partial^2\psi}{\partial y^2}+\frac{d^3\psi_o}{dy^3}+Gr\frac{\partial\theta}{\partial y}\sin\alpha=0 \tag{19}$$

$$\frac{(1+Rd)}{\mathrm{Pr}}\frac{\partial^2\theta}{\partial y^2}+Ec\left[\left(\frac{\partial^2\psi}{\partial y^2}\right)^2+\frac{1}{\gamma^2}\left(\frac{\partial^3\psi}{\partial y^3}\right)^2\right]+EcM^2\left(\frac{\partial\psi}{\partial y}\right)^2+A=0 \tag{20}$$

with the corresponding boundary conditions are

$$\psi=\frac{F}{2},\ \frac{\partial\psi}{\partial y}+L\frac{\partial^2\psi}{\partial y^2}=-1,\frac{\partial^3\psi}{\partial y^3}=0,\theta=0 \text{ at } y=h_1=1+a\cos(2\pi x) \tag{21}$$

$$\psi=-\frac{F}{2},\ \frac{\partial\psi}{\partial y}-L\frac{\partial^2\psi}{\partial y^2}=-1,\frac{\partial^3\psi}{\partial y^3}=0,\theta=1 \text{ at } y=h_2=-d-b\cos(2\pi x+\phi) \tag{22}$$

where L is the velocity slip parameter and F is the flux in the wave frame and the constants a, b, ϕ and d should satisfy the relation

$$a^2+b^2+2ab\cos\phi\le(1+d)^2. \tag{23}$$

The dimensionless mean flow rate Θ in the fixed frame is related to the non-dimensional mean flow rate F in wave frame by

$$\Theta=F+1+d \tag{24}$$

and in which

$$F=\int_{h_1}^{h_2}\frac{\partial\psi}{\partial y}dy \tag{25}$$

Numerical Solution

The solution of system of coupled non –linear Eqs. (20) - (22) with corresponding boundary conditions in Eq. (23) – (24) are obtained using NDSolve in Mathematica computational software. This section contains the plots and related analyses for different embedded parameters. This section includes the graphs for velocity, temperature, concentration and pressure gradient.

Velocity distribution

Fig. 2 displays the velocity profile for various values of Hartmann number. The velocity decreases and drops with Hartmann number M. Fig. 3 depicts velocity profiles of different values of parameter for osmosis parameter. Velocity profile is seen to raise as osmosis parameter k enlarges. Fig. 4 depicts that the consequences of the parameter λ_1 on the profile of velocity. It is clear that enhance the strength of λ_1 resulted in enhancing the velocity. Fig. 5 indicate that the velocity rises with increasing Da. Fig. 6 reveals that velocity is seen to decrease with the higher values of couple stress parameter. Fig. 7 shows that velocity diminishes with increasing L.

Temperature distribution

Fig. 8 – 11 depicts the deviations in temperature profiles for various values of parameters A, k, Ec and $\Pr$. Fig. 8 presents the consequences of the parameter A on the profile of temperature. It is clear that enhance the strength of A resulted in increasing the temperature. Fig. 9 shows that temperature rises with enhancing k. Fig. 10 shows that the temperature enhances significantly with a rise in Ec. Fig. 11 shows a very significant effect of $\Pr$ on the temperature profiles. It is clear from this figure that the Brinkman number has a impulse to diminish the temperature in the micro-channel. It may be inferred that the thermal conductivity of the fluid declines by enhancing the ratio of momentum diffusivity to thermal diffusivity.

Pumping characteristics

Figs. 13 - 15 represent the profiles of pressure gradient $\left(\frac{dp}{dx}\right)$ for the effects of Slip parameter (L), Osmosis parameter (k) and the couple stress parameter (γ). The pressure gradient has oscillatory behavior in the whole range of the x-axis. From all figures, it is clear that the pressure gradient diminishes with the higher values of L, k and γ. The pressure rise is a significant physical measure in the peristaltic mechanism. The results are prepared and discussed for different physical parameters of interest through Figs. 16 – 18 and which are plotted for dimensionless pressure rise ΔP_λ versus the dimensionless flow rate Θ to the effects of Hartmann number M, chemical reaction parameter γ_1, heat generation parameter β and couple stress parameter γ. The pumping regions are peristaltic pumping are $(\Theta > 0, \Delta P_\lambda > 0)$, augment pumping $(\Theta < 0, \Delta P_\lambda < 0)$, retrograde pumping $(\Theta < 0, \Delta P_\lambda > 0)$, co pumping $(\Theta > 0, \Delta P_\lambda < 0)$ and free pumping $(\Theta = 0, \Delta P_\lambda = 0)$. Fig. 16 is depicted that the pressure rise ΔP_λ depressing with an enhance in Hartmann number M in the both peristaltic pumping region and free pumping region. Fig. 17 depicts that the quite opposite nature that of for the effect of the heat generation parameter β .The influence of couple stress fluid parameter γ on the pressure rise is decreases and which is elucidated from Fig. 18.

Nusselt number

Figs. (19) – (21) exhibits the influence of incorporated parameters such as Hartmann number M, Osmosis parameter k and Joule heating parameter A respectively on magnitude of Nusselt number. The heat transfer coefficient has oscillatory in nature due to peristaltic motion of walls. The heat transfer rate enhances for M, k and A from Figs. 19 - 21.

Sherwood number

The mass transfer coefficient shows the impact of different parameters of λ_1 and k from Figs. 22 – 23. Fig. 22 depicts the Sherwood number depresses with the impact of λ_1 whereas it observes the mass transfer coefficient enhances as the parameter k rises from Fig. 23.

Trapping Phenomenon

The phenomenon of trapping in flow of fluid is trapping and is presented by drawing streamlines in the Figs. 24 - 27. A bolus is having by splitting of a streamline under important conditions and it is followed along with the wave in the wave frame. This process is called trapping. The bolus of trapping is observed to expand by enhancing M from Figs. 24 – 25. However the size of bolus decreases by the rising effects of λ_1 as shown in Figs. 26 – 27.

Concluding Remarks

We have investigated the peristaltic transport of a heat and mass transfer of couple stress fluid on the combined impacts of electro-osmotically and pressure driven flow in an inclined asymmetric micro channel whose walls are varying sinusoidally with different wave trains. Effects of thermal radiation, chemical reaction and Joule heating have been accounted. The numerical solution for velocity, temperature distribution, concentration distribution and pumping characteristics are presented using small wave length and small Reynolds number. The important findings of present study are summarized as follows

- The Electro – osmotic flow of couple stress fluids in an inclined asymmetric channel is strongly depend on Debye length.
- Velocity diminishes with an enhance of L and γ.
- Temperature rises with an strength of A where as depresses with an enhance of Rd.
- It is observed that pressure gradient has oscillatory behavior.
- Pressure rise decreases with an effect of increasing γ
- The absence of Electro – Osmosis, our results are in good agreement with Gnaneswara Reddy *et al.* [33].

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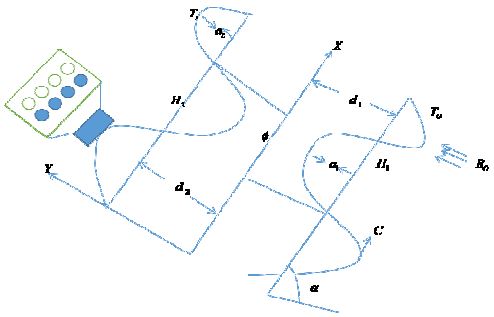

Fig. 1. Physical Model

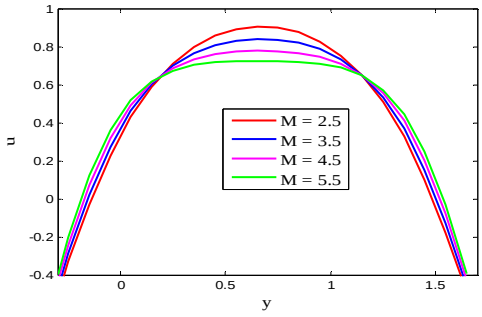

Fig.2. u for M

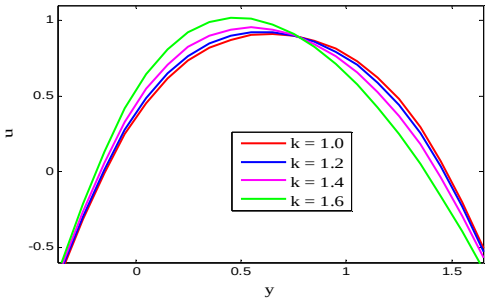

Fig.3. u for k

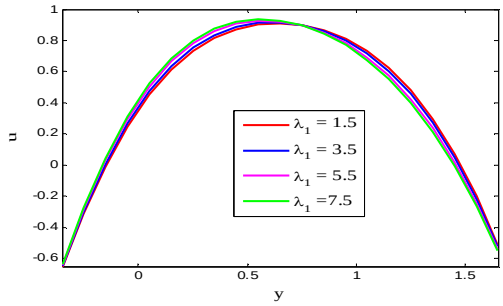

Fig. 4. u for λ_1

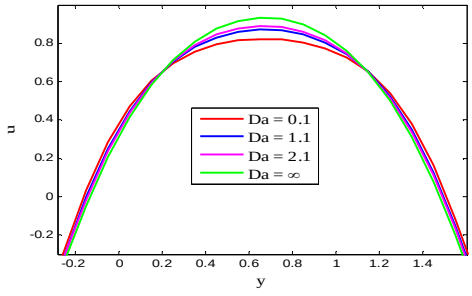

Fig. 5. u for Da

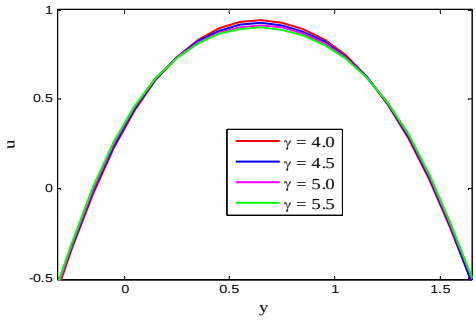

Fig. 6. u for γ

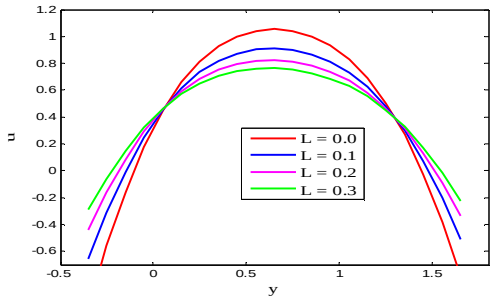

Fig. 7. u **for** L

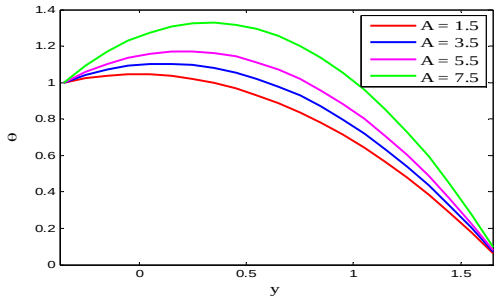

Fig. 8. θ **for** A

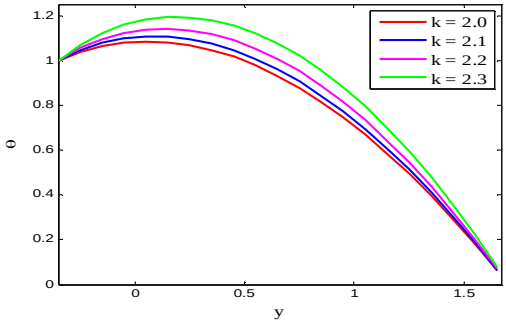

Fig. 9. θ **for** k

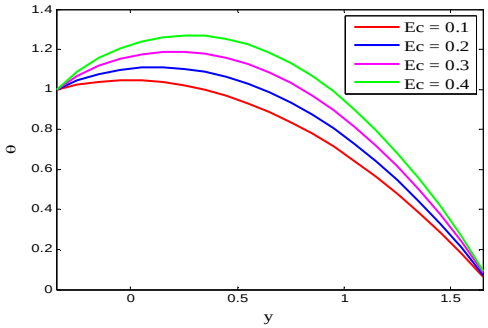

Fig. 10. θ **for** Ec

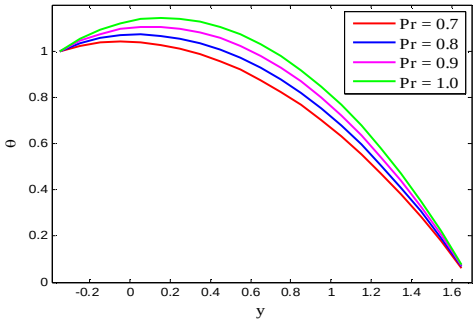

Fig. 11. θ **for** Pr

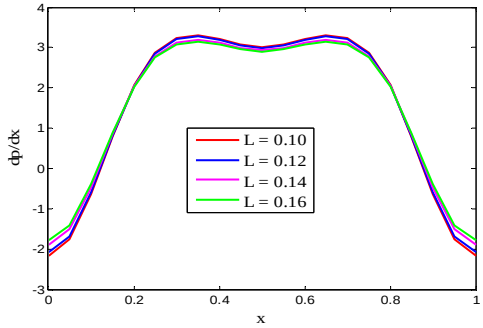

Fig. 12. $\frac{dp}{dx}$ **for** L

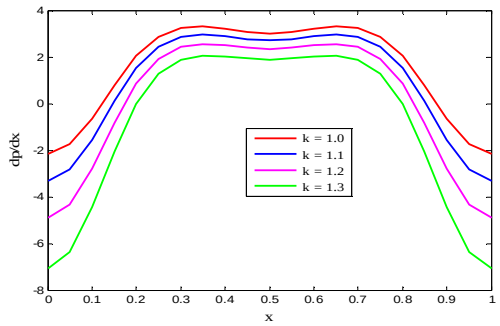

Fig. 13. $\frac{dp}{dx}$ **for** k

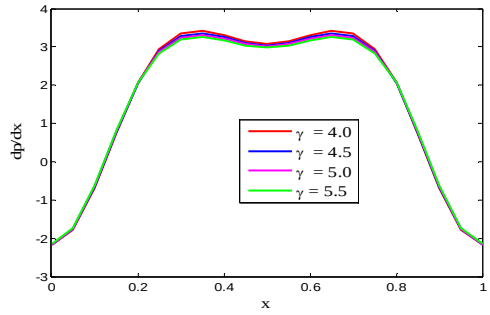

Fig. 14. $\frac{dp}{dx}$ **for** γ

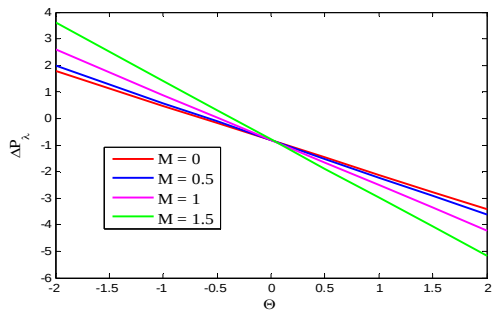

Fig. 15 ΔP_λ **for** M

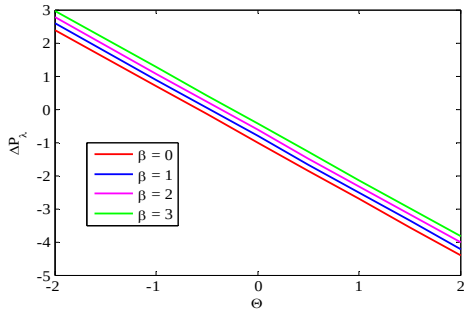

Fig. 16. ΔP_λ **for** β

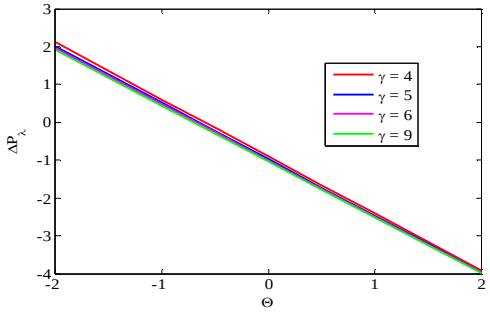

Fig. 17. ΔP_λ **for** γ

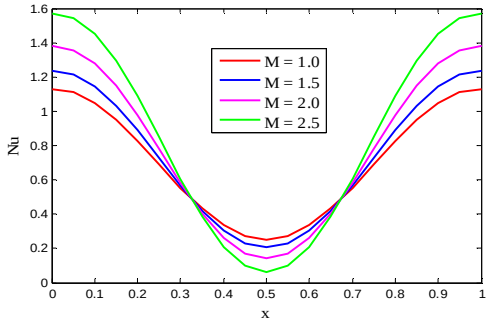

Fig. 18. Nu **for** M

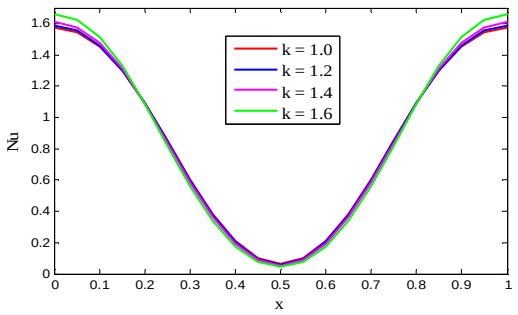

Fig. 19. Nu **for** k

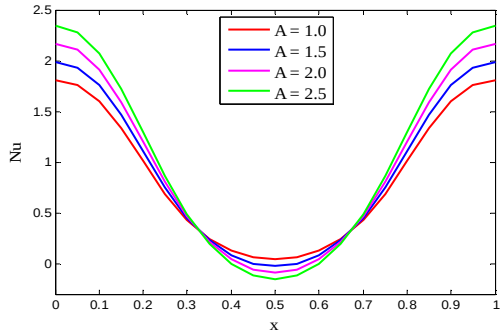

Fig. 20. Nu **for** A

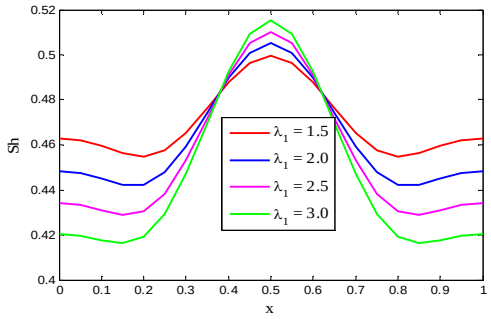

Fig. 21. Sh **for** λ_1

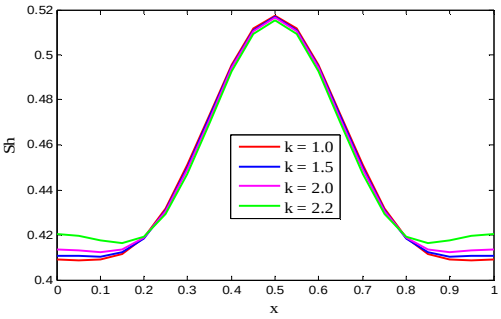

Fig. 22. Sh **for** k

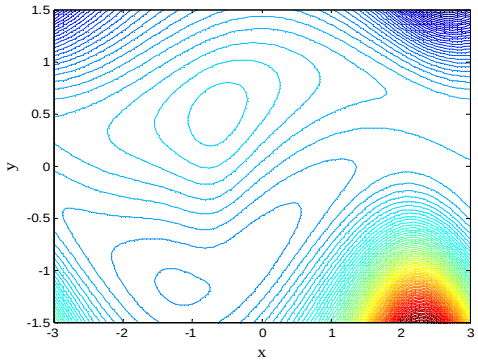

Fig. 23. Effect of M **on stream lines for** $M = 1.5$.

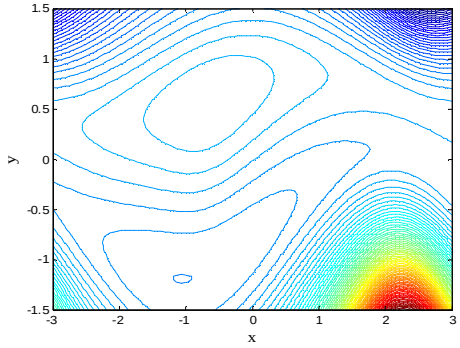

Fig.24. Effect of M **on stream lines for** $M = 1.6$.

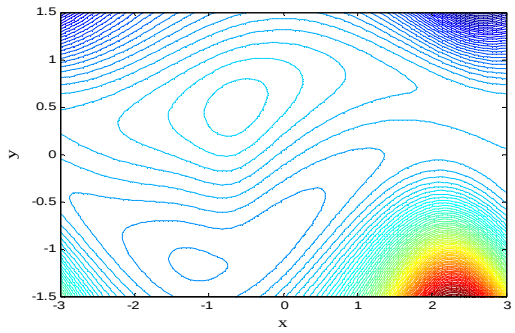

Fig.25. Effect of λ_1 on stream lines for $\lambda_1 = 1.5$.

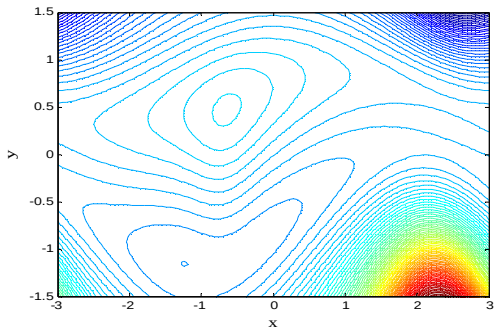

Fig.26. Effect of λ_1 on stream lines for $\lambda_1 = 1.6$.