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INFLUENCE OF INCLINED MAGNETIC FIELD AND WALL SLIP CONDITIONS ON STEADY FLOW BETWEEN A PARALLEL FLAT WALL AND A LONG WAVY WALL WITH SORET EFFECT

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ABSTRACT

In this paper, we have investigated the heat and mass transfer effects on Magneto hydro dynamic flow of a steady viscous incompressible and electrically conducting fluid through a non – isothermal parallel flat wall and a long wavy wall in the presence of Soret effect. A uniform inclined magnetic field is applied in the direction normal to the walls. The equations governing the flow are solved with the boundary conditions. The effect of various physical quantities viz., Prandtl number, Peclet number, Hartmann number, heat source parameter, suction parameter, slip parameter, soret number and hall parameter are studied with the help of graphs. The expression for skin friction, the rate of heat transfer and the rate of mass transfer are also obtained and discussed through graphs.

KEYWORDS*:* Wavy Wall, Inclined Magnetic Field, Non-Isothermal Plate, Diffusion –Thermo Effect, Steady Flow

When heat and mass transfer occur in a moving fluid simultaneously, the relations between the fluxes and the driving potentials are of more complicate nature. MHD flow of an electrically conducting fluid attracted the interest of many researchers due to its important applications in various engineering fields. It has many important applications in the design of power generators, heat exchangers, pumps and flow meters. Heat transfer by convection has applications in numerous technological problems including combustion, furnace design, fluidized bed heat exchanger, nuclear reactor safety, fire spreads, solar fans and solar collectors.

MHD flow of viscous fluid between parallel porous walls in steady state flow of fluid in the presence of transverse magnetic field is studied by Ramesh Yadav, Manju Agarwal and Vivek Joseph (2016). The numerical solution of a two – dimensional, steady, incompressible, electrically conducting, laminar free convection boundary layer flow of a continuously moving vertical porous plate in the presence of a transverse magnetic field and heat generation using shooting technique is done by Rushi Kumar and Gangadhar (2012). Makinde, Zimba, Anwar Beg (2012) studied numerically the chemically reactive boundary layer flow of an electrically conducting fluid past a semi – infinite moving vertical plate with convective heat exchange at the surface in the presence of magnetic field with Dufour and Soret effects. The effect of inclined magnetic field on unsteady flow past a moving vertical plate with variable temperature is examined by Navneet Kumar Singh, Vinod Kumar and Gaurav Kumar Sharma (2016).

Shankar and Sinha (1976) studied the Rayleigh problem for a wavy wall. It gives a good illustration of the interaction between a viscous fluid field and its related inviscid fluid. The effect of induced magnetic field and slip on the peristaltic flow of Jeffrey fluid in a non – uniform channel and flow analysis in the presence of heat and mass transfer is investigated by Najma Saleem, Hayat and Alsaedi (2012)

Rajeev Taneja and Jain (2004) examined the problem of an MHD free convection flow in the presence of a temperature dependent heat source in a viscous incompressible fluid between a long vertical wavy wall and a parallel flat wall with constant heat flux and slip flow boundary condition. Muthuraj and Srinivas (2009) discussed about the MHD flow of a viscous fluid between a parallel flat wall and a long wavy wall in the presence of a slip condition considering the thermo diffusion effect with constant suction velocityV_0

Hall effect was discovered by Edwin Hall in 1879. It is important when the magnetic field is high or when the collision frequency is low. Hall current are of great importance in many astrophysical problems such as Hall accelerators and flight MHD, as well as flows of plasma in a MHD power generator.

Sulochana and Manjula (2014) investigated the effect of hall current and thermal diffusion on the convective heat and mass transfer flow of a viscous electrically conducting fluid in a vertical channel bounded by wavy walls in the presence of temperature dependent heat source under the influence of inclined magnetic field.

The Hall current effect and thermal diffusion on the convective heat and mass transfer flow of a viscous electrically conducting fluid through a porous medium in a vertical channel bounded by wavy walls in

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the presence of heat generating source and an inclined magnetic field has been analyzed by Vijayalakshmi, Rajeswara Rao and Prasada Rao (2014).

Bhaskar Chandra Sarkar, Sanatan Das and Rabindra Nath Jana (2014) studied the MHD flow of a viscous incompressible electrically conducting fluid between two parallel plates in a rotating system in the presence of an inclined magnetic field taking Hall effect into account. The Hartmann flow of a viscous incompressible electrically conducting fluid in a rotating system in the presence of an inclined magnetic field with Hall effect is studied by Seth, Raj Nandkeolyar and Ansari (2010).

Sankar Kumar Guchhait, Rabindra Nath Jana, Sanatan Das (2015) presented unsteady hydro magnetic free convective flow of a viscous incompressible electrically conducting fluid in the presence of an inclined magnetic fluid taking hall currents into account. Priya Johari (2014) studied the steady MHD flow of a viscous incompressible fluid due to the uniform rotation of a disk of infinite extent in a porous medium with the influence of heat transfer and Hall effects. The effects of the MHD and hall current of the medium on the steady flow and heat transfer have been computed and discussed. In this paper, the work of Muthuraj and Srinivas is extended by considering the slip boundary condition with the Hall effect and inclined magnetic field.

FORMULATION OF THE PROBLEM

We have considered a steady viscous incompressible electrically conducting fluid flowing through a non-isothermal parallel flat wall and a long wavy wall in the presence of Soret effect and inclined magnetic field. To simplify the equations governing the fluid flow, the following assumptions was made.

- The flow is steady and incompressible
- It is assumed that there is no applied voltage, the force due to electric field is negligible.
- It is also assumed that the magnetic Reynolds number is very small and hence the induced magnetic field is negligible in comparison to the applied magnetic field.
- A uniform inclined magnetic field is applied in the direction normal to the walls.
- The wavy and flat walls are maintained at constant temperatures T_1'andT_2'.
- Viscous dissipation and Joule heating terms are negligible because small velocity only encounters in free convective flows.

The MHD flow of a viscous fluid through a non – isothermal parallel flat wall and a long wavy wall is taken along x and y directions, so that the flat wall is represented by y = 0 and the wavy wall by y = d + ε*coskx (see Fig.1).

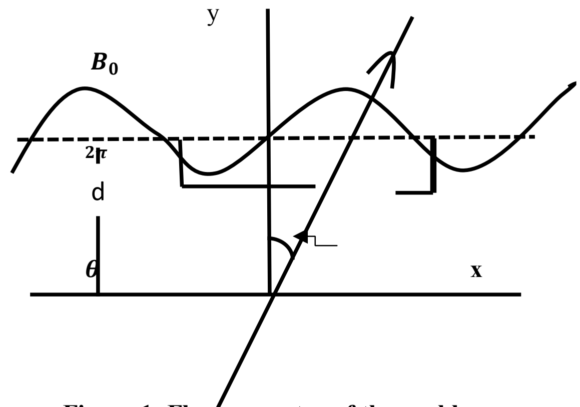

Figure 1: Flow geometry of the problem

In the presence of inclined magnetic field and temperature dependent heat source, the governing equations for this problem are based on the balance laws of mass, linear momentum, energy conservation and concentration.

These can be written as

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

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)$$
$$-\frac{u\sigma B_0^2\mu_e^2\cos^2\theta}{1+m^2\cos^2\theta} \tag{2}$$

$$\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\vartheta\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{K}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\frac{Q}{\rho C_p}(T-T_1') \tag{4}$$

$$\left(u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}\right)=D_m\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}\right)$$
$$+\frac{D_m k_T}{\bar{T}}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{5}$$

The boundary conditions of the problem are

u = $L_1\left(\frac{\partial u}{\partial y}\right)$, v = - V_0, T = T_1', C = C_1'at y= 0

u = $-L_1\left(\frac{\partial u}{\partial y}\right)$, v = 0, T = T_2', C = C_2'

at y = d+$\varepsilon * coskx$ (6)

where, $L_1=\left(\frac{2-m_1}{m_1}\right)$L,

Since the flat wall is infinite in length,

$$\frac{\partial u}{\partial x}=0 \tag{7}$$

On integrating equation (1) and using equation (6), we obtain

$$v = -V_0 \qquad (8)$$

We introduce the following non – dimensional variables

$$(x^*, y^*) = \frac{1}{d}(x, y)\,,\ (u^*, v^*) = \frac{1}{V_0}(u, v),$$

$$p^* = \frac{pd}{\mu_o V_0}, T^* = \frac{T - T_1'}{T_2' - T_1'},\ \phi^* = \frac{C - C_1'}{C_2' - C_1'}. \qquad (9)$$

In view of equations (8) and (9), equations (2) - (5) reduce to

(Omitting * symbols for clarity)

$$\frac{d^2u}{dy^2} + R\frac{du}{dy} - M^2\frac{\cos^2\theta}{1+m^2\cos^2\theta}u = \frac{dp}{dx} \qquad (10)$$

$$\frac{dp}{dy} = 0 \qquad (11)$$

$$\frac{d^2T}{dy^2} + PrR\frac{dT}{dy} + \alpha T = 0 \qquad (12)$$

$$\frac{d^2C}{dy^2} + Pe\frac{dC}{dy} + Sr\frac{d^2T}{dy^2} = 0 \qquad (13)$$

Together with boundary conditions,

$u = \gamma u'$, $v = -1$, $T = 0$, $\phi = 0$ at $y = 0$

$u = -\gamma u'$, $v = 0$, $T=1$, $\phi = 1$ at $y = h$ (14)

where $h = 1 + \varepsilon\cos\lambda x$

From equation (11), we observe that the pressure of the fluid p is independent of y.

Method of Solution

Solving equation (10) using the boundary conditions (14), we obtain

$$u(y) = \frac{c}{M^2}\frac{1+m^2\cos^2\theta}{\cos^2\theta}\left(\frac{\left((e^{\beta_4 h}-1)+\gamma\beta_4(1+e^{\beta_4 h})\right)e^{\beta_3 y} - \left((e^{\beta_3 h}-1)+\gamma\beta_3(1+e^{\beta_3 h})\right)e^{\beta_4 y}}{(1-\gamma^2\beta_3\beta_4)(e^{\beta_4 h}-e^{\beta_3 h}) + \gamma(e^{\beta_3 h}+e^{\beta_4 h})(\beta_4-\beta_3)} - 1\right) \qquad (15)$$

Making use of equation (14) in equation (12), we obtain

$$T(y) = \frac{e^{\beta_1 y} - e^{\beta_2 y}}{e^{\beta_1 h} - e^{\beta_2 h}} \qquad (16)$$

Incorporating equation (16) into (13) then solving, we get

$$\phi(y) = \frac{(1-e^{-Pey})}{(1-e^{-Peh})} + \frac{S_r}{e^{\beta_1 h}-e^{\beta_2 h}}\left(\frac{\beta_1(1-e^{\beta_1 y})}{Pe+\beta_1} - \frac{\beta_2(1-e^{\beta_2 y})}{Pe+\beta_2}\right) + \frac{S_r(1-e^{-Pey})}{(e^{\beta_1 h}-e^{\beta_2 h})(1-e^{-Peh})}\left(\frac{\beta_2(1-e^{\beta_2 h})}{Pe+\beta_2} - \frac{\beta_1(1-e^{\beta_1 h})}{Pe+\beta_1}\right) \qquad (17)$$

where $c = \frac{dp}{dx}$

$$\beta_1 = \frac{-PrR + \sqrt{Pr^2R^2 - 4\alpha}}{2}$$

$$\beta_2 = \frac{-PrR - \sqrt{Pr^2R^2 - 4\alpha}}{2}$$

$$\beta_3 = \frac{-R + \sqrt{R^2 + \frac{4M^2\cos^2\theta}{1+m^2\cos^2\theta}}}{2}$$

$$\beta_4 = \frac{-R - \sqrt{R^2 + \frac{4M^2\cos^2\theta}{1+m^2\cos^2\theta}}}{2}$$

Skin Friction

The skin friction at the flat wall y = 0 and the wavy wall y = h is given by

$$\tau_0 = \left(\frac{\partial u}{\partial y}\right)_{y=0} = \frac{c}{M^2}\frac{1+m^2\cos^2\theta}{\cos^2\theta}\left(\frac{[(e^{\beta_4 h}-1)+\gamma\beta_4(1+e^{\beta_4 h})]\beta_3 - [(e^{\beta_3 h}-1)+\gamma\beta_3(1+e^{\beta_3 h})]\beta_4}{(1-\gamma^2\beta_3\beta_4)(e^{\beta_4 h}-e^{\beta_3 h}) + \gamma(e^{\beta_3 h}+e^{\beta_4 h})(\beta_4-\beta_3)}\right) \qquad (18)$$

$$\tau_1 = \left(\frac{\partial u}{\partial y}\right)_{y=h} = \frac{c}{M^2}\frac{1+m^2\cos^2\theta}{\cos^2\theta}\left(\frac{[(e^{\beta_4 h}-1)+\gamma\beta_4(1+e^{\beta_4 h})]\beta_3 e^{\beta_3 h} - [(e^{\beta_3 h}-1)+\gamma\beta_3(1+e^{\beta_3 h})]\beta_4 e^{\beta_4 h}}{(1-\gamma^2\beta_3\beta_4)(e^{\beta_4 h}-e^{\beta_3 h}) + \gamma(e^{\beta_3 h}+e^{\beta_4 h})(\beta_4-\beta_3)}\right) \qquad (19)$$

Nusselt Number

The Nusselt number at the flat wall y = 0 and the wavy wall y = h is given by

$$Nu_0 = (Nu)_{y=0} = -K\frac{\beta_1 - \beta_2}{e^{\beta_1 h} - e^{\beta_2 h}} \qquad (20)$$

$$Nu_1 = (Nu)_{y=h} = -K\frac{\beta_1 e^{\beta_1 h} - \beta_2 e^{\beta_2 h}}{e^{\beta_1 h} - e^{\beta_2 h}} \qquad (21)$$

Sherwood Number

The Sherwood number at the flat wall y = 0 and the wavy wall y = h is given by

$$Sh_0 = \left(\frac{\partial\phi}{\partial y}\right)_{y=0} = \frac{(1+Pe)}{(1-e^{-Peh})} + \frac{S_r}{e^{\beta_1 h}-e^{\beta_2 h}}\left(\frac{\beta_1(1-\beta_1)}{Pe+\beta_1} - \frac{\beta_2(1-\beta_2)}{Pe+\beta_2}\right) + \frac{S_r(1+Pe)}{(e^{\beta_1 h}-e^{\beta_2 h})(1-e^{-Peh})}\left(\frac{\beta_2(1-e^{\beta_2 h})}{Pe+\beta_2} - \frac{\beta_1(1-e^{\beta_1 h})}{Pe+\beta_1}\right) \qquad (22)$$

$$Sh_1 = \left(\frac{\partial\phi}{\partial y}\right)_{y=h} = \frac{(1+Pee^{-Peh})}{(1-e^{-Peh})}$$

$$+\frac{S_r}{e^{\beta_1 h}-e^{\beta_2 h}}\left(\frac{\beta_1(1-\beta_1 e^{\beta_1 h})}{Pe+\beta_1}-\frac{\beta_2(1-\beta_2 e^{\beta_2 h})}{Pe+\beta_2}\right)$$
$$+\frac{S_r(1+Pee^{-Peh})}{(e^{\beta_1 h}-e^{\beta_2 h})(1-e^{-Peh})}\left(\frac{\beta_2(1-e^{\beta_2 h})}{Pe+\beta_2}-\frac{\beta_1(1-e^{\beta_1 h})}{Pe+\beta_1}\right) \quad (23)$$

FINDINGS

The formulation of the effect of inclined magnetic field on the flow of a viscous incompressible fluid through a non-isothermal flat wall and a long wavy wall with constant heat source in the presence of Soret effect has been carried out in the preceding sections. This enables to carry out numerical computation for velocity, temperature and concentration, also skin friction, Nusselt number and Sherwood number for various values of material parameters. Numerical evaluation of the analytical results is reported graphically in figures (2) – (19). Taking Hall parameter (m = 0.5) and angle of inclination θ of the magnetic field ($\theta = 60^{\circ}$), the velocity, temperature, concentration, Skin friction, Nusselt number and Sherwood number profiles for various non – dimensional parameter are depicted graphically with the help of MATLAB 7.14 software.

The velocity profile for different slip parameter is shown in Figure 2. It is observed that the increasing slip parameter leads to increase the fluid velocity.

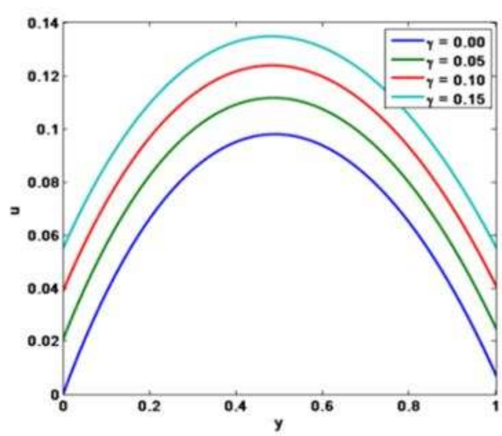

Figure 2: Velocity profile for various slip parameter (γ) [c = -1, M = 2, R = 0.5, x= 1, ε= 0.02, λ= 0.4, m = 0.5, θ =60°]

The velocity profile for different suction parameter is shown in Figure 3. It is clearly known that the velocity profile decrease monotonically with the increase of suction parameter.

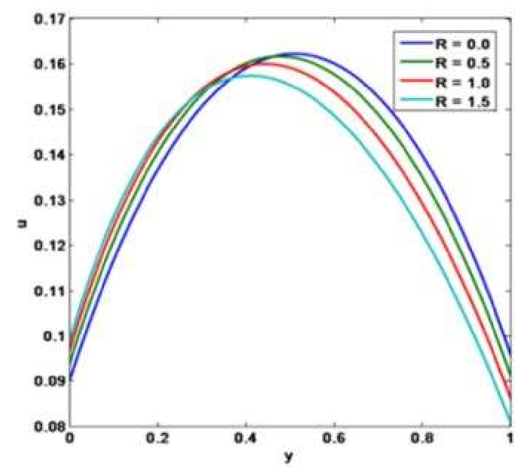

Figure 3:Velocity profile for various suction parameter (R) [c=-1, M=2,γ= 0.3, x = 1, ε= 0.02, λ= 0.4, m = 0.5, θ =60°]

The velocity profile for different Hartmann number is shown in Figure 4. As expected the fluid velocity decreases due to an increase in Hartmann number.

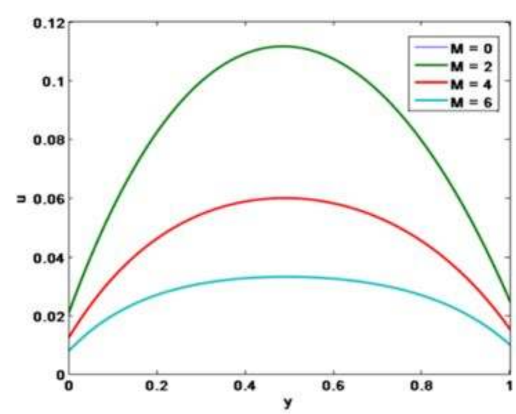

Figure 4: Velocity profile for various Hartmann number (M) [c = -1,γ= 0.05, R=0.5,x=1, ε=0.02, λ=0.4, m=0.5,θ =60°]

The velocity profile for different values of Hall parameter is shown in figure 5. It is evident that the velocity profile increases with the increase of Hall parameter.

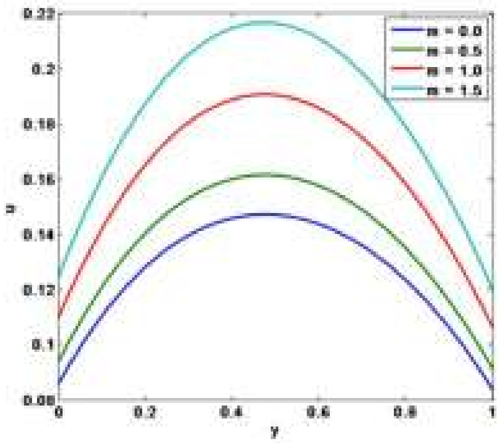

Figure 5: Velocity profile for various Hall parameter (m) [c = -1, γ= 0.3, R = 0.5, x = 1, ε= 0.02, λ= 0.4, M = 2, θ =60°]

The temperature profile for different values of heat source parameter is shown in Figure 6. It is noticed that increase in the heat generation causes the fluid temperature to increase.

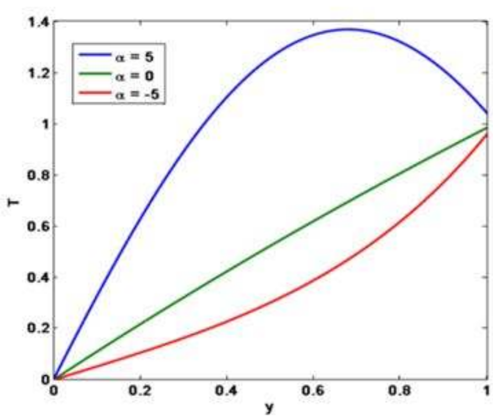

Figure 6: Temperature profile for various heat source parameter (α)[Pr = 0.5, R = 0.5, x = 1, ε= 0.02, λ= 0.4]

The temperature profile for different values of suction parameter is shown in Figure 7. It is observed that, in the case of heat generation (α> 0) the temperature increases with the increase in suction parameter. On the other hand, the heat absorption (α< 0) produces the opposite effect.

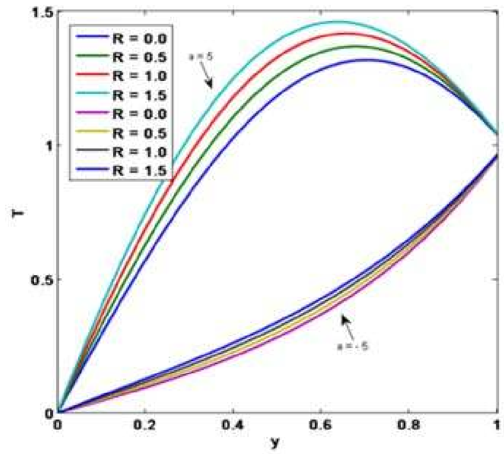

Figure 7: Temperature profile for various suction parameter (R) [Pr = 0.5, x = 1, ε= 0.02, λ= 0.4]

The temperature profile for different values of Prandtl number is shown in figure 8. It is known that the increasing Prandtl number decreases the fluid temperature.

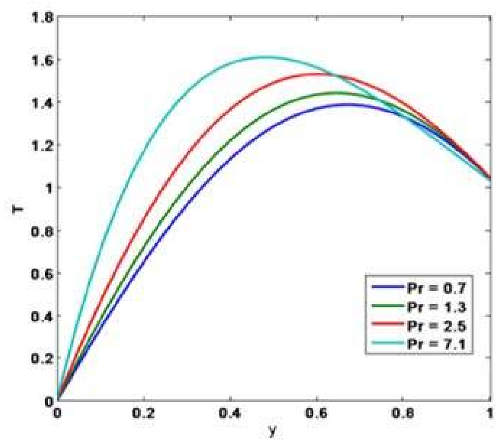

Figure 8: Temperature profile for various Prandtl number (Pr) [R = 0.5, α=5, x = 1, ε= 0.02, λ= 0.4]

The concentration profile for different values of soret number is shown through Figure 9. It is well known that the fluid concentration decreases with increasing Soret number.

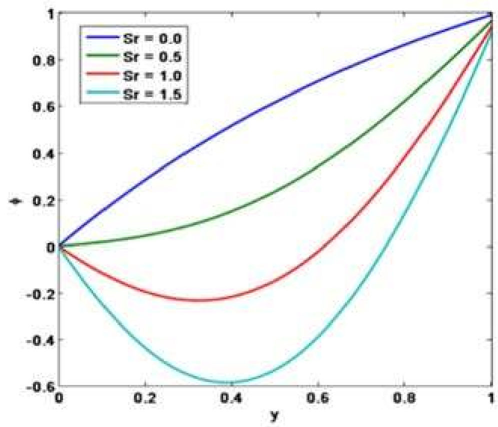

Figure 9: Concentration profile for various Soret number (Sr)[Pe =1, Pr = 0.5, R=0.5,α=5, x = 1, ε= 0.02, λ= 0.4]

Figure 10 disciples the effect of suction parameter on the concentration profile. It is known that the increase in suction parameter results a decrease in the fluid concentration.

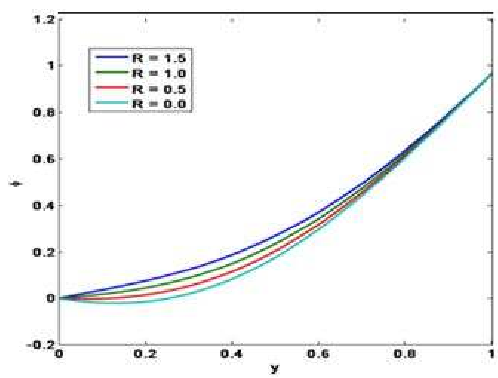

Figure 10: Concentration profile for various suction parameter (R) [Pe = 1,Pr=0.5, Sr=0.5,α=5, x=1, ε= 0.02, λ= 0.4]

The concentration profile for different values of Peclet number is shown in Figure 11. It is well known that the increasing Peclet number decreases the fluid concentration when α< 0 (heat absorption) whereas it is reversed when α> 0 (heat generation).

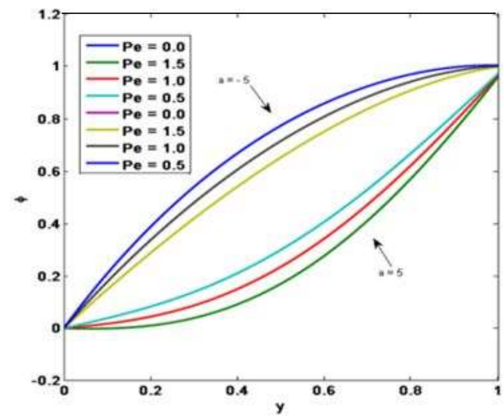

Figure 11: Concentration profile for various Peclet number (Pe) [Sr = 0.5, Pr = 0.5, R=0.5, x = 1, ε= 0.02, λ= 0.4]

The concentration profile for different values of Prandtl number is shown in Figure 12. It is observed that the concentration decreases with increasing Prandtl number.

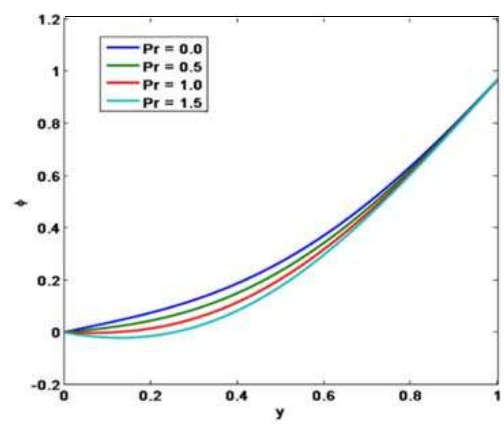

Figure 12: Concentration profile for various Prandtl number (Pr) [Pe=1, Sr=0.5, R=0.5,α=5, x= 1, ε= 0.02, λ= 0.4]

The skin friction for different values of suction parameter is shown in Figure 13. It exhibits that the magnitude of skin friction increases with an increase of suction parameter at the wavy wall y = h.

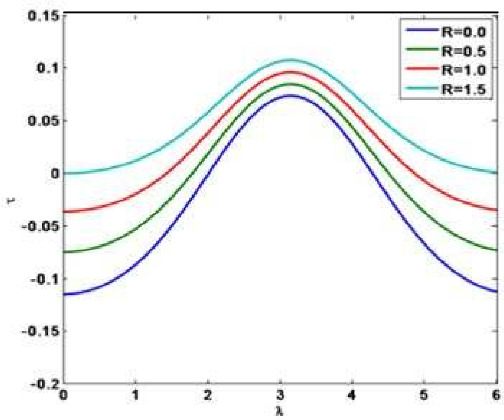

Figure 13: Skin friction for various suction parameter (R) at wavy wall

[c = -1, M = 2, x = 1.0, ε= 0.4, γ= 0.05, m = 0.5, θ =60°]

The skin friction for various suction parameter at the flat wall y = 0 is shown in Figure 14. It is clear that the skin friction increases with an increase in suction parameter.

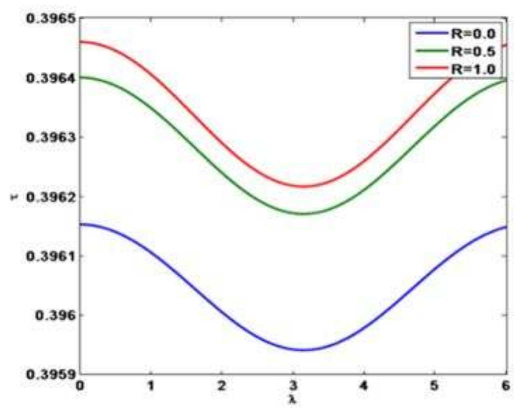

Figure 14: Skin friction for various suction parameter (R) at flat wall [c = -1, M=2, x=1.0, ε= 0.02, r=5, m=0.5, θ =60°]

The skin friction for different values of slip parameter is shown in Figure 15. The graph reveals that the skin friction increases with increasing slip parameter at the wavy wall y = h.

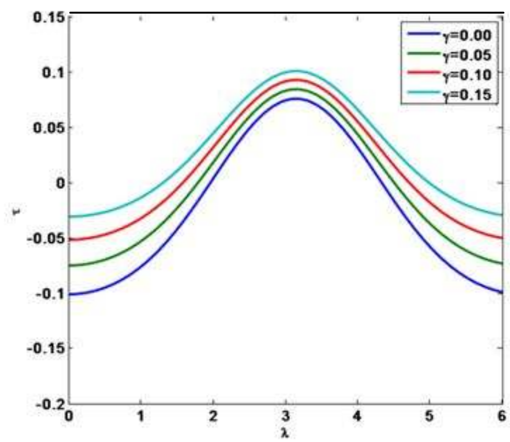

Figure 15: Skin friction for various slip parameter (γ) at wavy wall [c = -1, M = 2, x = 1.0, ε= 0.02, r = 5, m = 0.5, θ =60°]

Figure 16 depicts the variation of skin friction at the flat wall y = 0. It is well known that the skin friction decreases with increase of slip parameter.

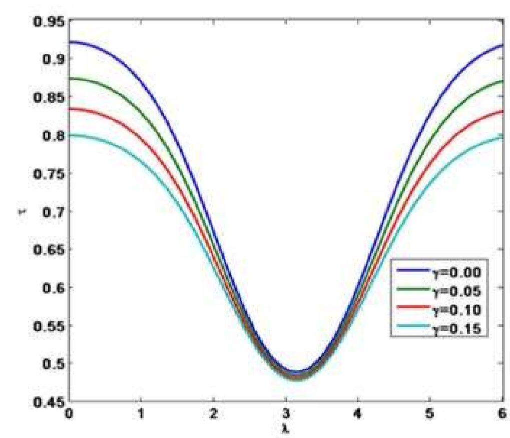

Figure 16: Skin friction for various slip parameter (γ) at flat wall[c = -1, M = 2, x = 1, ε= 0.02, R =0.5, m = 0.5, θ =60°]

The Nusselt number for different values of Prandtl number is shown in Figure 17. It is shown that the Nusselt number increases with an increase of Prandtl number at the flat wall y = 0, but the Nusselt number decreases with an increase of Prandtl number at the wavy wall y = h.

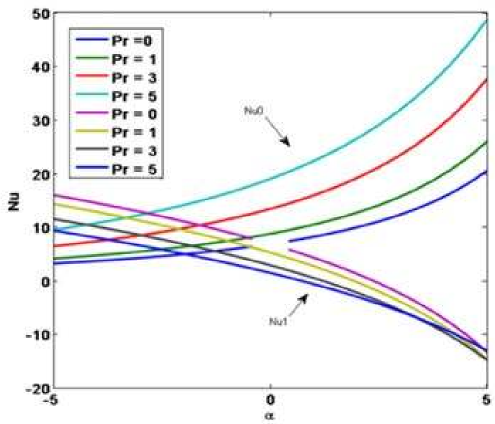

Figure 17: Nusselt number for various Prandtl number (Pr) [R=0.5, x = 1.0, ε= 0.02, λ= 0.4, K = 7.0]

Figure 18 exhibits the variation of Nusselt number. It is observed that the Nusselt number increases with an increase of suction parameter at the flat wall y = 0, but the Nusselt number decreases with an increase of suction parameter at the wavy wall y = h.

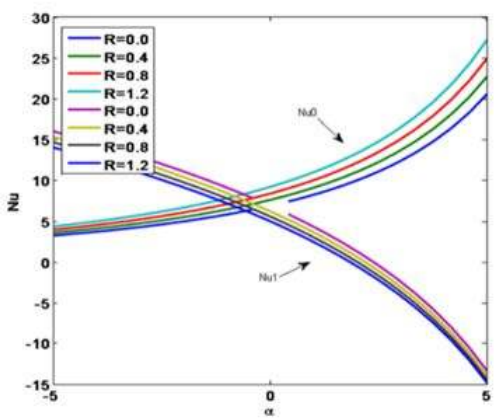

Figure 18: Nusselt number for various suction parameter (R)[Pr = 0.5, K=7.0, x =1.0, ε= 0.02, λ= 0.4]

The Sherwood number for different values of suction parameter is shown in Figure 19. It is shown that Sherwood number increases with increase of suction parameter at y=h and decreases with increase of suction parameter at y = 0.

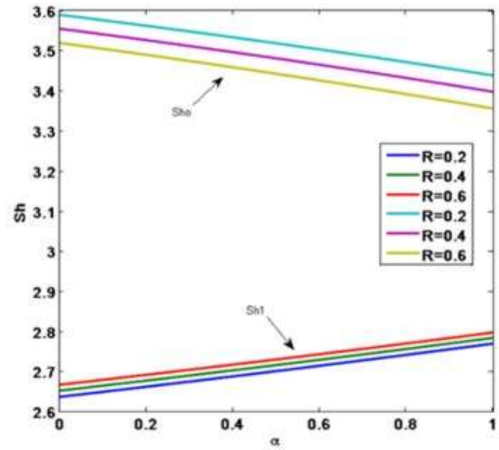

Figure 19: Sherwood number for various suction parameter (R) [Pe = 1, Pr = 0.5, Sr = 0.5, x = 1, ε= 0.02,$\lambda = 0.4$]

CONCLUSION

A uniform inclined magnetic field is applied in the direction normal to the walls. The influence of applied inclined magnetic field and wall slip effect on the MHD flow between a parallel flat wall and a long wavy wall has been analyzed. The effect of pertinent parameters on flow, heat and mass transfer characteristics are discussed in detail. Graphical results shows the influence of the various non – dimensional parameters which occurs in the problem under study.

The following conclusions are made based on the assumptions taken

i) Velocity increases with the increase of slip parameter and Hall parameter, decreases with the increase of suction parameter and Hartmann number.

ii) Temperature increases with the increase of heat source parameter, decreases with the increase of Prandtl number and in the case of heat generation (α>0) the temperature increases with the increase in suction parameter. On the other hand heat absorption (α< 0) produces the opposite effect.

iii) Concentration increases with the increase of suction parameter, decreases with the increase of Soret number and Prandtl number whereas increase of Peclet number decreases the fluid concentration when α< 0 (heat absorption) whereas it is reversed when α> 0 (heat generation).

iv)Skin friction increases with the increase of suction parameter at both the walls and for the increase in slip parameter skin friction increases at the flat wall and decreases at the wavy wall.

v) Nusselt number increases with increasing values of Prandtl number and suction parameter at the flat wall but it decreases with increasing values of Prandtl number and suction parameter at the wavy wall.

vi) Sherwood number increases with increase of suction parameter at the wavy wall and decreases with increase of suction parameter at the flat wall.

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