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Variable Viscosity and Thermal Conductivity Effect of Soret and Dufour on Inclined Magnetic Field in Non-Darcy Permeable Medium with Dissipation

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Authors' contributions

This work was carried out in collaboration between both authors. Author RAK formulated the problem and the derivation of equation and reviewed the literatures. Author SOS solved the problem, carried out the mathematical analysis, did the tables and graphs and discussion of findings. Both authors read and approved the final manuscript.

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Abstract

The analysis of thermal-diffusion (Soret) and diffusion-thermo (Dufour) effects on variable thermal conductivity and viscosity in a dissipative heat and mass transfer of an inclined magnetic field in a permeable medium past a continuously stretching surface for power-law difference in the concentration and temperature are examined. The flow is incompressible with the thermal conductivity and fluid viscosity are assumed to be temperature dependent. The local similarity variables for various values of the parameters are considered for the momentum, heat and mass equations. The dimensionless equations are solved numerically using fourth order Runge-Kutta scheme coupled with shooting method. It was noticed that an increase in the values of m enhances the temperature profiles as heat moves from the plate surface to the ambient medium when $m \succ 0$, otherwise it flows away from the medium to the stretching sheet. Finally, the influences of Skin friction, Nusselt and Sherwood numbers are also presented and discussed.

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Keywords: Variable viscosity; Soret; non-Darcy flow; thermal conductivity; Dufour.

1 Introduction

The study of the consequence of variable viscosity of the fluid and thermal conductivity with an inclined magnetic field in an incompressible flow stimulated by the instantaneous actions of buoyancy forces consequential from non-Darcy porous medium on heat and mass transfer is important from the practical and theoretical point of view due to it applications in planetary atmosphere research and others. During many mechanical forming processes, heat generation is essential in the aspect of chemical reaction. Presently, improvement has been significantly achieved in the analysis of MHD heat and mass transfer flow as a result of it usefulness in several devices, such as Hall accelerator, power engineering, MHD power generator and underground spreading of chemical wastes are the few areas where the combined diffusion-thermo and thermal-diffusion influences are observed.

There are numerous engineering cases where joint heat and mass transfer take place concurrently such as desert coolers, chemical reactors, humidifiers, dehumidifiers etc. In few of these, [1-3] carried out analysis on radiative mixed convection MHD flow in a permeable medium with heat and mass transfer near a vertical surface while Singh & Makinde [4] analyzed computational dynamics of Newtonian heating magnetohydrodynamic flow of volumetric heat generation past an inclined surface. [5-6] studied flow of heat and mass transfer for hydrodynamic radiative fluid through a porous moving plate. It was reported that the interface of the magnetic field is counter prolific in improving the concentration and velocity profiles favorable in achieving superior temperature inside the fluid flow field. I-Chung [7] reported on heat and mass transfer over a stretching sheet in magnetohydrodynamic flow. It was observed that the temperature at unchanging position raised with an increase in the magnetic field and heat generation terms but reduced with an increase in the Prandtl number. The magnetic field term affects the velocity profile and as well accelerates the temperature profile indirectly.

Due to its several applications, an analytical study was carried out involving permeable plates with an inclined magnetic poiseuille fluid flow by Manyonge et al. [8]. Inclined magnetic field with chemical reaction effects on semi infinite porous surface through a permeable media was examined by Sugunamma et al. [9]. It was noticed that the velocity decreased as the inclined magnetic field and Hartmann number increases.

The above cited authors studied with the assumption that the physical characteristics of the ambient fluid were constants. However, the physical characteristics of the flow fluid can vary considerably in the presence of temperature, particularly for fluid viscosity. In other to forecast the flow and the rate of heat transfer, it is important to consider the temperature dependent viscosity of the fluid. [10-11] studied the effects of magnetohydrodynamic fluid, variable thermal conductivity and viscosity in a convective boundary conditions past a permeable sheet. [12-15] carried out analysis on the influences of variable thermal conductivity and viscosity on hydromagnetic flow over a moving permeable surface with heat source. It was reported that an increase in parameter value of θ_r caused the velocity profiles to increase. Devi and Gururaj [16] examined the flow of heat transfer of power-law velocity and nonlinear radiation along with variable viscosity on magnetohydrodynamic past a moving surface.

The above studies continued their discussion by assuming the magnetic field to be at right angle to the flow, Soret and Dufour effects were also taken to be insignificant. Nevertheless, it was believed that these bodily characteristics changes considerably whenever the effect of variable thermal conductivity and viscosity are regarded. An incompressible flow fluid possessions are appreciably varied contrast to constant physical properties. The present study focused on the fluid chattels which are temperature dependent. Consequently, the main objective of the study is to examine the effects of Soret and Dufour on variable thermal conductivity and viscosity with viscous dissipation and inclined magnetic field in a permeable medium.

2 Problem Formulation

Consider an incompressible, laminar flow fluid with variable thermal conductivity and viscosity through permeable sheet. The flow is driven by of buoyancy forces past a porous medium. The flow fluid is in x-direction with y-axis normal to it. The fluid viscosity is assumed to vary as a reciprocal of a linear function of temperature. An inclined magnetic field B_0 is applied at angle α lying in the range $0 \prec \alpha \prec \frac{\pi}{2}$ in the flow direction. The sheet is maintained at the temperature and species concentration T_w, C_w and free stream temperature and species concentration T_∞, C_∞ respectively. Applying Darcy-forchhemier model, the geometry and the equations governing the problem are:

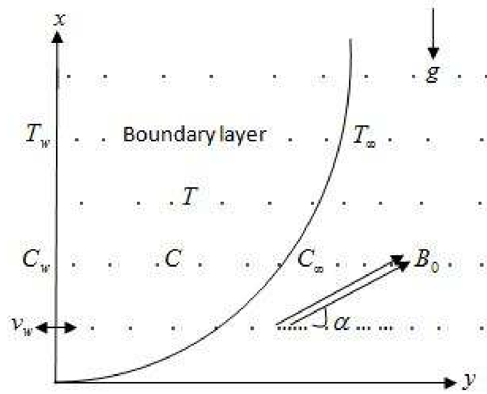

Fig. 1. The geometry of the model

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho_\infty}\frac{\partial}{\partial y}\left(\mu(T)\frac{\partial u}{\partial y}\right)-\frac{\mu(T)}{\rho_\infty K}u-Fu^2-\frac{1}{\rho_\infty}\sigma B_0^2 usin^2\alpha+g\beta_T(T-T_\infty)+g\beta_C(C-C_\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{1}{\rho_\infty C_p}\frac{\partial}{\partial y}\left(k(T)\frac{\partial T}{\partial y}\right)+\mu\left(\frac{\partial u}{\partial y}\right)^2+\frac{DK_r}{C_pC_s}\frac{\partial^2 C}{\partial y^2}+\frac{1}{\rho_\infty C_p}Q_0(T-T_\infty) \tag{3}$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}+\frac{DK_r}{T_m}\frac{\partial^2 T}{\partial y^2}-\gamma(C-C_\infty) \tag{4}$$

with the boundary conditions:

$$\begin{aligned}&u=u_w(=bx), v=v_w, T=T_w(=T_\infty+Ax^m), C=C_w(=C_\infty+Bx^n) \;\; at \;\; y=0\\&u=0, T=T_\infty, C=C_\infty \;\; as \;\; y\to\infty\end{aligned} \tag{5}$$

where u and v are the Darcian velocity component in x and y direction, T and C are the temperature and species concentration of the fluid. u_w is the fluid velocity at the wall. The physical quantities σ, ν, μ, ρ_∞, K, C_p, F, k, D, λ and Q_0 are the fluid electric conductivity, kinematics viscosity, dynamic viscosity, free stream density, permeability of the medium, specific heat at constant pressure, Forchheimer inertia coefficient, thermal conductivity, mass diffusion coefficient, reaction rate coefficient and internal heat generation respectively. g is the gravitational acceleration, β_T and β_C are the coefficients of thermal and concentration expansion, A, B, m, n, b are prescribed constants, F is the forchheimer parameter of the medium. K_r is the ratio of thermal diffusion, C_s is the susceptibility concentration, T_m is the temperature of mean fluid and v_w is the suction velocity across the sheet.

The viscosity is taken to be differ as a reciprocal temperature function Lai and Kulacki [17].

$$\frac{1}{\mu} = \frac{1}{\mu_\infty}[1+\gamma(T-T_\infty)] \quad or \quad \frac{1}{\mu} = s(T-T_r) \tag{6}$$

where $T_r = T_\infty - \frac{1}{\gamma}$ and $s = \frac{\gamma}{\mu_\infty}$

Both T_r and s are constants which as to do with fluid thermal property and the reference state, where $s \prec 0$ and $s \succ 0$ are for gases and liquids.

The thermal conductivity $k(T)$ is linear, taken to vary as a function of temperature Chiam [18].

$$k(T) = k_\infty(1+\delta\theta) \tag{7}$$

where $\delta = \frac{(k_w - k_\infty)}{k_\infty}$, is the thermal conductivity term.

Using stream function $\psi(x, y)$ with similarity transforms

$$\psi = (b\nu)^{\frac{1}{2}} x f(\eta), \eta = \left(\frac{b}{\nu}\right)^{\frac{1}{2}} y \tag{8}$$

where the velocity components, temperature and concentration respectively become

$$u = \frac{\partial\psi}{\partial y} = bxf'(\eta), v = -\frac{\partial\psi}{\partial x} = -(b\nu)^{\frac{1}{2}} f(\eta), \theta(\eta) = \frac{T-T_\infty}{T_w - T_\infty} \; and \; \phi(\eta) = \frac{C-C_\infty}{C_w - C_\infty} \tag{9}$$

Using equations (6)-(9) in the governing equations, the continuity equation is satisfied while equations (2) to (4) become

$$f''' - \frac{\theta-\theta_r}{\theta_r} ff'' - \frac{1}{\theta-\theta_r}\theta' f'' + \frac{\theta-\theta_r}{\theta_r}(1+\varphi) f'^2 - D_a f' + \frac{\theta-\theta_r}{\theta_r} H_a^2 sin^2\alpha f' - \frac{\theta-\theta_r}{\theta_r}(G_r\theta + G_c\phi) = 0 \quad (10)$$

$$\frac{\partial}{\partial\eta}[(1+\delta\theta)\theta'] + P_r f\theta' - P_r(mf' - Q)\theta - P_r E_c \frac{\theta_r}{\theta-\theta_r}(f'')^2 + P_r D_u \phi'' = 0 \quad (11)$$

$$\phi'' + S_c f\phi' + S_c S_r \theta'' - S_c(nf' + \lambda)\phi = 0 \quad (12)$$

The corresponding boundary conditions becomes

$$\begin{aligned} &f' = 1, f = f_w, \theta = 1, \phi = 1 \quad at \ \eta = 0 \\ &f' = 0, \theta = 0, \phi = 0 \quad as \ \eta \to \infty \end{aligned} \quad (13)$$

where $\lambda = \frac{Q}{\rho_\infty C_p b}$ is the heat source term, $H_a^2 = \frac{\sigma B_0^2}{\rho_\infty b}$ is the Hartmann number, $D_a = \frac{\nu}{K^* b}$ is the Darcy number, $f_w = \frac{\nu_w}{\sqrt{b\nu}}$ is suction parameter, $\varphi = Fx$ is the Forchheimer inertia number, $D_u = \frac{DKT(C_w - C_\infty)}{\nu C_s C_p (T_w - T_\infty)}$ is the Dufour number, $S_r = \frac{DK_T(T_w - T_\infty)}{\nu T_m (C_w - C_\infty)}$ is the Soret number, $G_c = \frac{g\beta_C (C_w - C_\infty)}{b^2 x}$ is the solutant Grashof number, $G_r = \frac{g\beta_T (T_w - T_\infty)}{b^2 x}$ is the thermal Grashof number, $S_c = \frac{\nu}{b}$ is the Schmidt number, $E_c = \frac{u_w^2}{C_p(T_w - T_\infty)}$ is the Eckert number, $P_r = \frac{\mu_\infty C_p}{k_\infty}$ is the Prandtl number, $\theta_r = \frac{T_r - T_\infty}{T_w - T_\infty} = -\frac{1}{\gamma(T_w - T_\infty)}$ is the viscosity term and $\frac{1}{\mu} = s(T - T_r)$ takes the form $\mu = \frac{\mu_\infty}{(1 - \theta\theta_r^{-1})}$.

The principal variation in the free stream viscosity value μ_∞, takes place at the plate surface when $\mu = \frac{\mu_\infty}{(1 - \theta_r^{-1})}$ where θ_r is positive for gases and negative for liquids. From the expansion, as $-\theta_r \to \infty$, $\mu \to \mu_\infty$, that is the boundary layer viscosity variation is irrelevant while as $-\theta_r \to 0$ the variation viscosity increases considerably.

The substantial parameters of attention for this flow are the skin friction C_f, the Nusselt N_u as well as sherwood numbers Sh which are respectively defined as:

$$C_f = \frac{\tau_w}{\rho_\infty u_w^2/2}, \ Nu = \frac{xq_w}{k_\infty(T_w - T_\infty)}, \ Sh = \frac{xq_m}{D(C_w - C_\infty)} \quad (14)$$

with τ_w, q_w and q_m are respectively taking to be

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad q_{w_x} = k\left(\frac{\partial T}{\partial y}\right)_{y=0}, \quad q_{m_x} = D\left(\frac{\partial C}{\partial y}\right)_{y=0} \tag{15}$$

Thus, the skin friction, Nusselt and Sherwood numbers becomes

$$Re_x^{\frac{1}{2}}C_f = \frac{2\theta_r}{\theta_r - 1} f''(0), \; Nu_x Re_x^{-\frac{1}{2}} = (1+\delta)\theta'(0), \; Sh_x Re_x^{-\frac{1}{2}} = \phi'(0) \tag{16}$$

where $Re_x = \frac{u_w x}{\nu}$ is the Reynolds number.

3 Results and Discussion

The coupled non-linear equations along with the boundary conditions are solved numerically. The computational analysis are examined for different values of the terms. The following parameter values are adopted for the computation: $S_r = G_c = m = D_u = \varphi = n = 1$, $\theta_r = -0.2$, $\delta = 0.1$, $\lambda = G_r = D_a = Q = 0.5$, $P_r = 0.71$, $E_c = 0.2$, $S_c = 0.62$, $H_a = 4$ and $\alpha = 30^0$.

Table 1 represents the computational results, this show the influence of some parameters on the heat transfer rate at the wall in an existing studied comparing with the present study.

Table 2 shows the numerical results, this depict the influence of some bodily parameters on flow. It is observed that a rise in the value of the parameters H_a, α and D_a reduces the skin friction and causes a rise in the energy and mass gradient at the wall while a rise in the values of E_c and θ_r causes an increase in the skin friction and the temperature gradient at the wall but decreases the concentration gradient at the wall. Also, as the values of D_a and m increases there is reduction in the skin friction and increase in the concentration gradient while a rise in the value of D_a enhances the temperature gradient at the wall and variational rise in the values of m decreases the heat gradient.

Fig. 2 depicts the influence of magnetic field term H_a on the fluid flow. An increase in the values of H_a retarded the flow velocity and cause it to be heater as it moves beside the sheet which bring about decrease in the velocity profile due to the present of Lorentz force that drag the flow rate .

Fig. 3 shows the effect of the inclined magnetic field on the velocity. It is observed that an increase in the inclination of the magnetic field influence the buoyancy force which accordingly decreases the driving force to the flow fluid and thereby decreases the flow velocity.

Table 1. Comparison of $\theta'(0)$ for $K_1 = 0, \alpha = 0, \lambda = 0, H_a = 0, f_w = 0, s = 0, S_c = 0, n = 0,$ $\theta_r \to -\infty, E_c = 0, G_r = 0, G_c = 0, D_a = 0, \varphi = 0$ for various values of m, Q and P_r

Q	m	P_r	Salawu and dada [19]	Ahmed [20]	Present results
	0	0.7	-0.45605	-0.45605	-0.45616
	0	1.0	-0.582225	-0.58223	-0.58224
	0	10.0	-2.30797	-2.30800	-2.30795
-1.0	2	5.0	-4.02823	-4.02823	-4.02821

Table 2. Effect of H_a, α, D_a, E_c, m and θ_r on $f''(0)$, $\theta'(0)$ and $\phi'(0)$ (P-Parameters)

P	values	$f''(0)$	$\theta'(0)$	$\phi'(0)$	P	values	$f''(0)$	$\theta'(0)$	$\phi'(0)$
H_a	2.0	-4.19815	-0.50168	-0.51189	Ec	0.2	-7.10682	-0.35571	-0.29979
	3.0	-5.61624	-0.39348	-0.43453		0.5	-7.09543	-0.13086	-0.43890
	4.0	-7.10252	-0.27127	-0.35203		1.0	-7.06130	0.56517	-0.86958
	5.0	-8.53985	-0.14963	-0.27433		1.5	-7.02918	1.25193	-1.29459
α	0^0	-2.71619	-0.60204	-0.58969	m	0.5	-7.07087	0.01752	-0.53497
	30^0	-7.10252	-0.27127	-0.35203		1.0	-7.10252	-0.27127	-0.35203
	45^0	-9.44808	-0.07307	-0.22819		1.5	-7.13096	-0.51738	-0.19622
	60^0	-11.14212	0.06663	-0.15172		2.0	-7.15610	-0.73217	-0.06032
D_a	0.1	-7.05163	-0.27725	-0.35677	θ_r	-0.1	-11.01313	-0.27145	-0.32819
	5.0	-7.63773	-0.21184	-0.30692		-0.3	-5.70285	-0.27043	-0.36914
	10.0	-8.16791	-0.15730	-0.26834		-0.7	-3.95945	-0.26659	-0.40920
	20.0	-9.08756	-0.06927	-0.21124		2.0	-1.63282	-0.23465	-0.59150

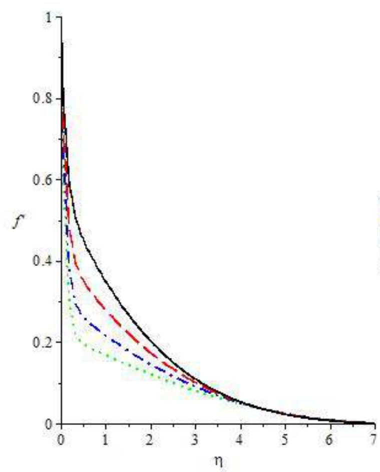

Fig. 2. Velocity profiles for different values of H_a

Fig. 4 illustrates the effect of variation in the mass transfer boundary layers with Soret number. It is seen that the mass transfer boundary layers thickness increases as the Soret number rises thereby causes a rise in the concentration fields since mass is unable to transfer away from the system due to thickness in the mass boundary layer.

The influence of viscosity on the flow, energy and mass transfer are represented in Figs. 5, 6 and 7. A rise in the values of θ_r retarded the fluid velocity near the plate surface at $\eta \le 1$ but it increases as it moves away from the plate while an increase in θ_r enhances the energy and mass field, due to the thickness in the thermal and mass boundary layer that reduces the amount of heat and mass transfer.

Fig. 8 represents the effect of thermal boundary layers with the Dufour number D_u. It is noticed that the thermal boundary layers thickness increases with a rise in the Dufour number and thereby enhance the heat within the system that turn to increase the temperature profile.

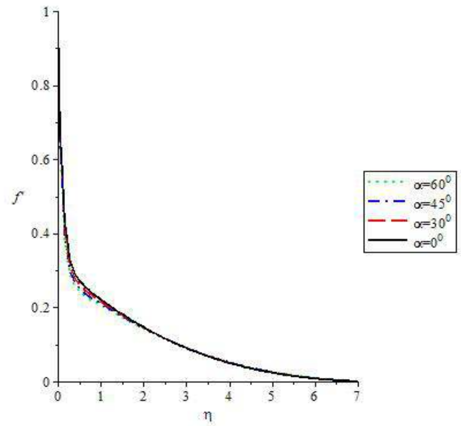

Fig. 3. Velocity profiles for different values of α

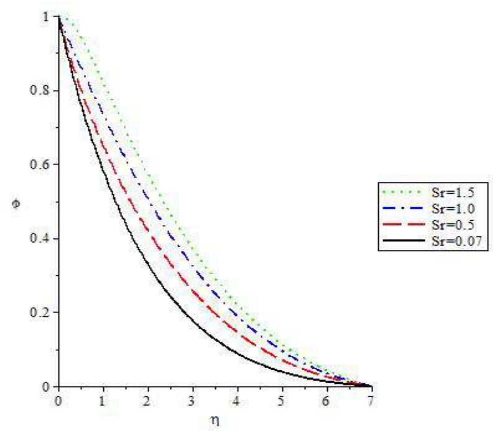

Fig. 4. Concentration profiles for different values of S_r

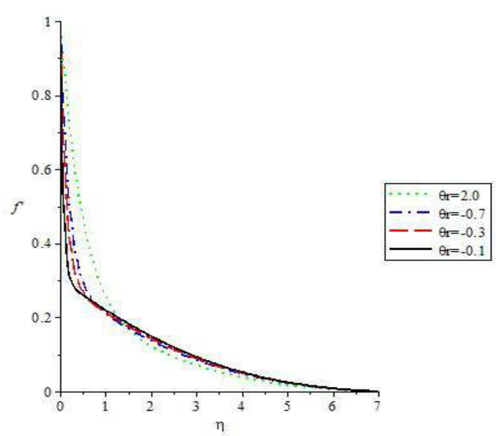

Fig. 5. Velocity profiles for different values of θ_r

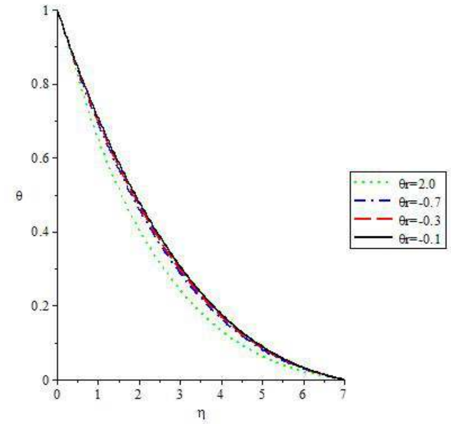

Fig. 6. Temperature profiles for different values of θ_r

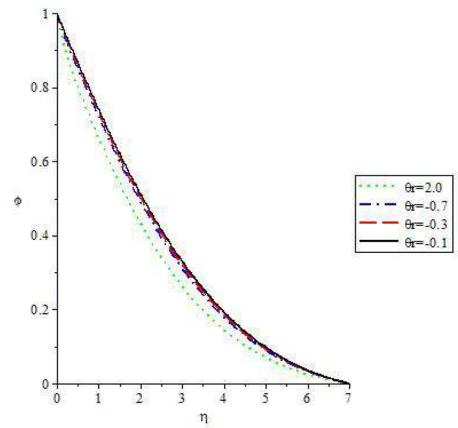

Fig. 7. Concentration profiles for different values of θ_r

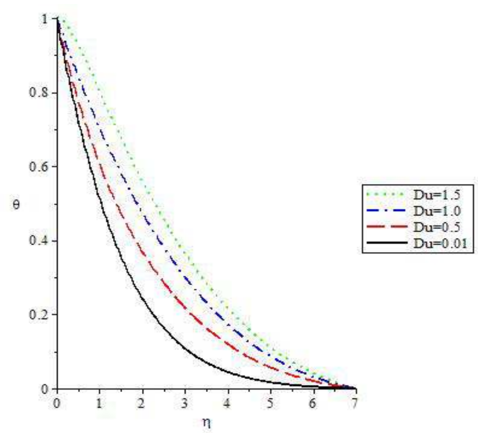

Fig. 8. Temperature profiles for different values of D_u

The influence of thermal conductivity δ on the heat transfer is presented in Fig. 9. It is clearly noticed from the profile that a rise in the thermal conductivity parameter affected the boundary layer to generate heat and enhances temperature profiles.

Fig. 10 represents the effect of m on the temperature. It is noticed that an increase in the values of m increases the temperature field. Heat moves from the plate surface to the ambient medium when $m \succ 0$, otherwise it moves away from the ambient medium to the stretching sheet.

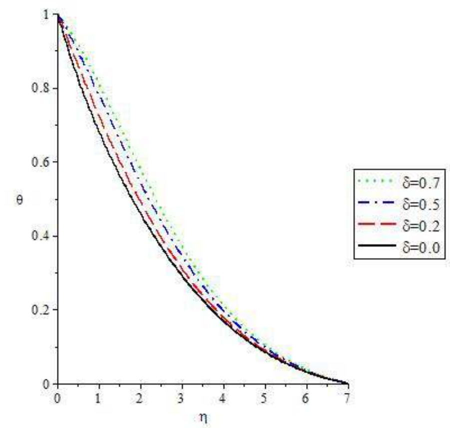

Fig. 9. Temperature profiles for different values of δ

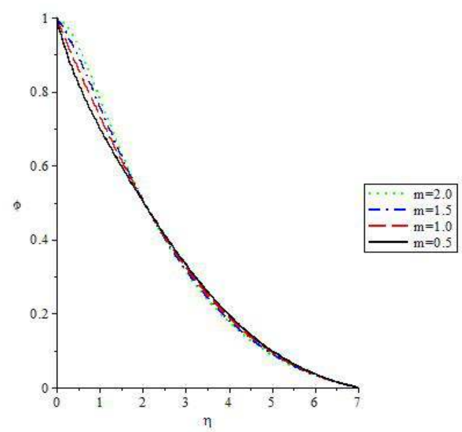

Fig. 10. Temperature profiles for different values of m

4 Conclusion

The influences of variable thermal conductivity and viscosity dissipative heat and mass transfer on inclined magnetic field in a Darcy-forrcheimer media are investigated. From the numerical results, it can be deduced that, an increase in the values of H_a, α, θ_r and D_a retarded the movement of the flow by causes decrease in the flow velocity while a rise in the Soret parameter values manifested as a rise in the flow velocity and concentration distributions. α, δ and D_u enhances the temperature boundary layer thickness by causing a rise in the temperature profile while θ_r and m decrease the temperature distribution. Also, it is seen that θ_r reduces the mass boundary layer thereby decreases the concentration profile.

Competing Interests

Authors have declared that no competing interests exist.

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