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Effects of Variable Viscosity and Thermal Conductivity on Dissipative Heat and Mass Transfer of Magnetohydrodynamic Flow in a Porous Medium

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ABSTRACT

The study of dissipative heat and mass transfer of an electrically conducting fluid under the combined influence of buoyancy forces in a stretching sheet in the presence of magnetic field is investigated. The fluid viscosity and thermal conductivity are assumed to vary linearly as a function of temperature. The governing partial differential equations of the problem are reduced to a system of coupled non-linear ordinary differential equations by applying similarity variables and then solved numerically. The results for Skin friction, Nusselt and Sherwood numbers are presented and discussed.

Keywords: Viscosity; Dissipation; Thermal conductivity; Porous medium; Buoyancy force

Aims Research Journal Reference Format:
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1. INTRODUCTION

Many transport processes occur in industrial applications such as plastic and rubber manufacturing, metal extrusion, glass fibre and many more in which the transfer of heat and mass takes place simultaneously as a result combined buoyancy effects of thermal diffusion and diffusion of chemical species. Many studies have been reported for vertical, horizontal and inclined plate in presence of a transverse magnetic field. In view of the industrial applications of heat transfer, Mohamed and Fahd [1] considered laminar mixed convection boundary layers induced by a linearly stretching permeable surface while Swati, Iswar and RamaSwati [2] analyzed MHD flow and heat transfer past a porous stretching non-isothermal surface in porous medium with variable free stream temperature. The effects of variable fluid properties and MHD on mixed convection heat transfer from a vertical heated plate embedded in a sparsely packed porous medium was examined by Nalinakshi, Dinesh and Chandrashekar [3].

Combined heat and mass transfer problems with chemical reaction are of importance and recently received a considerable amount of attention, in processes such as drying, evaporation at the surface of a water body, energy transfer in a wet cooling tower and the flow in a desert cooler, heat and mass transfer occur simultaneously. Therefore, Alireza, Mahmood and Seyed [4] carried out analytical solution for magnetohydrodynamic stagnation point flow and heat transfer over a permeable stretching sheet with chemical reaction. Okedoye [5] examined analytical solution of MHD free convective heat and mass transfer flow in a porous medium. Reddy [6] studied scaling transformation for heat and mass transfer effects on steady MHD free convection dissipative flow past an inclined porous surface while Alam, Hossain and Mollah [7] studied MHD free convective flow along an inclined permeable stretching sheet with viscous dissipation and chemical reaction. In both studies, the effects of viscous dissipation parameter i.e., the Eckert number E_c was reported to have causes a rise in the temperature as well as the velocity distribution. Eshetu and Shankar [8] investigated heat and mass transfer through a porous media of MHD flow of nanofluids with thermal radiation, viscous dissipation and chemical reaction effects. Ishrat and Samad [9] analyzed radiative heat and mass transfer of an MHD free convection flow along a stretching sheet with chemical reaction, heat generation and viscous dissipation. Also, Reddy, Ibrahim and Bhagavan [10] reported on similartiy transformations of heat and mass transfer effects on steady MHD free convection dissipation fluid flow past an inclined porous surface with chemical reaction. Non of the above authors considered the effects of variable viscosity and thermal conductivity on the flow profiles.

The magnetohydrodynamic boundary layer flow of an incompressible and electrically conducting fluid is encountered in geophysics, astrophysics and in many engineering and industrial processes. Therefore, the study of boundary layer flow over continuous solid surface moving with constant velocity in an ambient fluid was pioneering by Sakiadis [11]. In the investigation, momentum transfer for a flow over a continuously moving plate in quiescent fluid was analyzed. The problem was extended by Erickson, Fan and Fox [12] by including blowing or suction at the moving surface. Subsequently Tsou, Sparrow and Golldstien [13] reported a combined analytical and experimental study of the flow and temperature fields in the boundary layer on a continuous moving surface. Thiagarajan and Sangeetha [14] examined nonlinear MHD boundary layer flow and heat transfer past a stretching plate with free stream pressure gradient in presence of variable viscosity and thermal conductivity while Mureithi [15] carried out studies on the boundary layer flow over a moving surface in a fluid with temperature-dependent viscosity. Abdou [16] investigated the effect of radiation with temperature dependent viscosity and thermal conductivity on unsteady a stretching sheet through porous media.

The study was extended by Gitima [17] to include magnetic field effects on the flow. Subsequently, Krishnendu, Layek and Rama [18] carried out studied on boundary layer slip flow and heat transfer past a stretching sheet with temperature dependent viscosity. Dulal and Hiranmoy [19] reported on the effects of temperature-dependent viscosity and variable thermal conductivity on MHD non-Darcy mixed convective diffusion of species over a stretching sheet. Hunegnaw and Naikoti [20] examined MHD effects on heat transfer over stretching sheet embedded in porous medium with variable viscosity, viscous dissipation and heat source/sink. Abel and Mahesha [21] studied heat transfer in MHD viscoelastic fluid flow over a stretching sheet with variable thermal conductivity, non-uniform heat source and radiation while Ahmed [22] investigated variable viscosity and thermal conductivity effects on MHD flow and heat transfer in viscoelastic fluid over a stretching sheet. Moreover, Hazarika and Utpal [23] analyzed the effects of variable viscosity and thermal conductivity on MHD flow past a vertical plate and Hunegnaw and Kishan [24] examined unsteady MHD heat and mass transfer flow over stretching sheet in porous medium with variable properties considering viscous dissipation and chemical reaction.

In the above studies, the effect of chemical as well as the combined effect of buoyancy forces, temperature dependent viscosity and thermal conductivity on heat and mass transfer has not been considered. However, it is known that fluid of physical properties can change significantly with temperature. When the effects of variable viscosity and thermal conductivity are taken in to account, the flow characteristics are significantly changed compared to constant physical properties. Therefore, the present study examining temperature dependent viscosity and thermal conductivity over a stretching sheet with variable surface temperature and concentration subjected to buoyancy forces and uniform magnetic field in a porous medium with viscous dissipation. Hence, in the problem under consideration, the viscosity and thermal conductivity have been assumed to be a function of temperature.

2. MATHEMATICAL FORMULATION

A free convective heat and mass transfer of an electrically conducting, steady and incompressible fluid flow above a heated stretching sheet with dissipation in a porous medium under the influence of uniform transverse magnetic field, buoyancy forces, variable viscosity and thermal conductivity are considered. The flow is assumed to be in the x-direction with y-axis normal to it. The magnetic field of uniform strength B_0 is introduced in the direction of the flow. The stretching sheet and species concentration is fixed by two equal and opposite forces introduced along the x-axis. The plate is maintained at the temperature and species concentration T_w, C_w and free stream temperature and species concentration T_∞, C_∞ respectively.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \qquad (1)$$

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

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\frac{\partial^2 T}{\partial y^2}+\frac{\partial T}{\partial y}\frac{\partial k}{\partial y}+\mu\left(\frac{\partial u}{\partial y}\right)^2+Q_0\left(T-T_\infty\right) \qquad (3)$$

$$u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}=D\frac{\partial^2 C}{\partial y^2}-\gamma\left(C-C_\infty\right) \qquad (4)$$

subject to the following boundary conditions:

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

where u, v, T and C are the velocity component in the x direction, velocity component in the y direction, temperature of the fluid and species concentration respectively. B_0 is the magnetic field strength and u_w is the fluid velocity at the wall. The physical quantities $\nu=\frac{\mu}{\rho}$, μ, ρ, K^*, σ, C_p, k,

Q_0, D and λ are the fluid kinematics viscosity, coefficient of viscosity, density, permeability of the porous medium, electric conductivity of the fluid, specific heat at constant pressure, thermal conductivity, rate of specific internal heat generation or absorption, mass diffusion coefficient and reaction rate coefficient respectively. g is the gravitational acceleration, β_T and β_C are the thermal and concentration expansion coefficients, A, B, b are prescribed constants.

The fluid variable viscosity is assumed to be a function of temperature in the form Mukhopadhyay *et al.* [25] and Pantokratoras [26].

$$\mu = \mu_\infty[\alpha + r(T_w - T)] \quad (6)$$

where μ_∞ is the fluid free stream dynamic viscosity, α and r are constants and $r(>0)$. The viscosity-temperature relation is $\mu = \alpha - rT$ which agrees quite well with the relations $\mu = \frac{1}{(r_1 + r_2 T)}$ where $\alpha = \frac{1}{r_1}$, $r = \frac{r_2}{r_1}$ and $\mu = e^{-\alpha T}$ when second and higher order terms are neglected as in Saikrishnan and Roy [27] as well as Bird et al. [28] respectively.

The fluid thermal conductivity, k, is assumed to vary as a linear function of temperature in the form [29].

$$k = k_\infty(1 + \beta\theta) \quad (7)$$

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

Finding solution to the stretching boundary problem, the following similarity transform are introduced

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

the velocity, temperature and concentration components are related to the stream function $\psi(x, y)$ by

(9)

Introducing equations (6)-(9), the continuity equation is automatically satisfied and equations (2)-(4) becomes.

$$[\alpha + A(1-\theta)]f''' + (f - A\theta')f'' - f'^2 - (D_a[\alpha + A(1-\theta)] + M)f' + G_r\theta + G_c\phi = 0 \quad (10)$$

$$\frac{\partial}{\partial\eta}[(1+\beta\theta)\theta'] + P_r E_c[\alpha + A(1-\theta)](f'')^2 + P_r f\theta' - P_r(f' - Q)\theta = 0 \quad (11)$$

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

The corresponding boundary conditions becomes

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

where $A = r(T_w - T_\infty)$ is the viscosity parameter, $Q = \frac{Q_0}{\rho C_p b}$ is the heat source/sink parameter, $\lambda = \frac{\gamma}{b}$ is the concentration parameter, $M = \frac{\sigma B_0^2}{\rho b}$ is the magnetic parameter, $D_a = \frac{\nu}{K^* b}$ is the Darcy number, $G_r = \frac{g\beta_T(T_w - T_\infty)}{b^2 x}$ is the thermal Grashof number, $G_c = \frac{g\beta_C(C_w - C_\infty)}{b^2 x}$ is the thermal Grashof number, $E_c = \frac{u_w^2}{C_p(T_w - T_\infty)}$ is the Eckert number, $P_r = \frac{\mu_\infty C_p}{k}$ is the Prandtl number and $S_c = \frac{\nu}{D}$ is Schmidt number.

The physical quantity of practical interest are the local skin friction C_f, the Nusselt nuber N_u and the local sherwood number Sh defined as:

$$C_f = \frac{\tau_w}{\rho u_w^2}, \quad Nu = \frac{q_w x}{k(T_w - T_\infty)}, \quad Sh = \frac{q_m x}{D(C_w - C_\infty)} \quad (14)$$

where k is the thermal conductivity of the fluid, τ_w, q_w and q_m are respectively given by

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad q_w = k\left(\frac{\partial T}{\partial y}\right)_{y=0}, \quad q_m = D\left(\frac{\partial T}{\partial y}\right)_{y=0} \quad (15)$$

Therefore, the local skin friction coefficient, local Nusselt number and local Sherwood number are

$$C_f Re_x^{\frac{1}{2}} = f''(0), \quad NuRe_x^{-\frac{1}{2}} = \theta'(0), \quad ShRe_x^{-\frac{1}{2}} = \phi'(0) \quad (16)$$

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

Table 1: Effect of M , α , A , S_c , E_c , P_r , β and λ on $f^{''}(0)$ $\theta^{'}(0)$ and $\phi^{'}(0)$ (P-Parameters)

P	values	$f^{''}(0)$	$-\theta^{'}(0)$	$-\phi^{'}(0)$	P	$values$	$f^{''}(0)$	$-\theta^{'}(0)$	$-\phi^{'}(0)$
M	0.5	-0.49754	0.80459	0.88389	E_c	0.03	-0.49754	0.80439	0.88389
	2.0	-1.08423	0.70835	0.80802		0.50	-0.46962	0.73173	0.88864
	3.0	-1.39678	0.65657	0.76941		1.00	-0.44227	0.66271	0.89338
	5.0	-1.91489	0.57271	0.70987		1.50	-0.41704	0.60107	0.89785
α	1.0	-0.49754	0.80439	0.88389	P_r	0.5	-0.43965	0.66046	0.89480
	2.0	-0.46716	0.81392	0.89412		0.71	-0.49754	0.80439	0.88389
	3.0	-0.44676	0.81982	0.90113		2.0	-0.68001	1.42489	0.85880
	4.0	-0.43177	0.82368	0.90629		5.0	-0.83201	2.32510	0.84879
A	0.0	-0.36775	0.81223	0.89020	β	0.1	-0.49754	0.80439	0.88389
	1.0	-0.49754	0.80439	0.88389		0.5	-0.45336	0.65251	0.89031
	2.0	-0.62108	0.79690	0.87808		1.0	-0.41181	0.54081	0.89741
	3.0	-0.74021	0.78981	0.87273		2.0	-0.35450	0.41859	0.90895
S_c	0.35	-0.43941	0.82363	0.64426	λ	0.1	-0.49754	0.80439	0.88389
	0.45	-0.46456	0.81522	0.74026		0.7	-0.53243	0.79395	1.08498
	0.62	-0.49754	0.80439	0.88389		1.0	-0.54527	0.79033	1.17113
	1.00	-0.54690	0.78926	1.14963		2.0	-0.57699	0.78196	1.41818

3. RESULTS AND DISCUSSION

To analyze the results, numerical computation has been carried out using shooting technique with fourth-order Runge-Kutta integration algorithm for the coupled nonlinear differential equations along with the boundary conditions. In the numerical solution, a check was made to confirm that smoothness conditions at the edge of the boundary layer were satisfied. Computations were carried out for different values of the parameters. The following default parameter values are adopted for computation: $G_r = G_c = A = \alpha = 1$, $Q = \beta = \lambda = D_a = 0.1$, $P_r = 0.71$, $S_c = 0.62$, $E_c = 0.03$ and $M = 0.5$.

Table 1 shows the numerical results, which represents the effect of some physical parameters on the flow as well as heat and mass transfer aspects of the investigation. It displays that an increase in the value of the parameters M , A , S_c , P_r and λ decrease the skin friction and causes increase in the temperature gradient at the wall except for P_r that causes decrease in Nusselt number also the parameters causes increase in the concentration gradient at the wall except for S_c and λ that cause decrease in Sherwood number while increase in the value of α , E_c and β cause corresponding increase in the skin friction and the temperature gradient at the wall except for α that causes decrease in the Nusselt number meanwhile the parameters decrease the concentration gradient at the wall.

Figure 1 shows the effect of imposition of magnetic field parameter on the fluid flow. Increase in the value of M retarding the fluid velocity and make it warmer as it moves along the plate by causing decrease in the velocity profiles. This result qualitatively agrees with the expectations, since the magnetic field exerts a retarding force on the free convection flow.

The effects of thermal Grashof number G_r and solutant Grashof number G_c on the velocity profiles are presented in figures 2 and 3. It is noticed that an increase in the relative effects of the thermal or species buoyancy force to the viscous hydrodynamic force in the boundary layer accelerates the velocity of the flow field. Thus, heat or mass transfer has a strong influence on the flow field.

Figure 4 illustrates the effect of porosity parameter D_a on the velocity profiles. It is observed that the velocity decreases as the porosity increases, this is because the wall of the surface provides an additional resistance to the fluid flow mechanism which causes the fluid to move at a slow rate with reduced temperature.

Figure 5 shows the velocity distribution for variation in the viscosity parameter A. It is noticed that the fluid velocity increases with increasing values of A and the momentum boundary layer thickness increases with A. The reason for this behavior is that, increase in the values A decreases the fluid viscosity which causes increase in the viscous boundary layer thickness.

Figure 6 displays the effect of thermal conductivity parameter on velocity profiles. When α increases, the velocity profile increases. This is because the viscous boundary layer get thicker as the values of α increases.

Figures 7 and 8 show the effect of Prandtl number P_r on the velocity and temperature profiles. Prandtl number is the ratio of momentum diffusivity to thermal diffusivity. An increase in the values of P_r results in the respectively decrease in the velocity and temperature profiles. The reason for this behavior is that an increase in the P_r results in a decrease in the boundary layer thickness and reduce the average temperature within the boundary layer. Hence, Prandtl number can be used to increase the rate of cooling in conducting flows.

Figures 9 and 10 depict the effect of the Schmidt number on the velocity and concentration distributions. As the Schmidt number S_c increases, the mass transfer rate increases. The Schmidt number is inversely proportional to the diffusion coefficient. Hence, the velocity and concentration decrease with increasing S_c.

The effect of heat source on the temperature profiles is represented in figure 11. From the figure, it is noticed that the temperature profiles increases when increasing the value of heat source Q. The temperature increases so that the thickness of thermal boundary layer increases. This result is very much significant for the flow where heat transfer is given prime importance.

The effect of the viscous dissipation parameter that is, the Eckert number E_c on the temperature is shown in figure 12. The Eckert number E_c represents the relationship between the kinetic energy in the flow and the enthalpy. It embodies the conversion of kinetic energy into internal energy by work done against the viscous fluid stresses. The positive Eckert number implies cooling of the plate that is, loss of heat from the plate to the fluid. Hence, greater viscous dissipative heat causes a rise in the temperature which is evident from figure 12.

The effect of variable thermal conductivity parameter β on the temperature profiles is displayed in figure 13. It is noticed from the plot that increasing the values of β results in increasing the magnitude of temperature due to increase in the thermal boundary layer thickness.

Figure 14 shows the influence of the reaction rate parameter on the concentration profiles. It is seen from the concentration distribution across the boundary layer decreases with increasing in λ. The reaction rate parameter is a decreasing agent and as a result, the solute boundary layer near the wall becomes thinner. This is due to the fact the conversion of the species takes place as a result of chemical reaction and thereby reduces the concentration in the boundary layer.

4. CONCLUSION

From the numerical results, it is noticed that, an increase in the values of M , D_a and P_r, and S_c slowdown the motion of the fluid thereby causing decrease in the velocity profiles while increase in the values of G_r, G_c, A and α cause a corresponding increase in the viscous boundary layer, as a result, the velocity distributions increases. Also, it is observed from the plots that an increase in the values of Q, E_c and β increases the thermal boundary layer thickness by causing increase in the temperature profiles while increase in P_r reduces the thermal boundary layer and causes heat heat to diffuse out of the system and thereby decreasing the temperature profiles. Meanwhile, variation in the values of S_c and λ retarded the concentration profiles due to thinner in solute boundary layer.

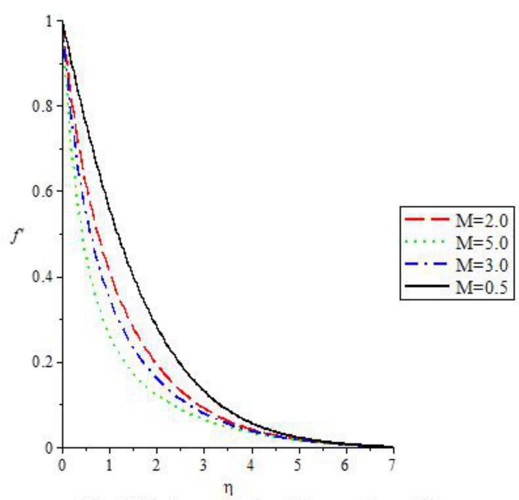

Fig. 1: Velocity profiles for different values of M

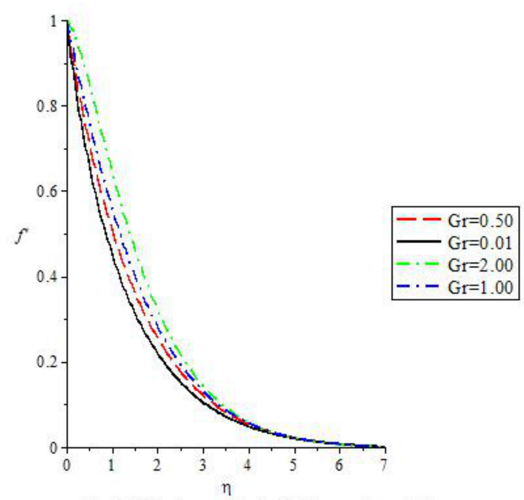

Fig. 2: Velocity profiles for different values of Gr

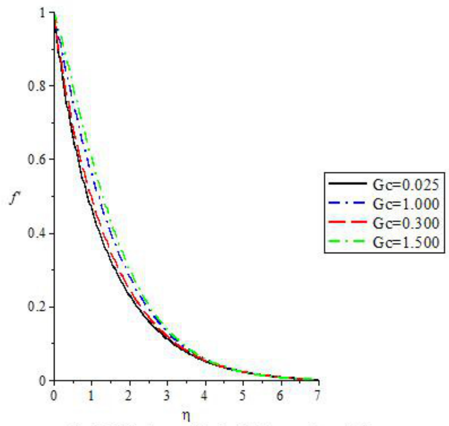

Fig. 3: Velocity profiles for different values of Gc

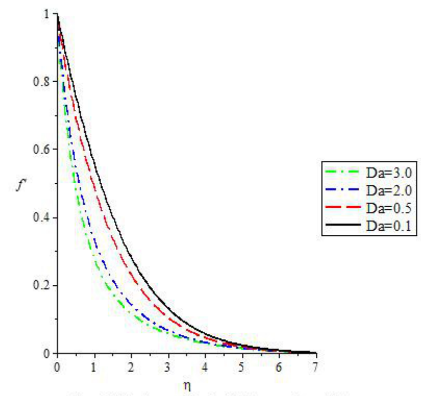

Fig. 4: Velocity profiles for different values of Da

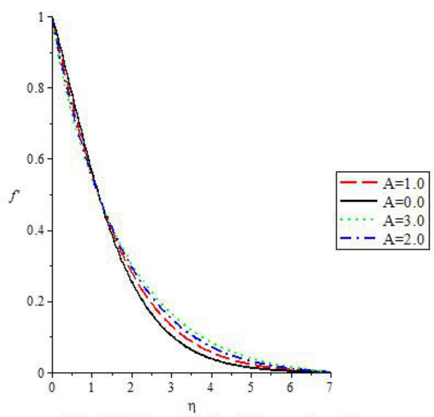

Fig. 5: Velocity profiles for different values of A

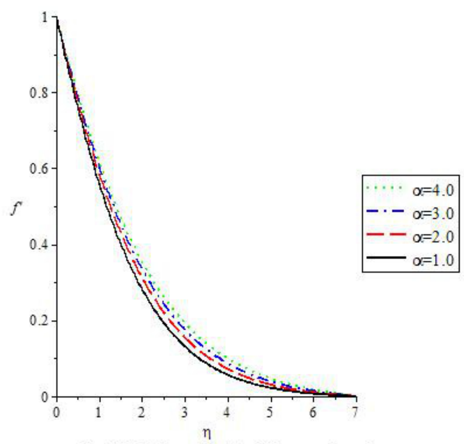

Fig. 6: Velocity profiles for different values of α

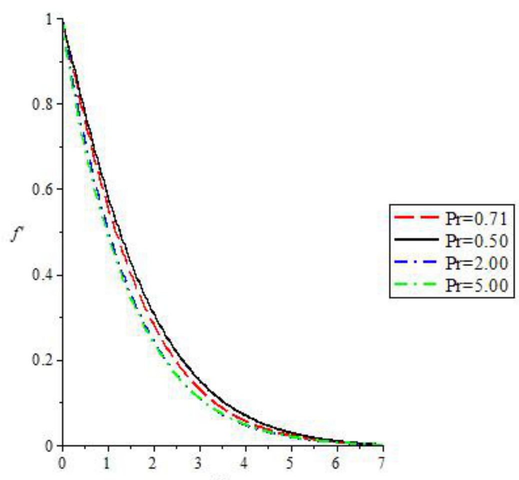

Fig. 7: Velocity profiles for different values of Pr

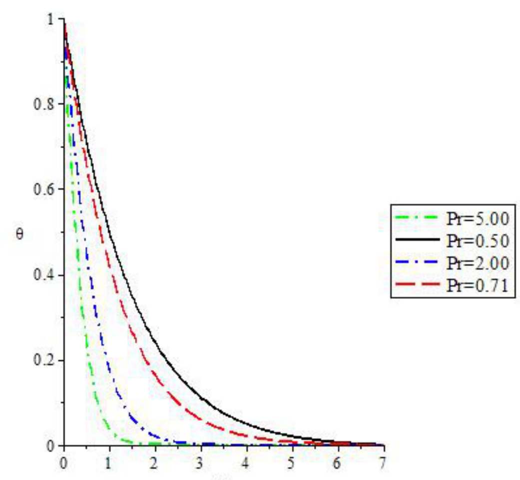

Fig. 8: Temperature profiles for different values of Pr

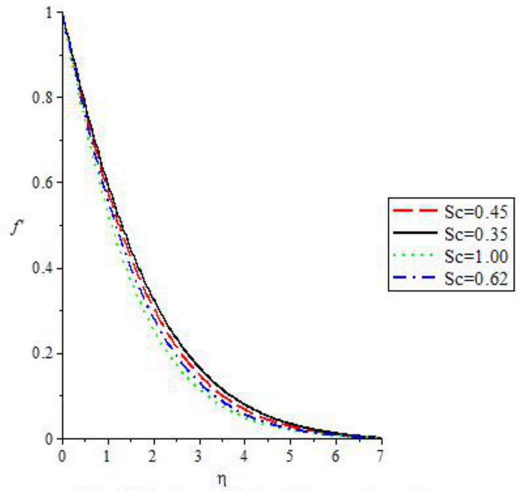

Fig. 9: Velocity profiles for different values of Sc

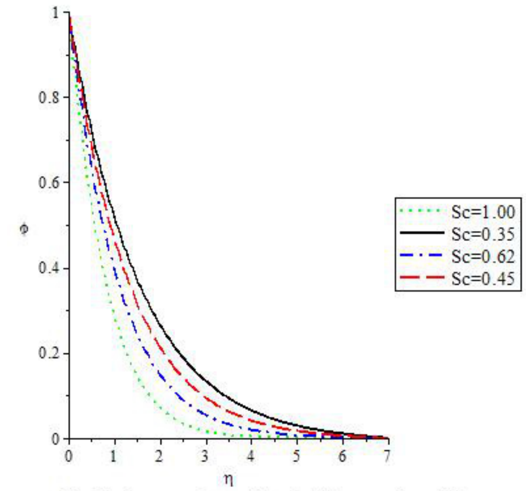

Fig. 10: Concentration profiles for different values of Sc

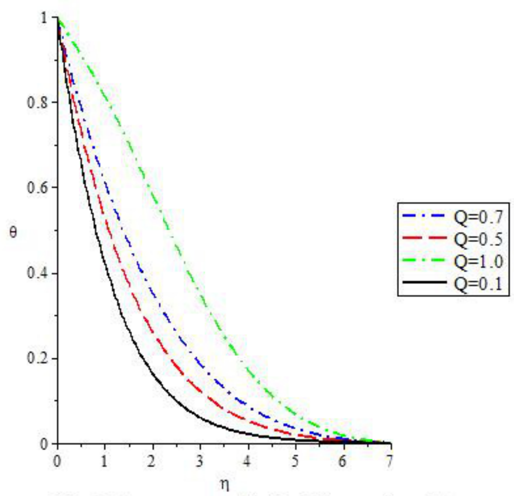

Fig. 11: Temperature profiles for different values of Q

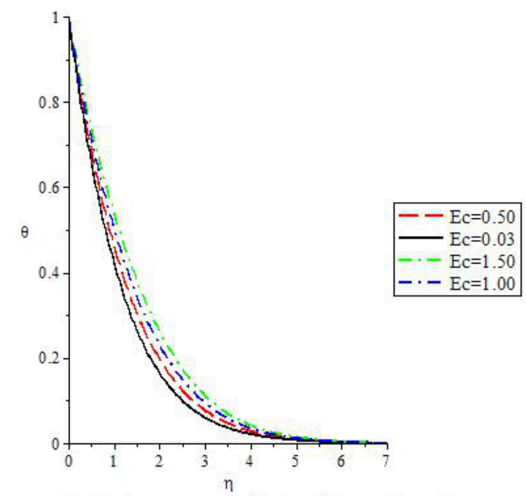

Fig. 12: Temperature profiles for different values of Ec

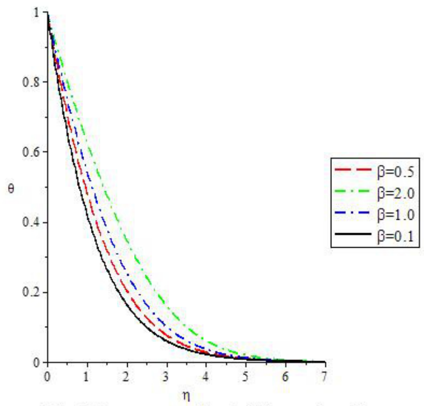

Fig. 13: Temperature profiles for different values of β

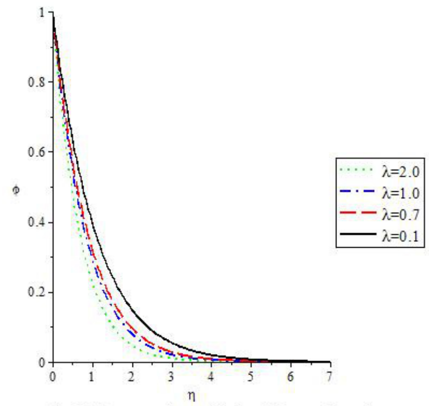

Fig. 14: Concentration profiles for different values of λ

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