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Dissipative Heat and Mass Transfer in Porous Medium Due to Continuously Moving Plate in Presence of Magnetic Field with Constant Heat and Mass Flux

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***Abstract*— *An analysis of dissipative effects on heat and mass transfer characteristics of natural convection about a continuously moving vertical plate bounding fluid saturated porous medium on one side in presence of magnetic field and constant heat and mass flux is investigated. The plate is subjected to a constant suction. The governing equations are solved by perturbation method and the pertinent findings are represented through graphs.*

***Keywords*— *Moving plate, heat and mass transfer, dissipation, porous medium, magnetic field, heat and mass flux.*

I. INTRODUCTION

Free convection flows are of great interest in a number of industrial applications such as fibre and granular insulation, geothermal systems, etc. Convection in porous media has applications in geothermal energy recovery, oil extraction, thermal energy storage and flow through filtering devices. Studies pertaining to coupled heat and mass transfer due to free convection has got wide applications in different realms, such as, mechanical, geothermal, chemical sciences, etc. and many industrial and technological, physical setups such as nuclear reactors, food processing, polymer production, etc. In nature, there exist flows which are caused not only by the temperature differences but also by concentration differences. These mass transfer differences do affect the rate of heat transfer. In industries, many transport process exist in which heat and mass transfer takes place simultaneously as a result of combined buoyancy effect of thermal and mass diffusion. The phenomenon of heat and mass transfer frequently exists in chemically processed industries such as food processing and polymer production. Magetohydrodynamics attracts the attention of many authors due to its applications in geophysics, in the study of stellar and solar structures, interstellar matter, radio propagation through the ionosphere, etc. In ionized states of gases at high temperature acts as an electrical conductor which are generally used in MHD Pumps, in MHD bearings and also in some engineering devices. The ionized gas or plasma can be made to interact with the magnetic field and can alter heat transfer and friction characteristics.

Despite all these important investigations, there are few investigations in porous medium taking dissipation aspects into account. It is worth mentioning that viscous dissipation in porous regime is to be reckoning with in many situations simply because due to its qualitative effects it may alter the thermal regime. Viscous heating serves as a heat source since it is the local production of heat energy due to shear stresses. Viscous dissipation aspects in porous media warrant careful attention simply because the porous matrix walls obstruct the fluid flow inside it. Hence, the shear within the fluid in the presence of porous medium has been taken into consideration while dealing with dissipation aspects. However, it is worth to note that though the dissipation is not that much dominant quantitatively as compared to its other counterpart effects but certainly there are areas such as tribology, instrumentation, etc where its qualitative effects are earnestly observed. Extensive analysis can be found in the literature about the expressions envisaging dissipation in porous medium. Nield [1] have presented an excellent relevant document. In this communication following Al-Hadhrami et al. [4] the dissipation φ in the porous medium is taken as

$$\varphi = \bar{\mu}\left(\frac{du}{dy}\right)^2 + \frac{\mu}{k}u^2 \quad (1)$$

Heat transfer effects on flow of viscous fluid through non homogeneous porous medium are studied by Singh et al. [5]. Abdel Khalek [6] examined MHD free convection with mass transfer from a moving permeable vertical surface and produced a perturbation solution. Israel-Cookey et al. [3] discussed influence of viscous dissipation on unsteady MHD free convection flow past an infinite heated vertical plate in porous medium with time-dependent suction. Kim [2] discussed unsteady MHD convective heat transfer past a semi-infinite vertical porous moving plate with variable suction. Senapati et.al [7] have studied magnetic effect on mass and heat transfer of a hydrodynamic flow past a vertical oscillating plate in presence of chemical reaction. Senapati et.al [8] also discussed the chemical effects on mass and heat transfer on MHD free convection flow of fluids in vertical plates and in between parallel plates in Poiseuille flow. Shekhawat et al. [9], have been dissicused the Dissipative heat and mass transfer in porous medium due to continuously moving plate.

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This paper deals with the study of effects of dissipative heat and mass transfer in porous medium due to continuously moving plate in presence of magnetic field and constant heat and mass flux.

II. Mathematical Formulation

We consider steady laminar flow and mass transfer of viscous incompressible fluid filled in a homogeneous porous medium in presence of magnetic field. The porous medium is bounded on one side by a vertical plate moving upwards with a uniform velocity v_0 and subjected to uniform heat and mass flux vis a vis a constant suction v_0. A Cartesian coordinate system is used where x-axis is taken along the plate in the moving direction of the plate and a magnetic field of uniform strength B_0 is applied normal to the plate along Y-axis. T_∞ is the temperature and C'_∞ is the mass concentration of fluid. Applying Boussinesq approximation and taking viscous dissipation in porous regime into account, the governing equations are as under:

$$\frac{\partial v}{\partial y'} = 0 \Longrightarrow v = -v_0 \tag{2}$$

$$v\frac{\partial u'}{\partial y'} = g\beta(T - T_\infty) + g\beta_c(C - C_\infty) + \bar{v}\frac{\partial^2 u'}{\partial y'^2} - \frac{v}{k_0}u' - \frac{\sigma B_0^{\,2}}{\rho}u' \tag{3}$$

$$v\frac{\partial T}{\partial y} = \frac{\bar{k}}{\rho C_p}\frac{\partial^2 T}{\partial y'^2} + \frac{\bar{v}}{C_p}\left(\frac{\partial u'}{\partial y'}\right)^2 + \frac{v}{C_p k_0}u'^2 \tag{4}$$

$$v\frac{\partial C'}{\partial y'} = D\frac{\partial^2 C'}{\partial y'^2} \tag{5}$$

with the following boundary conditions

$$\left.\begin{array}{l} u' = v_0,\ \frac{\partial T}{\partial y'} = -\frac{q}{k},\ \frac{\partial C'}{\partial y'} = -\frac{m}{D}\ at\ y' = 0 \\ u' \to 0,\ T \to T_\infty, C' \to C'_\infty\ as\ y' \to \infty \end{array}\right\} \tag{6}$$

where (u, v) are velocity components in x-y directions, g is acceleration due to gravity, T' is the temperature of the fluid, C' is the species concentration in the regime, β is the coefficient of thermal expansion, β_c is the volumetric expansion coefficient, $\bar{v}$ is the effective kinematic viscosity in the porous medium and ν is the kinematic viscosity of the fluid, $\bar{k}$ is effective thermal conductivity, ρ is the density of the fluid, k_0 is the permeability, C_p is the specific heat at constant pressure, D is the diffusion coefficient, q is the heat flux per unit area and m is the mass flux per unit area

Let us introduce the following non dimensional quantities

$$\left.\begin{array}{l} y = \frac{v_0 y'}{v},\ u = \frac{u'}{v_0},\ \theta = \frac{(T' - T'_\infty)v_0 k}{qv},\ Pr = \frac{q\mu C_p}{k},\ Sc = \frac{v}{D}, \\ C = \frac{(C' - C'_\infty)v_0 D}{mv},\ K = \frac{v_0^2 k_0}{v^2},\ M = \frac{\sigma B_0^2 v}{\rho v_0^2},\ Gr = \frac{g\beta q v^2}{v_0^4 k}, \\ Gm = \frac{g\beta_c m v^2}{v_0^4 D},\ Ec = \frac{k v_0^3}{v C_p q},\ S_1 = \frac{\bar{v}}{v}\ and\ S_2 = \frac{\bar{k}}{k} \end{array}\right\} \tag{7}$$

where Gr is Grashof number, Gm modified Grashof number, M is magnetic number, Pr is Prandtl number, Sc is Schmidt number, K is permeability parameter of porous medium, Ratio parameter of kinematic viscosity(S_1), Ratio parameter of conductivity (S_2) and Ec is Eckert number.

Using non-dimenssional parameters of (7), equations (3) to (5) with boundary conditions (6) reduce to

$$-\frac{\partial u}{\partial y} = Gr\theta + GmC + S_1\frac{\partial^2 u}{\partial y^2} - \left(M + \frac{1}{K}\right)u \tag{8}$$

$$-\frac{\partial \theta}{\partial y} = S_2\left(\frac{1}{Pr}\right)\frac{\partial^2 \theta}{\partial y^2} + S_1 Ec\left(\frac{\partial u}{\partial y}\right)^2 + \frac{Ec}{K}u^2 \tag{9}$$

$$-Sc\frac{\partial C}{\partial y} = \frac{\partial^2 C}{\partial y^2} \tag{10}$$

with the following boundary conditions

$$\left.\begin{array}{l} u = 1, \frac{\partial \theta}{\partial y} = -1, \frac{\partial C}{\partial y} = -1\ at\ y = 0 \\ u \to 0, \theta \to 0, C \to 0\ as\ y \to \infty \end{array}\right\} \tag{11}$$

III. Method of Solution

Solving equation (10) using the boundary condition (11), we get

$$C = \frac{e^{-Scy}}{Sc} \tag{12}$$

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The coupled momentum and energy equations are solved by perturbation method. Acknowledging the fact that the Ec number is very small for incompressible fluids, therefore, we take Ec as perturbation parameter. Hence, we take

$u = u_0 + Ecu_1$ and $\theta = \theta_0 + Ec\theta_1$ (13)

Using the above perturbations in the governing equation (8) – (9) and equating the constant and coefficients of Ec, we get

$$S_1 u_1'' + u_1' - \left(M + \frac{1}{K}\right)u_1 = -Gr\theta_1 \quad (14)$$

$$S_1 u_0'' + u_0' - \left(M + \frac{1}{K}\right)u_0 = -Gr\theta_0 - \frac{Gm\, e^{-Scy}}{sc} \quad 15)$$

$$S_2\theta_0'' + Pr\theta_0' = 0 \quad (16)$$

$$KS_2\theta_1'' + KPr\theta_1' = -S_1 PrKu_0'^2 - Pru_0^2 \quad (17)$$

With the following boundary conditions

$$\left.\begin{array}{l} u_0 = 1, u_1 = 0, \theta_0' = -1, \theta_1' = 0 \;\; at\; y = 0 \\ u_0 \to 0, u_1 \to 0, \theta_o \to 0, \theta_1 \to 0 \;\; as\; y \to \infty \end{array}\right\} \quad (18)$$

By solving equations (14) – (17) using the boundary conditions (18), we get

$$u_0 = A_{11}e^{-A_1 y} + A_{12}e^{-\frac{Pr}{S_2}y} + A_{13}e^{-Scy} \quad (19)$$

$$u_1 = A_{28}\, e^{-A_1 y} + A_{21}e^{-\frac{Pr}{S_2}y} + A_{22}e^{-2A_1 y} + A_{23}e^{-\frac{2Pr}{S_2}y} + A_{24}e^{-2Scy} + A_{25}e^{-\left(A_1+\frac{Pr}{S_2}\right)y} + A_{26}e^{-\left(Sc+\frac{Pr}{S_2}\right)y} + A_{27}e^{-(Sc+A_1)y} \quad (20)$$

$$\theta_0 = \frac{S_2}{Pr}e^{-\frac{Pr}{S_2}y} \quad (21)$$

$$\theta_1 = A_{20}e^{-\frac{Pr}{S_2}y} + A_{14}e^{-2A_1 y} + A_{15}e^{-\frac{2Pr}{S_2}y} + A_{16}e^{-2Scy} + A_{17}e^{-\left(A_1+\frac{Pr}{S_2}\right)y} + A_{18}e^{-\left(Sc+\frac{Pr}{S_2}\right)y} + A_{19}e^{-(Sc+A_1)y} \quad (22)$$

Substituting equations (19) to (22) in equation (13), we get

$$u = A_{11}e^{-A_1 y} + A_{12}e^{-\frac{Pr}{S_2}y} + A_{13}e^{-Scy} + Ec\left(A_{28}\, e^{-A_1 y} + A_{21}e^{-\frac{Pr}{S_2}y} + A_{22}e^{-2A_1 y} + A_{23}e^{-\frac{2Pr}{S_2}y} + A_{24}e^{-2Scy} + A_{25}e^{-\left(A_1+\frac{Pr}{S_2}\right)y} + A_{26}e^{-\left(Sc+\frac{Pr}{S_2}\right)y} + A_{27}e^{-(Sc+A_1)y}\right). \quad (23)$$

and

$$\frac{S_2}{Pr}e^{-\frac{Pr}{S_2}y} + Ec\left(A_{20}e^{-\frac{Pr}{S_2}y} + A_{14}e^{-2A_1 y} + A_{15}e^{-\frac{2Pr}{S_2}y} + A_{16}e^{-2Scy} + A_{17}e^{-\left(A_1+\frac{Pr}{S_2}\right)y} + A_{18}e^{-\left(Sc+\frac{Pr}{S_2}\right)y} + A_{19}e^{-(Sc+A_1)y}\right) \quad (24)$$

The non-dimensional Shearing stress at the wall,

$$\tau_0 = \left(\frac{\partial u}{\partial y}\right)_{y=0} = -\left[A_{11}A_1 + \frac{PrA_{12}}{S_2} + ScA_{13} + Ec\left(A_1A_{25} + 2A_1A_{22} + 2ScA_{24} + \frac{A_{21}Pr}{S_2} + \frac{2PrA_{23}}{S_2} + A_{25}\left(A_1 + \frac{Pr}{S_2}\right) + A_{26}\left(Sc + \frac{Pr}{S_2}\right) + A_{27}(Sc + A_1)\right)\right] \quad (25)$$

The non-dimensional rate of heat transfer, Nusselt Number

$$Nu = -\left(\frac{\partial\theta}{\partial y}\right)_{y=0} = 1 + Ec\left(\begin{array}{c}\left(\frac{PrA_{20}}{S_2}\right) + 2A_1A_{14} + \left(\frac{2Pr\,A_{15}}{S_2}\right) + 2ScA_{16} \\ +A_{17}\left(A_1 + \frac{Pr}{S_2}\right) + A_{18}\left(Sc + \frac{Pr}{S_2}\right) + A_{19}(Sc + A_1)\end{array}\right) \quad (26)$$

The non-dimensional rate of mass transfer, Sherwood Number

$$Sh = -\left(\frac{\partial C}{\partial y}\right)_{y=0} = 1 \quad (27)$$

where $A_1 = \frac{1+\sqrt{1+4S_1\left(M+\frac{1}{K}\right)}}{2S_1}$, $A_{11} = 1-(A_{12}+A_{13})$, $A_{12} = \frac{-Gr S_2^3}{S_1 Pr^3 - Pr^2 S_2 - S_2^2\left(M+\frac{1}{K}\right)}$,

$$A_{13} = \frac{-Gm}{S_1 Sc^3 - Sc^2 - sc\left(M+\frac{1}{K}\right)},\quad A_{14} = -\left(\frac{S_1 PrKA_1^2A_{11}^2 + A_{11}^2 Pr}{4KS_2A_1^2 - 2KPrA_1}\right),\quad A_{16} = -\left(\frac{S_1 PrKSc^2A_{13}^2 + A_{13}^2 Pr}{4KS_2Sc^2 - 2KPrSc}\right)$$

$$A_{15} = -\left(\frac{PrA_{12}^2S_2^2 + S_1Pr^3A_{12}^2K}{4KPr^2S_2 - 2KPr^2S_2}\right),\quad A_{17} = -\left(\frac{2S_1Pr^2KA_1A_{11}A_{12} + 2PrA_{11}A_{12}S_2}{K(A_1S_2+Pr)^2 - KPr(A_1S_2+Pr)}\right),$$

$$A_{18} = -\left(\frac{2S_1Pr^2KScA_{13}A_{12} + 2PrA_{13}A_{12}S_2}{K(ScS_2+Pr)^2 - KPr(ScS_2+Pr)}\right),\quad A_{19} = -\left(\frac{2S_1Sc\,PrKA_1A_{11}A_{13} + 2PrA_{11}A_{13}}{KS_2(A_1+Sc)^2 - KPr(A_1+Sc)}\right)$$

$$A_{20} = -\frac{S_2}{Pr}\left[2A_{14}A_1 + \frac{2A_{15}Pr}{S_2} + 2A_{16}Sc + A_{17}\left(A_1+\frac{Pr}{S_2}\right) + A_{18}\left(Sc+\frac{Pr}{S_2}\right) + A_{19}(Sc+A_1)\right]$$

$$A_{21} = -\left(\frac{GrA_{20}}{S_1\left(\frac{Pr}{S_2}\right)^2 - \frac{Pr}{S_2} - \left(M+\frac{1}{K}\right)}\right),\quad A_{22} = -\left(\frac{GrA_{14}}{4A_1^2S_1 - 2A_1 - \left(M+\frac{1}{K}\right)}\right),$$

$$A_{23} = -\left(\frac{GrA_{15}}{4S_1\left(\frac{Pr}{S_2}\right)^2 - 2\frac{Pr}{S_2} - \left(M+\frac{1}{K}\right)}\right),\quad A_{24} = -\left(\frac{GrA_{16}}{4Sc^2S_1 - 2Sc - \left(M+\frac{1}{K}\right)}\right),$$

$$A_{25} = -\left(\frac{GrA_{17}}{S_1\left(A_1+\frac{Pr}{S_2}\right)^2 - \left(A_1+\frac{Pr}{S_2}\right) - \left(M+\frac{1}{K}\right)}\right),\quad A_{26} = -\left(\frac{GrA_{18}}{S_1\left(Sc+\frac{Pr}{S_2}\right)^2 - \left(Sc+\frac{Pr}{S_2}\right) - \left(M+\frac{1}{K}\right)}\right)$$

$$A_{27} = -\left(\frac{GrA_{19}}{S_1(A_1+Sc)^2 - (A_1+Sc) - \left(M+\frac{1}{K}\right)}\right),\quad A_{28} = -(A_{21}+A_{22}+A_{23}+A_{24}+A_{25}+A_{26}+A_{27})$$

IV. RESULT AND DISCUSSION

In this paper, we have studied the dissipative heat and mass transfer in porous medium due to continuously moving plate in presence of magnetic field and constant heat and mass flux. The effect of the parameters Gr, Gm, M, R, Ec, S_1, S_2 , Pr and Sc on flow characteristics have been studied and shown by means of graphs and tables. In order to have physical correlations, we choose suitable values of flow parameters. The graphs of velocity and temperature are taken with respect to y. Shearing Stress is obtained in tables for different parameters.

Velocity profiles: The velocity profiles are depicted in Figs 1-4. Figure-(1) shows the effect of the parameters Gr and Gm on velocity at any point of the fluid, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the velocity increases with the increase of Grashoff number (Gr) and modified Grashoff number (Gm).

Figure-(2) shows the effect of the parameters M and K on velocity at any point of the fluid, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the velocity decreases with the increase of Magnetic parameter (M), where as increases with the increase of permeability parameter porous medium (K).

Figure-(3) shows the effect of the parameters S_1 and S_2 on velocity at any point of the fluid, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $Gr = 2$ and $Gm = 2$. It is noticed that the velocity decreases with the increase of (S_1), where as increases with the increase of (S_2).

Figure-(4) shows the effect of the parameters Pr and Sc on velocity at any point of the fluid, when M=2, K=2, Gr=2, Gm=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the velocity decreases with the increase of Schmidt number (Sc), where as increases with the increase of Prandtl number (Pr).

Temperature profile: The temperature profiles are depicted in Figs 5-8. Figure-(5) shows the effect of the parameters Gr and Gm on Temperature profile at any point of the fluid, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the temperature rises in the increase of Grashoff number (Gr) and modified Grashoff number (Gm).

Figure-(6) shows the effect of the parameters S_1 and S_2 on Temperature profile at any point of the fluid, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, Ec=0.01, $M = 2$ and $K = 2$. It is noticed that the temperature rises with the increase of S_1 and S_2.

Figure-(7) shows the effect of the parameters Sc and Pr on Temperature profile at any point of the fluid, when Gr=2, Gm=2, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the temperature falls in the increase of Schmidt number (Sc) and Prandtl number (Pr).

Figure-(8) shows the effect of the parameters M, K and Ec on Temperature profile at any point of the fluid, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, $S_1 = 0.8$ and $S_2 = 0.8$. It is noticed that the temperature falls in the increase of Magnetic parameter (M), where as rises with the increase of permeability parameter of porous medium (K) and Eckert number (Ec).

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Table I shows the effects of different parameters on Shearing stress. It is noticed that shearing stress increases in the increase of Grashoff number (Gr), modified Grashoff number (Gm), permeability parameter of porous medium (K), (S_2) and Eckert number (Ec), whereas decreases in the increase of Prandtl number (Pr), Magnetic parameter (M) and(S_1).

TABLE I. Effect of different parameters on shearing stress.

When K=2, Ec=0.01, $S_1 = 0.8$, $S_2 = 0.8$, and Sc=0.23				Shearing stress(τ)	When Pr=0.71, Gr=2, Gm=2, M=2 and Sc=0.23				Shearing stress(τ)
Pr	Gr	Gm	M		K	S_1	S_2	Ec	
0.71	2	2	2	6.575	2	0.8	0.8	0.01	6.575
1.2				6.213	4				7.160
7				0.749	6				7.364
0.71	4			7.848	0.8	1			5.670
	6			9.054		1.2			5.047
	2	4		14.528		0.8	1		6.644
		6		22.608			1.2		6.704
		2	4	3.332			0.8	0.02	6.608
			6	1.663				0.03	6.641

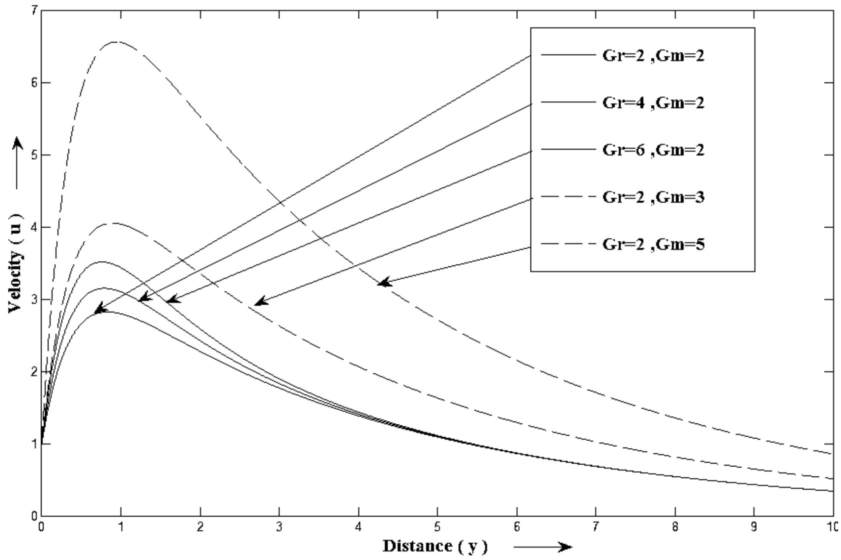

Fig. 1. Effect of Gr and Gm on velocity profile, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$

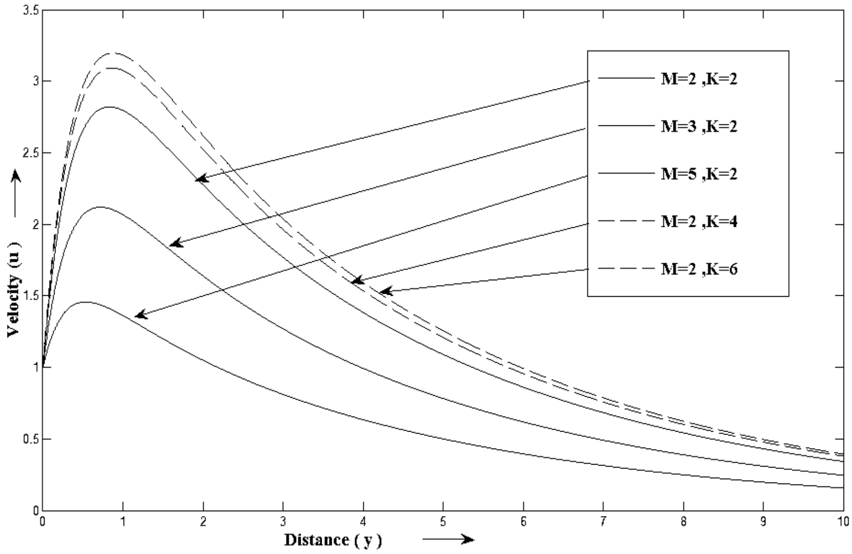

Fig. 2. Effect of M and K on velocity profile, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$

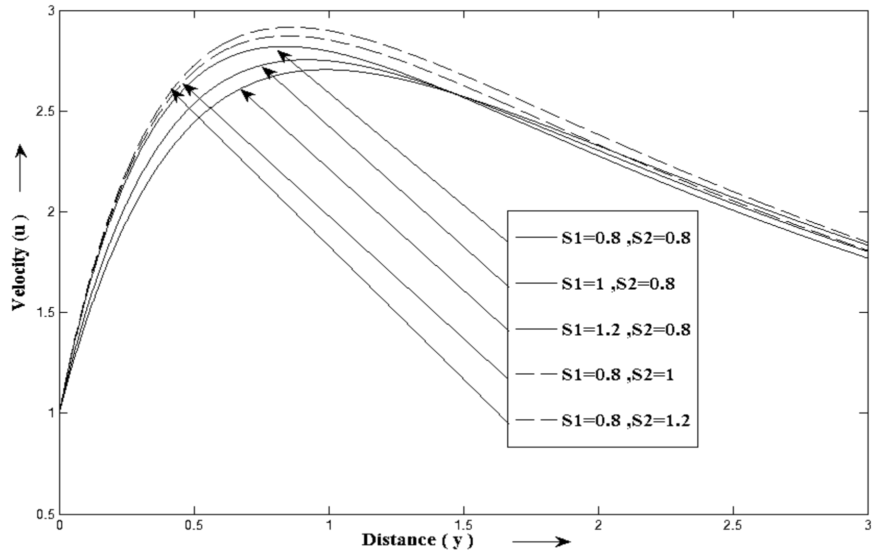

Fig. 3. Effect of S_1 and S_2 on velocity profile, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $Gr = 2$ and $Gm = 2$

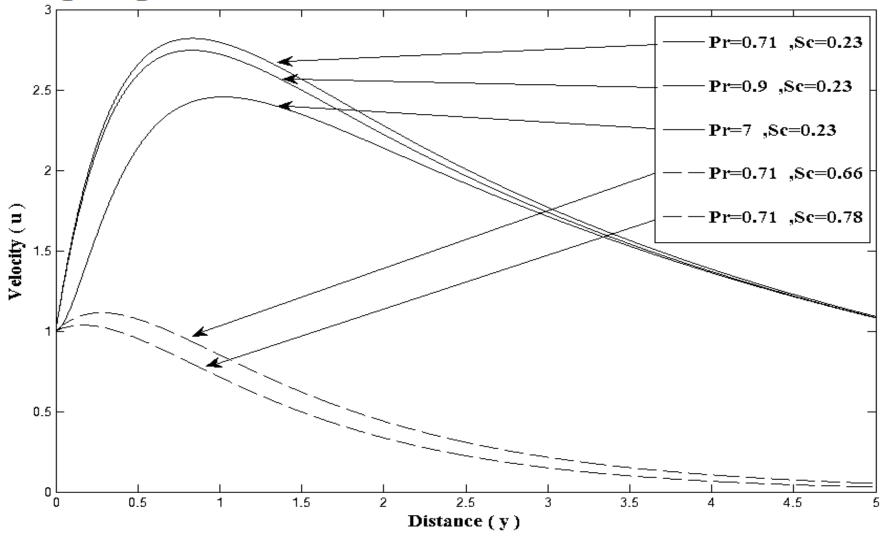

Fig. 4. Effect of Sc and Pr on velocity profile, when M=2, K=2, Gr=2, Gm=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$

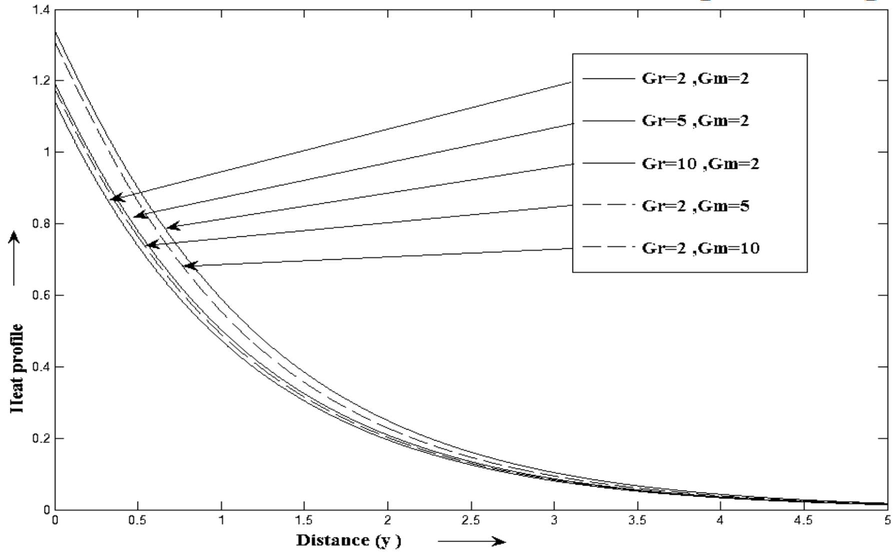

Fig. 5. Effect of Gr and Gm on Heat profile, when Sc=0.23, Pr=0.71, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$

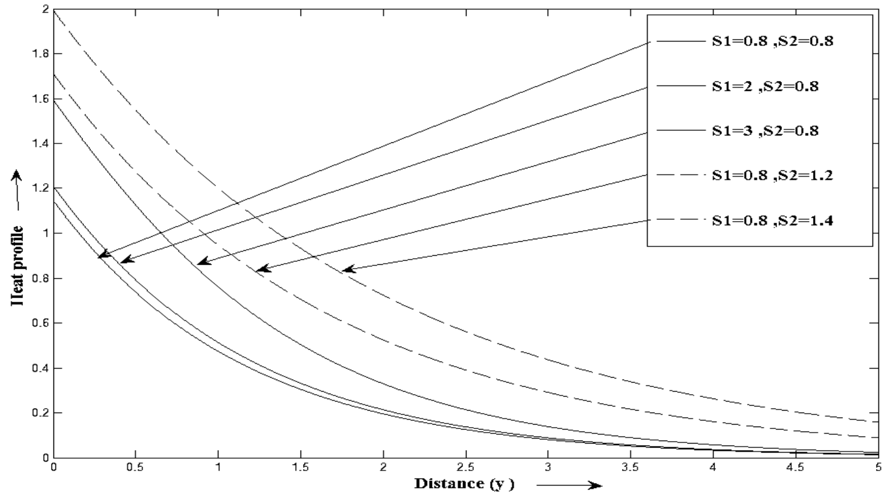

Fig. 6. Effect of S_1 and S_2 on velocity profile, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, Ec=0.01, $M = 2$ and $K = 2$

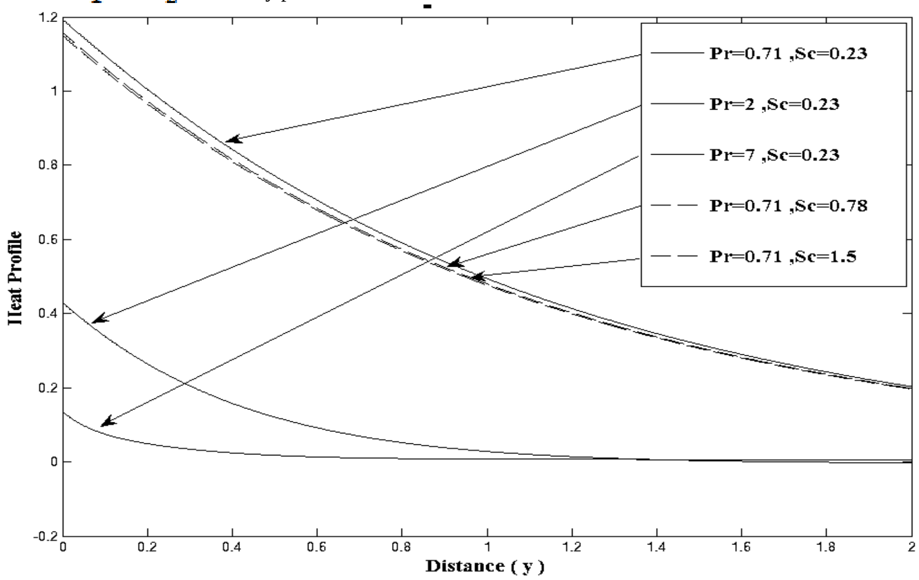

Fig. 7. Effect of Pr and Sc on Heat profile, when Gr=2, Gm=2, M=2, K=2, Ec=0.01, $S_1 = 0.8$ and $S_2 = 0.8$

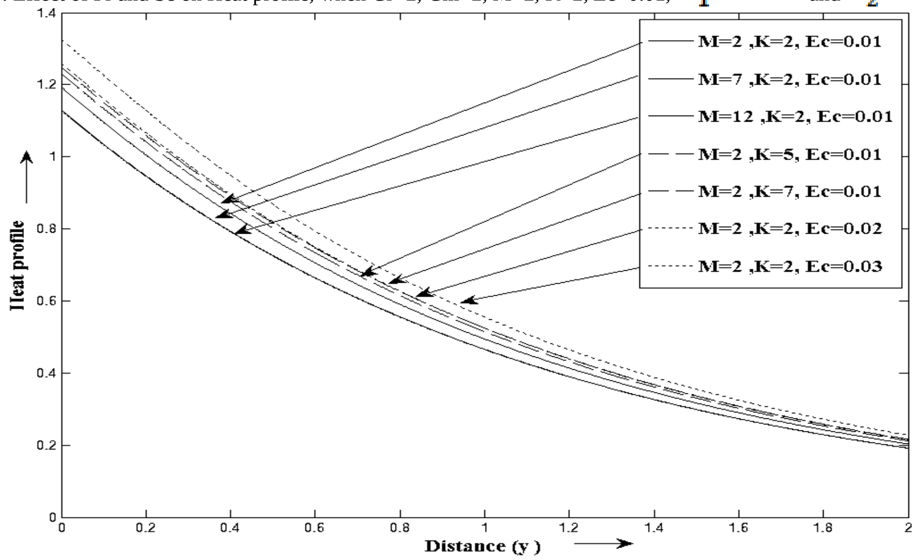

Fig. 8. Effect of M, K and Ec on Heat profile, when Sc=0.23, Pr=0.71, Gr=2, Gm=2, $S_1 = 0.8$ and $S_2 = 0.8$

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