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Radiation and chemical effects on MHD flow through porous media past an impulsively started exponentially accelerated vertical plate with variable temperature in the presence of heat generation

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ABSTRACT

Radiation and chemical effects on MHD flow through porous media past an impulsively started exponentially accelerated vertical plate with variable temperature in the presence of heat generation is studied here. The fluid considered is gray, absorbing-emitting radiation but a non-scattering medium. The governing equations involved in the present analysis are solved by Laplace transform techniques. The velocity, temperature, concentration, skin friction and Nusselt number are studied for different parameters like thermal Grashof number, mass Grashof number, Schmidt number, magnetic field parameter, Prandtl number, radiation parameter, heat source parameter, permeability parameter chemical reaction parameter and time.

Introduction

Study of MHD flow with heat and mass transfer plays an important role in biological Sciences. Effects of various parameters on human body can be studied and appropriate suggestions can be given to the persons working in hazardous areas having noticeable effects of magnetism and heat variation. Study of MHD flows also has many other important technological and geothermal applications. Some important applications are cooling of nuclear reactors, liquid metals fluid, power generation system and aero dynamics. The effects of radiation on free convection on the accelerated flow of a viscous incompressible fluid past an infinite vertical porous plate with suction has many important technological applications in the astrophysical, geophysical and engineering problem. The response of laminar skin friction and heat transfer to fluctuations in the stream velocity was studied by Lighthill [8]. Free convection effects on the oscillating flow past an infinite vertical porous plate with constant suction - I, was studied by Soundalgekar [19] which was further improved by Vajravelu et al. [21]. Further researches in these areas were done by Gupta et al.[3], Jaiswal et al.[6]and Soundalgekar et al. [20] by taking different models. Some effects like radiation and mass transfer on MHD flow were studied by Muthucumaraswamy et al. [10] to [11] and Prasad et al. [12]. Radiation effects on mixed convection along a vertical plate with uniform surface temperature were studied by Hossain and Takhar [5]. Mass transfer effects on the flow past an exponentially accelerated vertical plate with constant heat flux was studied by Jha, Prasad and Rai [7].

On the other hand, Radiation and free convection flow past a moving plate was considered by Raptis and Perdikis [18]. MHD flow past an impulsively started vertical plate with variable temperature and mass diffusion was studied by us [13]. Further, we had [14-15] considered rotation and radiation effects on MHD flow through porous media past an impulsively started vertical plate with variable temperature and rotation and radiation effects on MHD flow past an impulsively started vertical plate with variable temperature. Sahu [17] studied by combined effects of chemical reactions and heat generation/ absorption on unsteady transient free convection MHD flow between two long vertical parallel plates through a porous medium with constant temperature and mass diffusion. Rotation and chemical reaction effects on MHD flow through porous media past an impulsively started vertical plate with variable mass diffusion studied by us [16]. In this paper, we are considering the Radiation and chemical effects on MHD flow through porous media past an impulsively started exponentially accelerated vertical plate with variable temperature in the presence of heat generation. The results are shown with the help of graphs and tables.

Mathematical Analysis:

Consider an unsteady MHD flow of a viscous incompressible fluid through a porous medium past an infinite isothermal vertical plate with uniform mass diffusion in presence of a first order chemical reaction and radiation effect. The x' - axis is taken along the plate in the upward direction and y' -axis is taken normal to the plate. Initially the fluid and plate are at the same temperature. A transverse magnetic field B_0 , of uniform strength is applied normal to the plate. The viscous dissipation and induced magnetic field has been neglected due to its small effect. Initially, the fluid and plate are at the same temperature T_∞ and concentration C_∞ in the stationary condition. At time $t > 0$, temperature of the plate is raised to T_w and the concentration level near the plate is raised linearly with respect to time. To neglect the induced magnetic field effect we choose the flow of small Reynolds number. Hall effect and Joule heating effect are neglected. To allow heat generation effect we place a heat source in the flow. Under the above assumptions, the flow is governed by the following set of equations:

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$$\frac{\partial u'}{\partial t'} = g\beta\left(T' - T'_\infty\right) + g\beta^*\left(C' - C'_\infty\right) + \upsilon\frac{\partial^2 u'}{\partial y'^2} - \frac{\sigma B_0^2 u'}{\rho} - \frac{\upsilon u'}{K'}, \tag{1}$$

$$\rho C_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} - \frac{\partial q_r}{\partial y'} + Q^*\left(T' - T'_\infty\right), \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D\frac{\partial^2 C'}{\partial y'^2} - K_c\left(C' - C'_\infty\right). \tag{3}$$

The boundary conditions are as follows:

$$\left.\begin{aligned} &t' \le 0: \quad u' = 0,\ T' = T'_\infty,\ C' = C'_\infty \ \text{ for all } y' \ ; \\ &t' > 0: \quad u' = u_0 \exp(a't'),\ T' = T'_\infty + \left(T'_w - T'_\infty\right)\frac{u_0^2}{\upsilon}t',\ C' = C'_w \ \text{ at } y' = 0; \\ &\qquad u' \to 0,\ T' \to T'_\infty,\ C' \to C'_\infty \ \text{ as } y' \to \infty . \end{aligned}\right\} \tag{4}$$

where u' is velocity of the fluid, g -acceleration due to gravity, β -volumetric coefficient of thermal expansion, t' -time, T' -temperature of the fluid near the plate, T'_∞ - temperature of the fluid far away from the plate, β^* -volumetric coefficient of concentration expansion, C' -species concentration in the fluid, C_∞' - concentration in the fluid far away from the plate, υ -the kinematic viscosity, a' - constant, y' - the coordinate axis normal to the plates, ρ -density, C_p -specific heat at constant pressure, k -thermal conductivity of the fluid, D -mass diffusion coefficient, T'_w -temperature of the plate, C'_w -species concentration of the fluid, B_0 -uniform magnetic field, σ - Stefan – Boltzmann constant, K' -permeability of the porous medium, Q^* -heat generation/absorption coefficient, q_r - radiative heat flux in the y – direction and K_c -chemical reaction parameter.

The local radiant for the case of an optically thin gray gas is expressed by

$$\frac{\partial q_r}{\partial y'} = -4a^*\sigma\left(T'^4_\infty - T'^4\right), \tag{5}$$

where a^* is absorption constant.

Considering the temperature difference within the flow sufficiently small, T'^4 can be expressed as the linear function of temperature. This is accomplished by expanding T'^4 in a Taylor series about T'_∞ and neglecting higher-order terms

$$T'^4 \cong 4T'^3_\infty T' - 3T'^4_\infty. \tag{6}$$

Using equations (5) and (6), equation (2) becomes

$$\rho C_p \frac{\partial T'}{\partial t'} = k\frac{\partial^2 T'}{\partial y'^2} - 16a^*\sigma T'^3_\infty\left(T' - T'_\infty\right) + Q^*\left(T' - T'_\infty\right), \tag{7}$$

Introducing the following non - dimensional quantities:

$$\left.\begin{aligned} &u = \frac{u'}{u_0},\ t = \frac{t'u_0^2}{\upsilon}, y = \frac{u_0 y'}{\upsilon},\ \theta = \frac{\left(T' - T'_\infty\right)}{\left(T'_w - T'_\infty\right)},\ G_r = \frac{g\beta\upsilon\left(T'_w - T'_\infty\right)}{u_0^3}, \\ &R = \frac{16a^*\sigma\upsilon^2 T'^3_\infty}{ku_0^2}, C = \frac{\left(C' - C'_\infty\right)}{\left(C'_w - C'_\infty\right)}, M = \frac{\sigma B_0^2\upsilon}{\rho u_0^2}, k_0 = \frac{\upsilon K_c}{u_0^2}, a = \frac{a'\upsilon}{u_0^2} \\ &G_m = \frac{g\beta^*\upsilon\left(C'_w - C'_\infty\right)}{u_0^3},\ S_c = \frac{\upsilon}{D}, H = \frac{Q^*\upsilon^2}{ku_0^2}, K = \frac{\upsilon^2 K'}{u_0^2} \text{ and } P_r = \frac{\rho\upsilon C_p}{k}. \end{aligned}\right\} \tag{8}$$

where u is the dimensionless velocity, y -dimensionless coordinate axis normal to the plates, t -dimensionless time, θ -dimensionless temperature, C -dimensionless concentration, G_r -thermal Grashof number, G_m -mass Grashof number, μ -coefficient of viscosity, P_r -the Prandtl number, S_c -the Schmidt number, M - magnetic parameter, K_1 - dimensionless chemical reaction parameter, H - dimensionless heat source parameter and K -permeability parameter.

Using (8), equations (1), (3) and (7) reduce to:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + G_r\theta + G_m C - \left(M + \frac{1}{K}\right)u, \tag{9}$$

$$P_r \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} - R\theta + H\theta, \tag{10}$$

$$\frac{\partial C}{\partial t} = \frac{1}{S_c}\frac{\partial^2 C}{\partial y^2} - k_0 C. \tag{11}$$

Also, the boundary condition (4) reduces to:

$$\left.\begin{array}{l} t \le 0: \quad u = 0,\ \theta = 0,\ C = 0 \ \text{ for all } \ y \ ; \\ t > 0: \ u = \exp(at),\ \theta = t,\ C = 1 \ \text{ at } y = 0; \\ \qquad u \to 0,\ T \to 0,\ C \to 0 \ \text{ as } \ y \to \infty \ . \end{array}\right\} \tag{12}$$

The dimensionless governing equations (9) to (11), subject to the boundary conditions (12), are solved by the usual Laplace transform technique with some help from [1], [2] and [4]. The solutions derived are as follows:

$$\begin{aligned} u = {} & \frac{e^{at}}{2}\left[e^{-y\sqrt{M_1}} erfc\left(\eta - \sqrt{M_1 t}\right) + e^{y\sqrt{M+a}} erfc\left(\eta + \sqrt{M_1 t}\right)\right] \\ & + \left[A_1 e^{-y\sqrt{M^*}} erfc\left(\eta - \sqrt{M^* t}\right) + A_2 e^{y\sqrt{M^*}} erfc\left(\eta + \sqrt{M^* t}\right)\right] \\ & - \frac{G_2 e^{bt}}{2b}\left[e^{-y\sqrt{M_2}} erfc\left(\eta - \sqrt{M_2 t}\right) + e^{y\sqrt{M_2}} erfc\left(\eta + \sqrt{M_2 t}\right)\right] \\ & - \frac{G_1 e^{dt}}{2d^2}\left[e^{-y\sqrt{M_3}} erfc\left(\eta - \sqrt{M_3 t}\right) + e^{y\sqrt{M+d}} erfc\left(\eta + \sqrt{M_3 t}\right)\right] \\ & + \frac{G_1 e^{dt}}{2d^2}\left[e^{-y\sqrt{P_r}\sqrt{c+d}} erfc\left(\eta\sqrt{P_r} - \sqrt{(c+d)t}\right) + e^{y\sqrt{P_r}\sqrt{c+d}} erfc\left(\eta\sqrt{P_r} + \sqrt{(c+d)t}\right)\right] \\ & - A_3 e^{-y\sqrt{cP_r}} erfc\left(\eta\sqrt{P_r} - \sqrt{ct}\right) - A_4 e^{y\sqrt{cP_r}} erfc\left(\eta\sqrt{P_r} + \sqrt{ct}\right) \\ & + \frac{G_2 e^{bt}}{2b}\left[e^{-y\sqrt{S_c}\sqrt{k_0+b}} erfc\left(\eta\sqrt{S_c} - \sqrt{(k_0+b)t}\right) + e^{y\sqrt{S_c}\sqrt{k_0+b}} erfc\left(\eta\sqrt{S_c} + \sqrt{(k_0+b)t}\right)\right] \\ & - \frac{G_2}{2b}\left[e^{-y\sqrt{k_0 S_c}} erfc\left(\eta\sqrt{S_c} - \sqrt{k_0 t}\right) + e^{y\sqrt{k_0 S_c}} erfc\left(\eta\sqrt{S_c} + \sqrt{k_0 t}\right)\right], \end{aligned} \tag{13}$$

$$\theta = \frac{t}{2}\left[\theta_1 e^{-y\sqrt{cP_r}} erfc\left(\eta\sqrt{P_r} - \sqrt{ct}\right) + \theta_2 e^{y\sqrt{cP_r}} erfc\left(\eta\sqrt{P_r} + \sqrt{ct}\right)\right], \tag{14}$$

$$C = \frac{1}{2}\left[e^{-y\sqrt{k_0 S_c}} erfc\left(\eta\sqrt{S_c} - \sqrt{k_0 t}\right) + e^{y\sqrt{k_0 S_c}} erfc\left(\eta\sqrt{S_c} + \sqrt{k_0 t}\right)\right]. \tag{15}$$

Where $M^* = M + \frac{1}{K}$, $M_1 = M^* + a$, $M_2 = M^* + b$, $\eta = \frac{y}{2\sqrt{t}}$,

$b = \frac{M^* - k_0 S_c}{S_c - 1}$, $c = \frac{R-H}{P_r}$, $d = \frac{M^* - (R-H)}{P_r - 1}$, $G_1 = \frac{G_r}{1-P_r}$, $G_2 = \frac{G_m}{1-S_c}$, $G = \frac{G_1}{d^2} + \frac{G_2}{b}$, $M_3 = M^* + d$,

$A_1 = \frac{G}{2} + \frac{G_1}{d}\left(\frac{t}{2} - \frac{y}{4\sqrt{M^*}}\right)$, $A_2 = \frac{G}{2} + \frac{G_1}{d}\left(\frac{t}{2} + \frac{y}{4\sqrt{M^*}}\right)$, $A_3 = \frac{G_1}{2d^2} + \frac{G_1}{d}\left(\frac{t}{2} - \frac{y\sqrt{P_r}}{4\sqrt{c}}\right)$, $A_4 = \frac{G_1}{2d^2} + \frac{G_1}{d}\left(\frac{t}{2} + \frac{y\sqrt{P_r}}{4\sqrt{c}}\right)$,

$\theta_1 = \frac{t}{2} - \frac{yP_r}{4\sqrt{R-H}}$ and $\theta_2 = \frac{t}{2} + \frac{yP_r}{4\sqrt{R-H}}$.

Skin friction:

The non-dimensional skin friction is given by:

$$\tau = -\left(\frac{\partial u}{\partial y}\right)_{y=0} = \frac{G_1}{2d\sqrt{M^*}} erf\left(\sqrt{M^* t}\right) + \sqrt{M_1} e^{at} erf\left(\sqrt{M_1 t}\right) + e^{-M^* t}\left(1 + \frac{G_1 t}{d} - \frac{G_1}{d^2}\frac{G_2}{b}\right)$$
$$- \frac{G_2\sqrt{M_2} e^{bt}}{b} erf\left(\sqrt{M_2 t}\right) - \frac{G_1\sqrt{M_3} e^{dt}}{d^2} erf\left(\sqrt{M_3 t}\right) - \frac{G_1\sqrt{tP_r}}{d\sqrt{\pi}} e^{-ct}$$
$$- \frac{G_1\sqrt{P_r}}{2d}\left(t + \frac{1}{\sqrt{c}} + \frac{1}{d}\right) erf\left(\sqrt{ct}\right) - \frac{G_1 e^{dt}\sqrt{tP_r(c+d)}}{d^2} erf\left(\sqrt{(c+d)t}\right)$$
$$- \frac{\sqrt{S_c} G_2}{b}\left(\sqrt{k_0} erf\left(\sqrt{k_0 t}\right) + e^{bt}\sqrt{(b+k_0)} erf\left(\sqrt{(b+k_0)t}\right)\right)$$

Nusselt number:

The non-dimensional Nusselt number is given by:

$$Nu = -\left(\frac{\partial \theta}{\partial y}\right)_{y=0} = \left(\frac{P_r}{2\sqrt{R-H}} + \sqrt{cP_r}\right) erf\left(\sqrt{ct}\right) + \frac{\sqrt{tP_r}}{\sqrt{\pi}} e^{-ct}$$

Result and Discussions:

The velocity profiles for different parameters M, K, G_r, G_m, S_c, H, R, P_r, k_0 and t are shown by figures-1 to 10. From fig-1 it is clear that the velocity decreases when time parameter t is increased (keeping other parameters $S_c = 2.01$, $G_m = 10$, $G_r = 5$, $R = 2$, $K = 1$, $k_0 = 1$, $P_r = 0.71$, $M = 2$, $a = 1$ and $H = 1$ constant). In fig-2 velocity increases when magnetic field parameter M is increased (keeping other parameters $S_c = 2.01$, $G_m = 10$ $G_r = 5$, $R = 2$, $K = 1$, $k_0 = 1$, $P_r = 0.71$, $t = 0.2$, $a = 1$ and $H = 1$ constant).

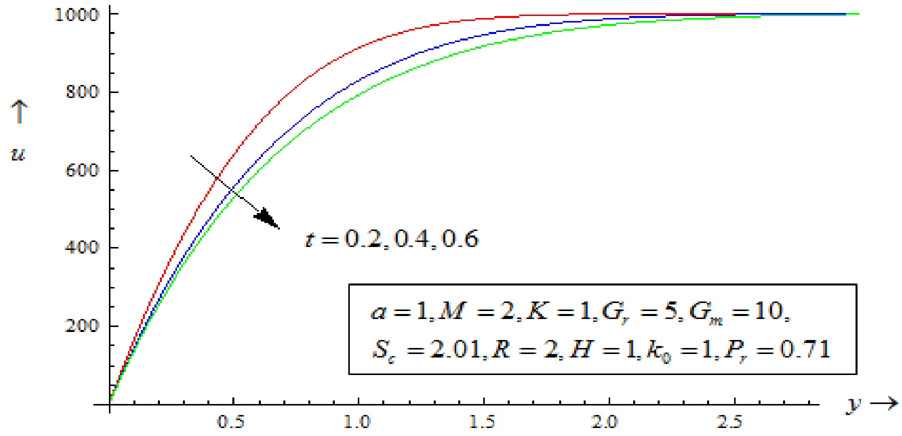

Fig 1. Velocity profile for different values of t

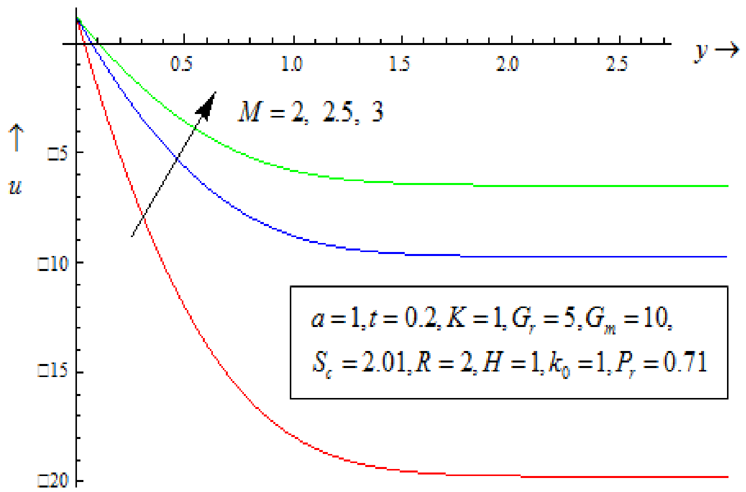

Fig 2: Velocity profile for different values of M

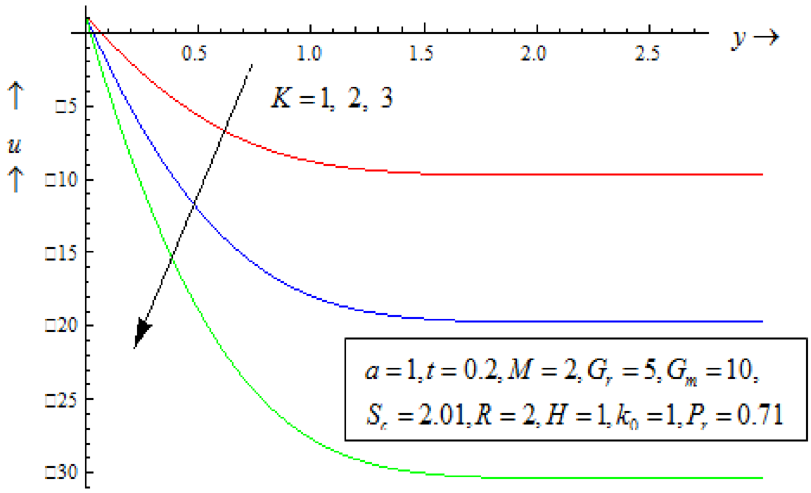

Fig 3: Velocity profile for different values of K

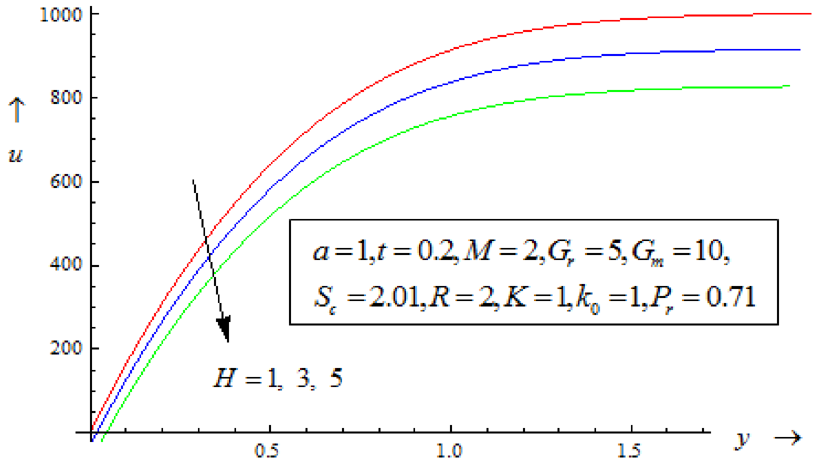

Fig 4. Velocity profile for different values of H

But in fig-3 represents opposite pattern, i.e. velocity decreases when permeability parameter K is increased (keeping other parameters $S_c = 2.01$, $G_m = 10$ $G_r = 5$, $R = 2$, $M = 2$, $k_0 = 1$, $P_r = 0.71$, $t = 0.2$, $a = 1$ and $H = 1$ constant). Fig-4 shows that the velocity decreases when the heat source parameter H is increased (keeping other parameters $S_c = 2.01$, $G_m = 10$ $G_r = 5$, $R = 2$, $M = 2$, $k_0 = 1$, $P_r = 0.71$, $t = 0.2$, $a = 1$ and $K = 1$ constant. Similar pattern is observed when R is increased (Fig-5). Here the parameters $S_c = 2.01$, $G_m = 10$ $G_r = 5$, $K = 1$, $M = 2$, $k_0 = 1$, $P_r = 0.71$, $t = 0.2$, $a = 1$ and $H = 1$ are kept constant. It is clear from fig-6 that the velocity increases when the Schmidt number is increased (keeping other parameters $R = 2$, $G_m = 10$ $G_r = 5$, $K = 1$, $M = 2$, $k_0 = 1$, $P_r = 0.71$, $t = 0.2$, $a = 1$ and $H = 1$ constant). Fig-7 and Fig-8 shows similar pattern. In both cases velocity increases when mass Grashof number and thermal Grash of number are increased.

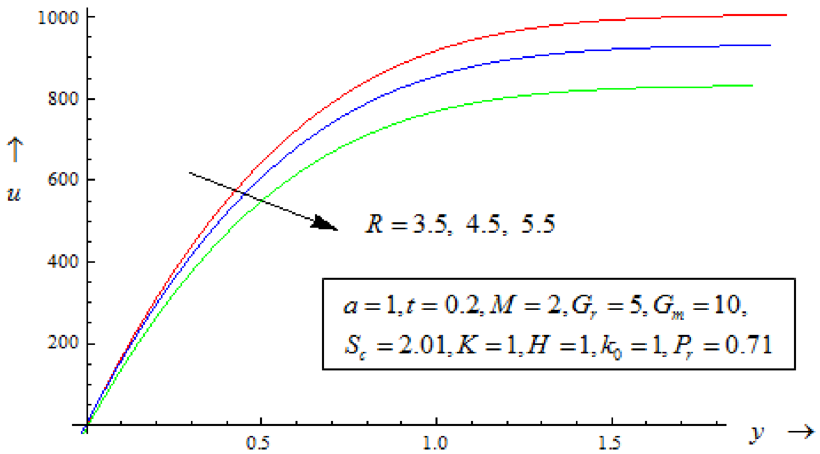

Fig 5: Velocity profile for different values of R

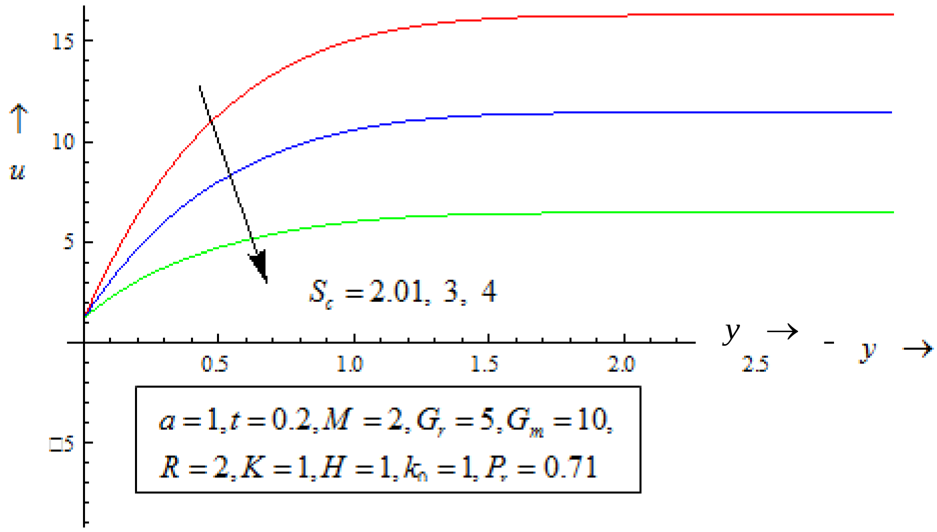

Fig 6. Velocity profile for different values of S_c

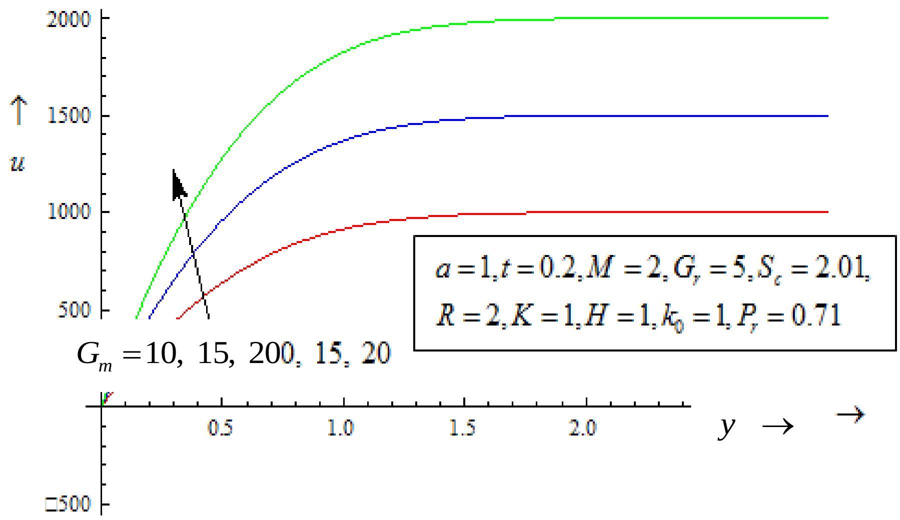

Fig 7. Velocity profile for different values of G_m

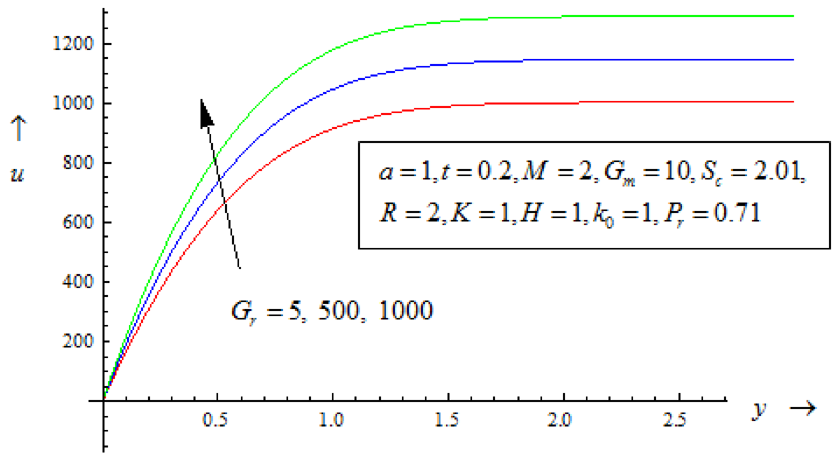

Fig 8. Velocity profile for different values of G_r

From fig-9 it is clear that velocity decreases when Prandtl number is increased (keeping other parameters $R=2$, $S_c=2.01$, $G_r=5$, $K=1$, $M=2$, $k_0=1$, $G_m=10$, $t=0.2$, $a=1$ and $H=1$ constant). In fig-10 velocity increases when chemical parameter is increased (keeping other parameters $R=2$, $S_c=2.01$, $G_r=5$, $K=1$, $M=2$, $P_r=0.71$, $G_m=10$, $t=0.2$, $a=1$ and $H=1$ constant).

Temperature profile for different parameters H, R, P_r and t are shown by figures-11 to 14. Fig-11 shows that the temperature is increased when time parameter increased. Fig-12 is showing the effect of Prandtl number. The temperature gets decreased when

Prandtl number is increased. It is observed that the temperature gets increased when the heat source parameter is increased (Fig-13). In fig-14 opposite pattern is observed, i.e. when radiation parameter is increased the temperature gets decreased.

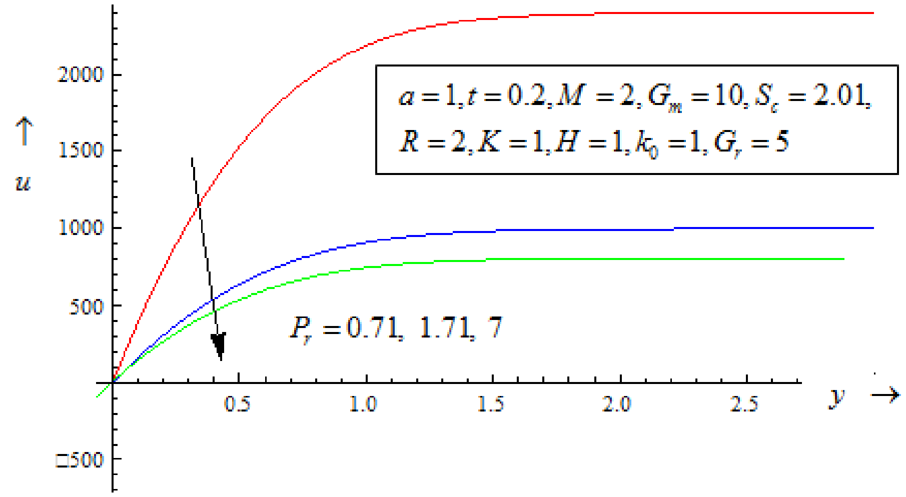

Fig 9. Velocity profile for different values of P_r

Concentration profiles for different parameters are shown by figures15 to 17. In fig-15 it is shown that the concentration is increased when time parameter is increased. But in fig-16 and fig-17 is observed, i.e. when chemical parameter and Schmidt number re increased, the concentration gets decreased.

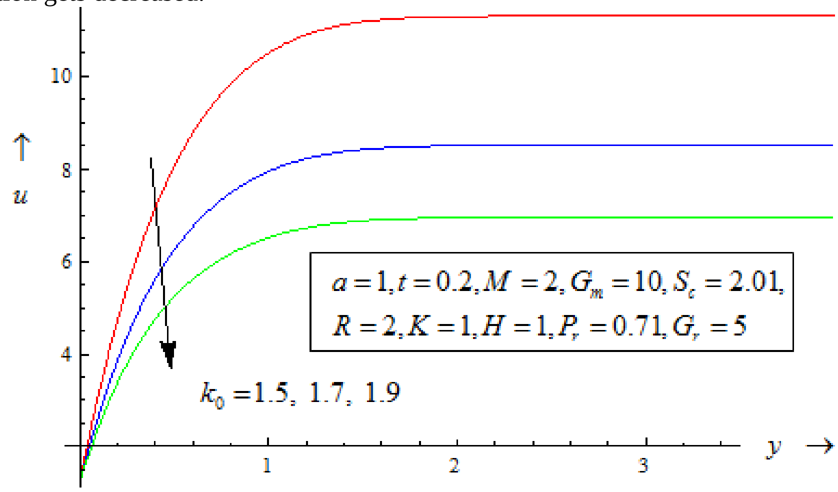

Fig 10. Velocity profile for different values of k_0

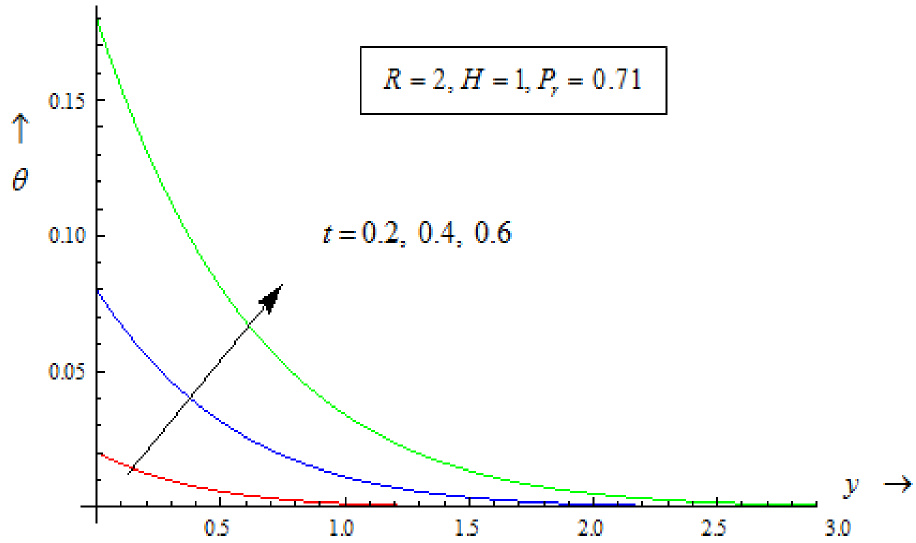

Fig 11. Temperature profile for different values of t

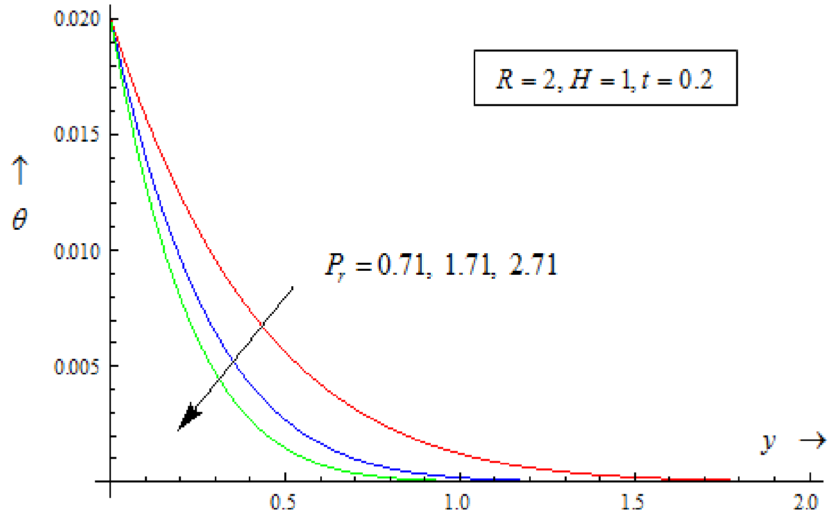

Fig 12. Temperature profile for different values of P_r

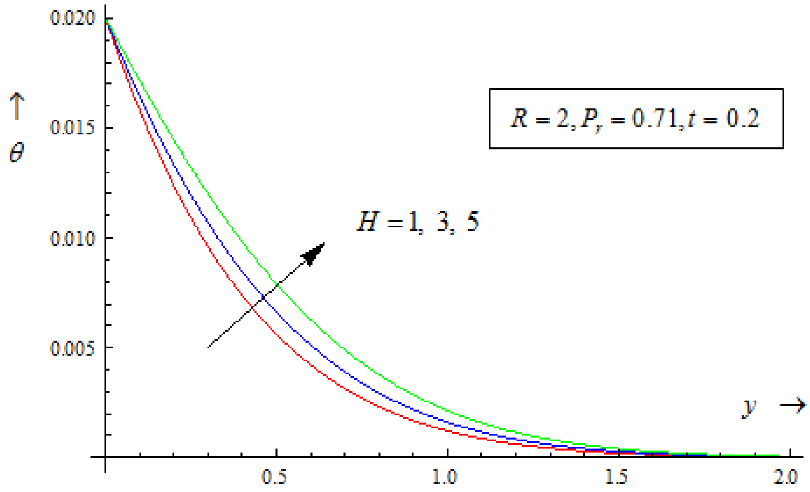

Fig 13. Temperature profile for different values of H

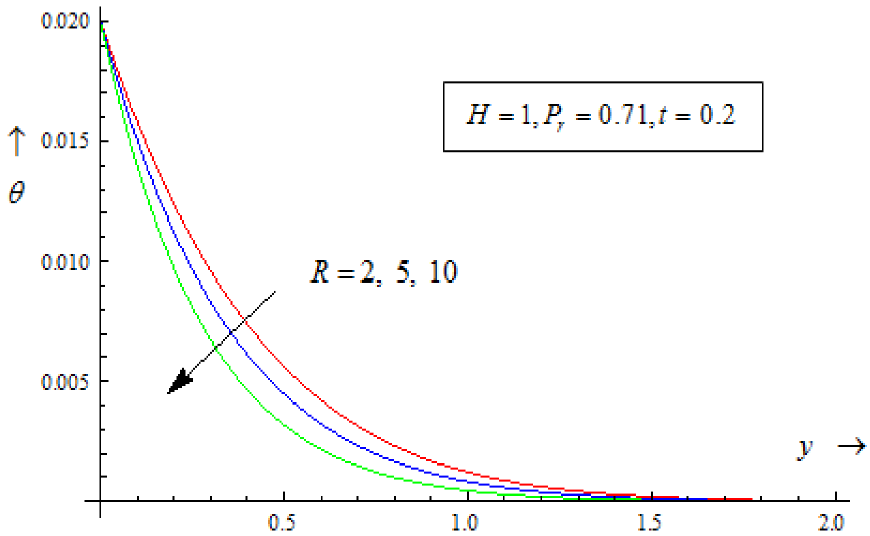

Fig 14. Temperature profile for different values of R

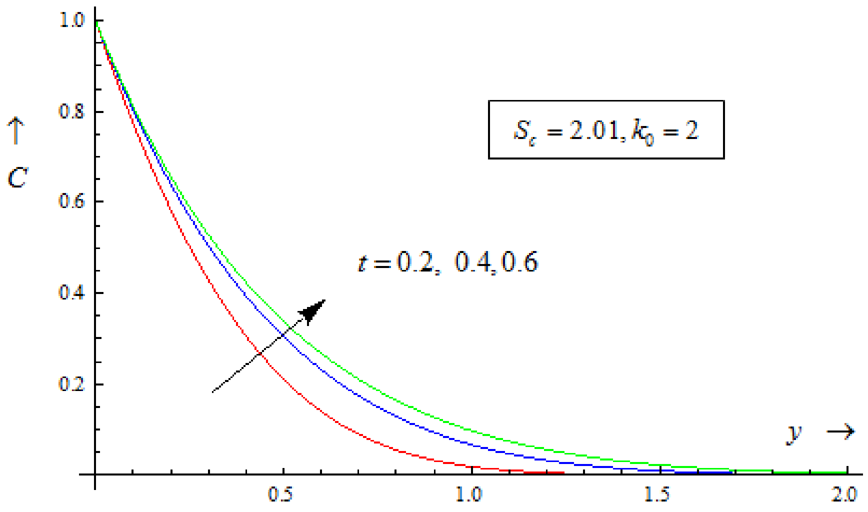

Fig 15. Concentration profile for different values of t

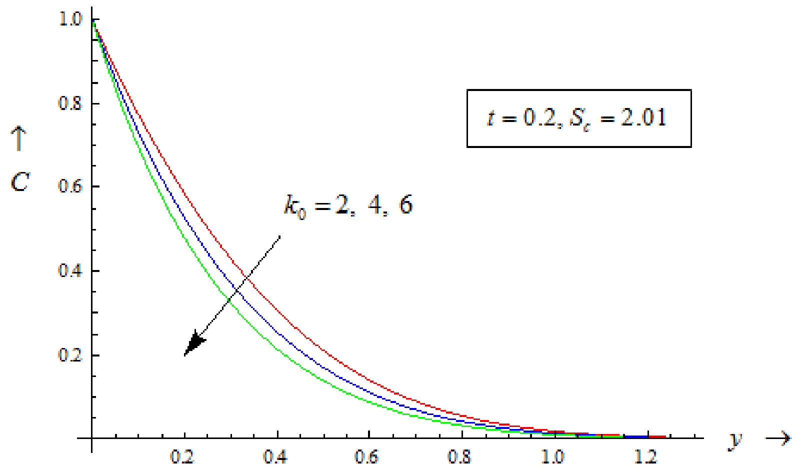

Fig 16. Concentration profile for different values of K_1

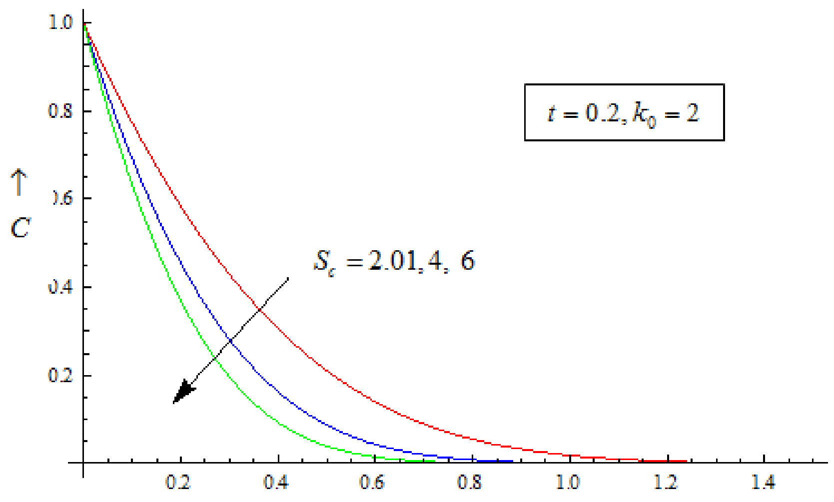

Fig 17. Concentration profile for different values of S_c

The values of skin friction are tabulated in Table-1 for different parameters. When the values of M, a, K, H, R, P_r, S_c and k_0 are increased (keeping other parameters constant), the value of τ is also increased. But if values of $G_m; G_r$ and t are increased, the value of τ gets decreased.

The values of Nusselt number are tabulated in Table-2 for different parameters. When the values of R, P_r and t are increased (keeping other parameters constant), the value of N_u is also increased. But if the values of H are increased, the value of τ gets decreased.

Conclusion:

In this paper a theoretical analysis has been done to study radiation and chemical effects on MHD flow through porous media past an impulsively started exponentially accelerated vertical plate with variable temperature in the presence of heat generation. Solutions for the model have been derived by using Laplace - transform technique. Some conclusions of the study are as below:

1. Velocity (u) increases with the increase in G_m, G_r and M, and decreases with increase in t, K, H, R, S_c, P_r and k_0.
2. Temperature (θ) increases with the increase in t and H, and decreases with increase in P_r and R.
3. Concentration (C) increases with the increase in t, and decreases with increase in k_0 and S_c.
4. Skin friction τ increases when permeability parameter, magnetic field parameter, Schmidt number, chemical reaction parameter, radiation parameter, heat source parameter and Prandtl number are increased but decreases when thermal Grashof number, mass Grashof number and time are increased.
5. Nusselt number N_u increases when radiation parameter, time parameter and Prandtl number are increased but decreases when heat source parameter is increased.

Table 1. Skin friction for different parameters

M	t	a	K	H	R	G_r	G_m	P_r	S_c	k_0	τ
2	0.2	1	1	1	2	5	10	0.71	2.01	1	-3027.3
4	0.2	1	1	1	2	5	10	0.71	2.01	1	35.50
6	0.2	1	1	1	2	5	10	0.71	2.01	1	37.48
2	0.4	1	1	1	2	5	10	0.71	2.01	1	-3433.83
2	0.6	1	1	1	2	5	10	0.71	2.01	1	-3724.40
2	0.2	2	1	1	2	5	10	0.71	2.01	1	-3026.42
2	0.2	5	1	1	2	5	10	0.71	2.01	1	-3022.11
2	0.2	1	2	1	2	5	10	0.71	2.01	1	-2932.03
2	0.2	1	1	3	2	5	10	0.71	2.01	1	-2149.87
2	0.2	1	1	1	4	5	10	0.71	2.01	1	-2940.39
2	0.2	1	1	1	2	10	10	0.71	2.01	1	-3811.78
2	0.2	1	1	1	2	5	20	0.71	2.01	1	-5866.14
2	0.2	1	1	1	2	5	5	0.71	2.01	1	-1464.98
2	0.2	1	1	1	2	5	10	2	2.01	1	527.94
2	0.2	1	1	1	2	5	10	0.71	3	1	-24.98
2	0.2	1	1	1	2	5	10	0.71	2.01	5	-1.28013
2	0.2	1	1	1	2	5	10	0.71	2.01	15	0.1484

Table 2. Nusselt Numbers for different parameters

H	R	t	P_r	N_u
1	2	0.2	0.71	0.801766
3	2	0.2	0.71	0.31965
5	2	0.2	0.71	-1.98394
1	5	0.2	0.71	1.91318
1	10	0.2	0.71	3.04879
1	2	0.4	0.71	1.05534
1	2	0.6	0.71	1.19593
1	2	0.2	2	0.894758
1	2	0.2	4	1.17385
1	2	0.2	6	1.46982

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