

EFFECT OF NON-UNIFORM HEAT SOURCE AND RADIATION ON UNSTEADY MHD FREE CONVECTION FLOW PAST AN INFINITE HEATED VERTICAL PLATE IN POROUS MEDIUM

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ABSTRACT

Influence of radiation and non-uniform heat source on unsteady, magneto-hydrodynamic free convection flow of viscous incompressible fluid past an infinite vertical heated plate embedded in porous medium of an optically thin environment with time dependent suction and viscous dissipation is investigated in this paper. Analytical solutions of the coupled non-linear equations are obtained for the velocity field and temperature distribution using oscillating time-dependent perturbation technique. Expressions for skin-friction and heat transfer rate are also derived. The effects of the material parameters on velocity, temperature, skin-friction, and rate of heat transfer are discussed quantitatively.

Keywords: *Non-Uniform heat source, time dependent suction, viscous dissipation*

1. INTRODUCTION

The study of magneto hydrodynamic natural convection flow and heat transfer of an electrically conducting fluid past a heated semi-infinite vertical porous plate finds useful applications in many engineering problems such as MHD generators, nuclear reactors, geothermal extractions, heat exchanger devices and boundary layer control in the field of aeronautics and aerodynamics.

Because of numerous applications in several engineering and industrial manufacturing processes, such flows have got renewed interest among researchers. The effects of radiation are of vital importance. Recent development in hypersonic flights, rocket combustion chambers, power plants for interplanetary flights and gas cooled nuclear reactors have focused attention on thermal radiations as a mode of energy transfer, and emphasized the need for an improved understanding of radiative transfer in these processes (Cowling, 1957; Ferraro & Plumpton, 1961). Cess (1966) investigated the interaction of radiation with laminar free convection heat transfer from a vertical plate

for an absorbing emitting liquid in the optically thick region and used the singular perturbation technique. Arpaci (1968) considered a similar problem in both, the optically thin and optically thick regions using the appropriate integral technique. Cheng and Ozisik (1972) investigated an absorbing, emitting and isotropically scattering fluid. Ali et. al. (1984) considered the effects of radiation on natural convective flow of a viscous fluid over a horizontal surface, while Bestman (1985) considered the same problem for the flow of non-Newtonian fluid along a vertical plate under uniform transverse magnetic field. Bestman & Adjepong (1988) also investigated free convection unsteady flow considering radiative heat transfer in a rotating fluid under the influence of uniform magnetic field. Ibrahim (1990) studied mixed convection and radiation interaction for flow of a viscous fluid considering horizontal and vertical surfaces, respectively. Hossain & Takhar (1996) studied the radiation effects on mixed convection along a vertical plate with uniform surface temperature and employed Keller Box finite

difference method. Hossain et. al. (2001) and Hossain et. al. (1999) extended this work for free convection and radiation interaction past a porous vertical plate in the presence of constant suction and with variable viscosity effects respectively. Azzam (2002) studied a similar problem for the effects of radiation on the flow and heat transfer past a moving vertical plate in the presence of magnetic field. Hydromagnetic flow showing the effects of radiation and heat transfer over a wedge was studied by Elbashbeshy and Dimian (2002) taking into account the variable viscosity. Cooney et. al. (2003) investigated the influence of viscous dissipation and radiation in unsteady MHD free convection flow past an infinite vertical heated plate in the optically thin environment with variable suction and used radiative heat flux in differential form.

The aim of the present investigation is to study the influence of radiation, variable suction and non-uniform heat source/sink on unsteady hydromagnetic free convection flow of a viscous fluid past a heated vertical porous plate taking into account the viscous dissipation. In the analysis, we considered both the space and the temperature dependent heat source/sink followed by Abo-Eldahab and El-Aziz (2004) and Abel et. al. (2007). Basu et. al. (2011) have studied Radiation and mass transfer effects on transient free convection flow of dissipative fluid past semi-infinite vertical plate with uniform heat and mass flux.

2. MATHEMATICAL FORMULATION

We consider the unsteady free convection flow of an incompressible viscous, electrically conducting, radiating fluid past an infinite porous heated vertical plate embedded in porous medium with time dependent suction and viscous dissipation. In Cartesian coordinate system the x' -axis is taken along the vertical porous plate in the upward direction and the z' -axis normal to the plate. A constant magnetic field of strength B_0 is maintained in the z' -direction and the plate moves uniformly along the positive x' -direction with velocity $w'(t')$. Initially, at time $t'=0$ the plate is at the temperature T'_∞ . At time $t' > 0$, the temperature of the plate is suddenly increased to T'_w and is maintained constant, which is highly enough to

initiate radiative heat transfer. Under Boussinesq's approximation the flow is governed by the following equations:

$$\frac{\partial w'}{\partial z'} = 0. \quad (1)$$

$$\frac{\partial u'}{\partial t'} + w' \frac{\partial u'}{\partial z'} = \vartheta \frac{\partial^2 u'}{\partial z'^2} + \frac{\partial w'}{\partial t'} - \left[\frac{\sigma_e}{\rho} \mu_e^2 H_0^2 + \frac{\vartheta}{K'} \right] (u' - w') + g\beta(T' - T'_\infty) \quad (2)$$

$$\frac{\partial T'}{\partial t'} + w' \frac{\partial T'}{\partial z'} = \frac{K_T}{\rho c_p} \left[\frac{\partial^2 T'}{\partial z'^2} - \frac{\partial}{\partial z'} q'_z \right] + \frac{\mu}{\rho c_p} \left(\frac{\partial u'}{\partial z'} \right)^2 + \frac{q'''}{\rho c_p}. \quad (3)$$

$$\frac{\partial^2 q'_z}{\partial z'^2} - 3\alpha^2 q'_z - 16\alpha\sigma T'^3_\infty \frac{\partial T'}{\partial z'} = 0 \quad (4)$$

The boundary conditions relevant to the problem are

$$\begin{aligned} u' &= w'(t') = w'_0 (1 + \varepsilon e^{i\omega' t'}), \\ T' &= T'_w \quad \text{at} \quad z' = 0 \\ u' &\rightarrow 0, \quad T' \rightarrow T'_\infty \quad \text{as} \quad z' \rightarrow \infty \end{aligned} \quad (5)$$

Since the medium is optically thin with relatively low density and $\alpha \ll 1$, the radiative heat flux given in equation (4) Cooney et. al. (2003) becomes

$$\frac{\partial}{\partial z} q'_z = 4\alpha^2 (T' - T'_\infty) \quad (6)$$

$$\text{where } \alpha^2 = \int_0^\infty \delta\lambda \frac{\partial B}{\partial T'}$$

Also from equation (1), it is obvious w' is either a constant or function of time t' only. Hence, we assume

$$w' = -w'_0 (1 + \varepsilon e^{i\omega' t'}) \quad (7)$$

such that $\varepsilon \ll 1$ and the negative sign indicates that the suction velocity is towards the plate.

In the energy equation (3) q''' is the space and temperature dependent internal heat generation/absorption (non-uniform heat

source/sinks), Abel et.al. (2007), which can be expressed in the simplest form as

$$q''' = \frac{K_T w_0^2}{g^2 \rho C_p} [A^*(T'_w - T'_\infty)(1 + \epsilon e^{i\omega t'}) + B^*(T' - T'_\infty)] \quad (8)$$

where A^* and B^* space and temperature dependent internal heat generation/absorption (non-uniform heat source/sinks).

We introduce following non-dimensional quantities and parameters

$$z = \frac{w'_0 z'}{g}, \quad t = \frac{w_0'^2 t'}{g}, \quad u = \frac{u'}{w_0}$$

$$\omega = \frac{g \omega'}{w_0'^2}, \quad w = \frac{w'}{w_0}$$

$$\theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}, \quad \frac{1}{K} = \frac{g^2}{K' w_0'^2}, \quad Pr = \frac{\mu C_p}{K_T}$$

$$Gr = \frac{g \beta (T'_w - T'_\infty)}{w_0'^3}, \quad Ec = \frac{U_0'^2}{C_p (T'_w - T'_\infty)}$$

$$R = \frac{4\alpha^2 g^2}{w_0'^2}, \quad M^2 = \frac{\sigma_e g \mu_e^2 H_0'^2}{\rho w_0'^2}$$

$$M_1 = M^2 + K^{-1}.$$

In view of (7) and above non-dimensional quantities and parameters, the Eqs. (2) and (3) transform to:

$$\frac{\partial u}{\partial t} - (1 + \epsilon e^{i\omega t}) \frac{\partial u}{\partial z} = \frac{\partial^2 u}{\partial z^2} + \frac{\partial w}{\partial t} - M_1(u - w) + Gr\theta \quad (9)$$

$$Pr \frac{\partial \theta}{\partial t} - Pr(1 + \epsilon e^{i\omega t}) \frac{\partial \theta}{\partial z} = \frac{\partial^2 \theta}{\partial z^2} - R\theta + EcPr \left(\frac{\partial u}{\partial z}\right)^2 + [A^*(1 + \epsilon e^{i\omega t}) + B^*\theta] \quad (10)$$

Eqs. (9) and (10) are now subject to the boundary conditions.

$$u = w = 1 + \epsilon e^{i\omega t}, \quad \theta = 1 \quad \text{at} \quad z = 0$$

$$u \rightarrow 0, \theta \rightarrow 0 \quad \text{as} \quad z \rightarrow \infty \quad (11)$$

3. METHOD OF SOLUTION

The Eqs. (9) and (10) are highly non-linear equations. Since ϵ is small ($\epsilon \ll 1$), we can advance for analytical solution of these equations, subject to the boundary conditions

(11), we use multiple parameters perturbation expansion of the form :

$$u(z, t) = u_0(z) + \epsilon u_1(z) e^{i\omega t}$$

$$\theta(z, t) = \theta_0(z) + \epsilon \theta_1(z) e^{i\omega t} \quad (12)$$

Introducing (12) in Eqs. (9)-(10) and neglecting the coefficients of $O(\epsilon^2)$, we obtain:

$$u_0'' + u_0' - M_1 u_0 = -M_1 - Gr \theta_0 \quad (13)$$

$$\theta_0'' + Pr \theta_0' - K_1 \theta_0 = -Ec Pr u_0'^2 - A^* \quad (14)$$

$$u_1'' + u_1' - K_2 u_1 = -u_0' - K_2 - Gr \theta_1 \quad (15)$$

$$\theta_1'' + Pr \theta_1' - K_3 \theta_1 = -Pr \theta_0' - 2Ec Pr u_0' u_1' - A^* \quad (16)$$

where dashes denote differentiation with respect to z .

$$K_1 = R - B^*, \quad K_2 = M_1 + i\omega \quad \text{and}$$

$$K_3 = K_1 + i\omega Pr$$

The boundary conditions (11), now transform to the following form:

$$u_0 = 1, \quad u_1 = 1, \quad \theta_0 = 1, \quad \theta_1 = 0, \quad \text{at} \quad z = 0$$

$$u_0 \rightarrow 0, \quad u_1 \rightarrow 0, \quad \theta_0 \rightarrow 0, \quad \theta_1 \rightarrow 0, \quad \text{as} \quad z \rightarrow \infty \quad (17)$$

The Eqs. (13) – (16) are coupled equations and cannot be solved under boundary conditions (17). To solve these equations, we further assume that the viscous dissipation (Eckert number Ec) is small. Hence, to obtain the velocity and temperature field, we assume:

$$u_0(z) = u_{00}(z) + Ec u_{01}(z)$$

$$\theta_0(z) = \theta_{00}(z) + Ec \theta_{01}(z)$$

$$u_1(z) = u_{10}(z) + Ec u_{11}(z)$$

$$\theta_1(z) = \theta_{10}(z) + Ec \theta_{11}(z)$$

Substituting (18) into Eqs. (13)-(16), we obtain:

$$u_{00}'' + u_{00}' - M_1 u_{00} = -M_1 - Gr \theta_{00} \quad (19)$$

$$u_{01}'' + u_{01}' - M_1 u_{01} = -Gr \theta_{01} \quad (20)$$

$$\theta_{00}'' + Pr \theta_{00}' - K_1 \theta_{00} = -A^* \quad (21)$$

$$\theta_{01}'' + Pr \theta_{01}' - K_1 \theta_{01} = -Pr u_{00}'^2 \quad (22)$$

$$u_{10}'' + u_{10}' - K_2 u_{10} = -u_{00}' - K_2 - Gr \theta_{10} \quad (23)$$

$$u''_{11} + u'_{11} - K_2 u_{11} = -u'_{01} - Gr\theta_{11} \quad (24)$$

$$\theta''_{10} + Pr\theta'_{10} - K_3\theta_{10} = -Pr\theta'_{00} - A^* \quad (25)$$

$$\theta''_{11} + Pr\theta'_{11} - K_3\theta_{11} = -Pr\theta'_{01} - 2Pr u'_{00} u'_{10} \quad (26)$$

The boundary conditions (17), transform to:

$$u_{00} = 1, u_{01} = 0, u_{10} = 1, u_{11} = 0, \theta_{00} = 1, \\ \theta_{01} = 0, \theta_{10} = 0, \theta_{11} = 0 \quad \text{at } z = 0$$

$$u'_{00} \rightarrow 0, u'_{01} \rightarrow 0, u'_{10} \rightarrow 0, u'_{11} \rightarrow 0,$$

$$\theta'_{00} \rightarrow 0, \theta'_{01} \rightarrow 0, \theta'_{10} \rightarrow 0, \theta'_{11} \rightarrow 0$$

$$\text{As } z \rightarrow \infty \quad (27)$$

Solving Eqs. (19) - (26) with boundary conditions (27) and substituting in (18) and using (12), the velocity and temperature distributions are given by:

$$\theta(z, t) = \theta_{00}(z) + Ec\theta_{01}(z) + \varepsilon[R_1(z, t) + iS_1(z, t)] \quad (28)$$

$$u(z, t) = u_{00}(z) + Ecu_{01}(z) + \varepsilon[R_2(z, t) + iS_2(z, t)] \quad (29)$$

4. SKIN-FRICTION AND HEAT TRANSFER RATE

The skin-friction (τ) at the plate $z = 0$ is given by:

$$\tau = \left(\frac{du_0}{dz}\right)_{z=0} + \varepsilon \left(\frac{du_1}{dz}\right)_{z=0} e^{i\omega t} \\ = \tau_1 + \varepsilon\tau_2 e^{i\omega t}$$

5. RESULTS AND DISCUSSION

In the present problem combined effect of radiation and non-uniform heat source on unsteady convection flow past an infinite heated vertical plate in porous medium with time dependent suction and viscous dissipation is studied. The velocity field and temperature distribution are evaluated in equations (28) and (29). The equations describing the convective flow are governed by magnetic parameter (M), Prandtl number (Pr), radiation parameter (R), permeability parameter (K), Grashof number

The heat transfer rate (Nu) at the plate $z = 0$ is given by :

$$Nu = \left(\frac{d\theta_0}{dz}\right)_{z=0} + \varepsilon \left(\frac{d\theta_1}{dz}\right)_{z=0} e^{i\omega t} \\ = Nu_1 + \varepsilon Nu_2 e^{i\omega t} \quad (31)$$

Where

$$\tau_1 = -m_2(1 - P_1 - P_2) - m_1 P_2 + \\ Ec[-m_2(P_6 - P_7 - P_8 - P_9) + m_1 P_6 - \\ 2m_1 P_7 - 2m_2 P_8 - (m_1 + m_2)P_9].$$

$$\tau_2 = -m_4(1 - P_{11} - P_{12} - P_{13} - P_{14}) - \\ m_1 P_{11} - m_2 P_{12} - m_3 P_{13} + Ec[-m_4 P_{35} - \\ 2m_1 P_{23} - 2m_2 P_{24} + m_1 P_{30} - m_2 P_{31} + \\ m_3 P_{32} - P_{36}].$$

$$Nu_1 = -m_1(1 - A^* K_1^{-1}) + Ec[-m_1(P_3 + \\ P_4 + P_5) + 2m_1 P_3 + 2m_2 P_4 + 2(m_1 + \\ m_2)P_5].$$

$$Nu_2 = m_3(P_{10} + A^* K_3^{-1}) - m_1 P_{10} \\ + Ec[-m_3 P_{33} - m_1 P_{15} \\ + 2m_1 P_{16} + 2m_2 P_{17} + P_{34}]$$

(Gr), Eckert number (Ec), space dependent heat source/sink (A^*) and temperature dependent heat source/sink (B^*). To be realistic, the values of Prandtl number (Pr) are chosen at one atmospheric pressure for air ($Pr = 0.71$), electrolyte solution ($Pr = 1.0$), water at 100°C ($Pr = 1.78$) and water at 60°C ($Pr = 3.0$). All numerical calculations are carried out for the fixed values of $n = 0.5$, $t =$

1.0 and $\varepsilon = 0.01$. The values of frequency parameter (ω), time (t) and perturbation parameter (ε) are fixed and non-zero; in all the cases, a convective flow regime in presence of variable suction velocity is considered. The values of the remaining parameters are chosen arbitrarily but do retain physical significance in real energy system applications [5]. The values of the space dependent heat source/sink parameter (A^*) and temperature dependent heat source / sink parameter (B^*) are chosen following Abel et. al. (2007). We now proceed with the discussion and results.

Fig.-1 depicts variations in the velocity field versus z for different numerical values of Prandtl number (Pr) and magnetic parameter (M) at the fixed values of $R = 2.0$, $K = 10.0$, $Gr = 14.0$, $Ec = 0.01$, $A^* = 0.3$ and $B^* = 0.3$. It is observed that the velocity increases near the plate and after attaining a maximum value it decreases asymptotically to horizontal axis. As expected, we observe a decrease in the velocity field as the Prandtl number (Pr) increases. In fact, increase in Prandtl number (Pr) decreases the temperature buoyancy effect which also leads to a decrease in the velocity boundary layer. This observation is in good agreement with in Mbeledogu and Ogulu (2007). It is also observed that an increase in magnetic parameter (M) results in a decrease in the velocity field consistent with many other studies.

Hence, hydromagnetic drag embodied in Eq. (9) retards the transient velocity. This is an important controlling mechanism in nuclear energy systems heat transfer, where momentum development can be reduced, for oscillatory

flow regimes, by enhancing the magnetic field

Fig.-2 illustrates the effect of free convection parameter (Gr) and permeability parameter (K) on velocity field versus z for fixed values of Prandtl number (Pr) and magnetic parameter (M) at the fixed values of $R = 2.0$, $M = 1.0$, $K = 10.0$, $Pr = 0.71$, $Ec = 0.01$, $A^* = 0.3$ and $B^* = 0.3$. We observe that velocity increases with increase in free convection parameter (Gr), i.e., maximum velocity corresponds to maximum free convection parameter ($Gr > 0$). Hence, buoyancy parameter (Gr) has dominant effect in escalating transient velocity [25]. Also, we note that transient velocity increases with increase in permeability parameter (K). As expected, as K increases, the bulk porous medium is lowered, which increases the momentum development of the flow regime, thereby enhancing transient velocity (Basu, at al. (2011)). It is interesting to note that in absence of buoyancy parameter, i.e., $Gr = 0.0$ the velocity decreases drastically but asymptotically as y increases. These observations are in good agreement of Mbeledogu and Ogulu (2007).

Fig.-3 shows the variation in the velocity field with respect to z for different numerical values of space dependent heat source/sink (A^*) and temperature dependent heat source/sink (B^*) at the fixed values for $R = 2.0$, $M = 1.0$, $Pr = 0.71$, $Ec = 0.01$, $Gr = 14.0$ and $K = 10.0$, where $A^* > 0$ and $B^* > 0$ corresponds to internal heat generation, i.e. heat source while $A^* < 0$ and $B^* < 0$ correspond to internal heat absorption, i.e., heat sink.

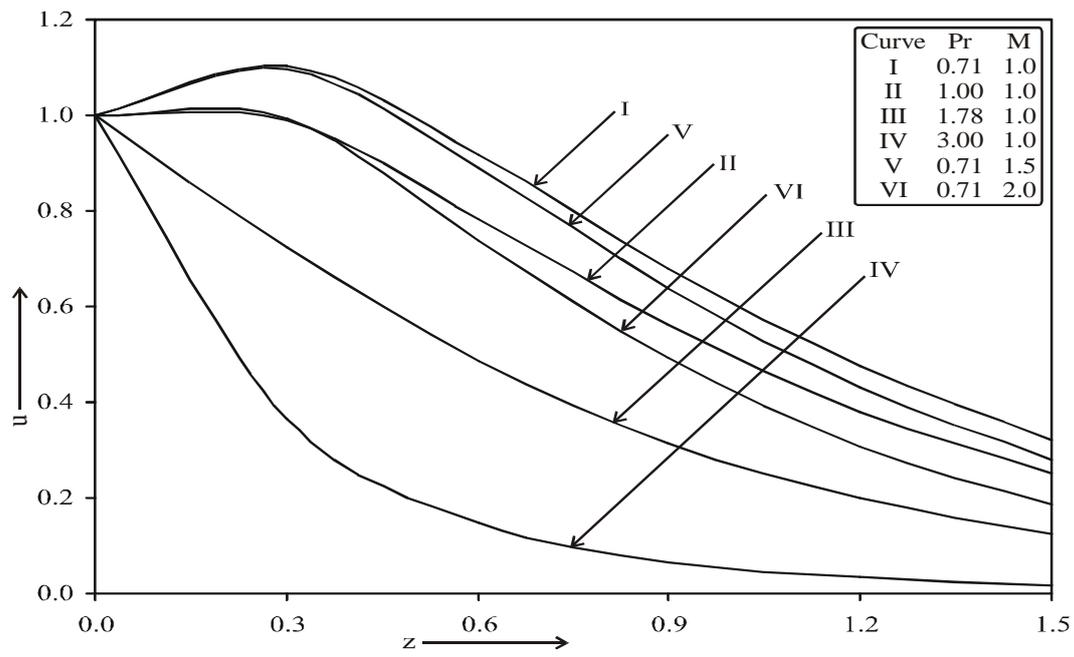


Fig-1: Effect of Pr and M on velocity field at $K = 10.0$, $Gr = 14.0$, $Ec = 0.01$, $R = 2.0$, $A^* = 0.3$ and $B^* = 0.3$

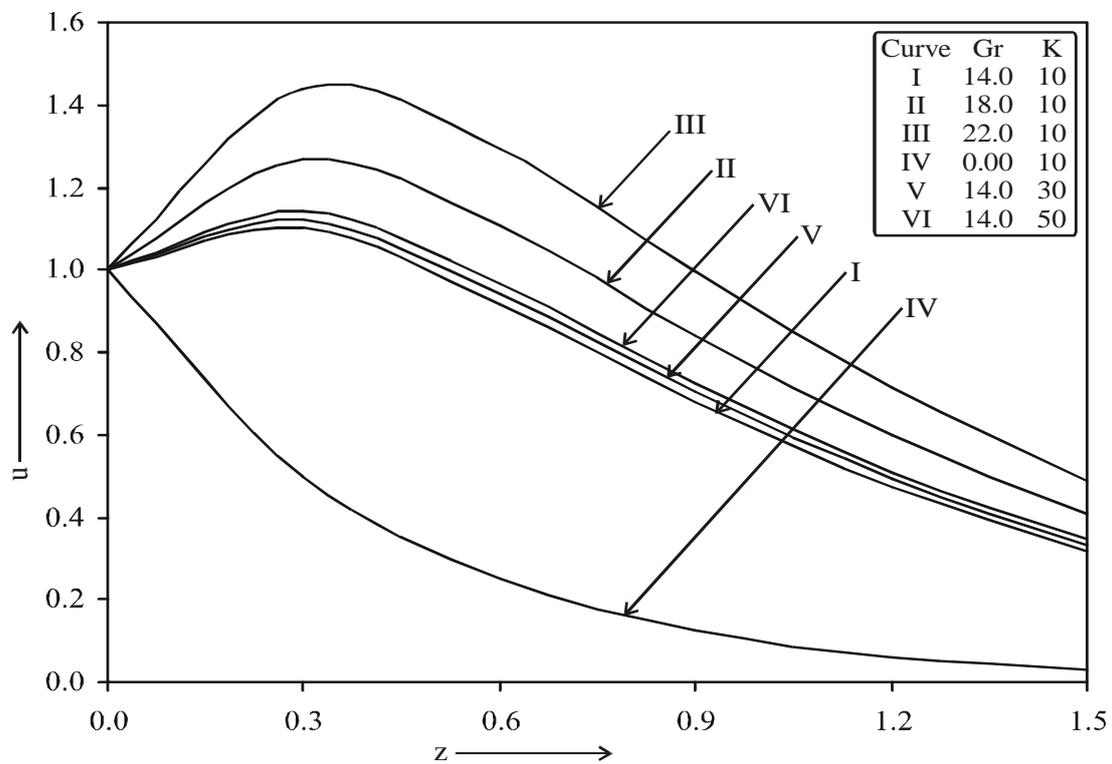


Fig-2: Effect of Gr and K on velocity field at $M = 1.0$, $Pr = 0.71$, $Ec = 0.01$, $R = 2.0$, $A^* = 0.3$ and $B^* = 0.3$

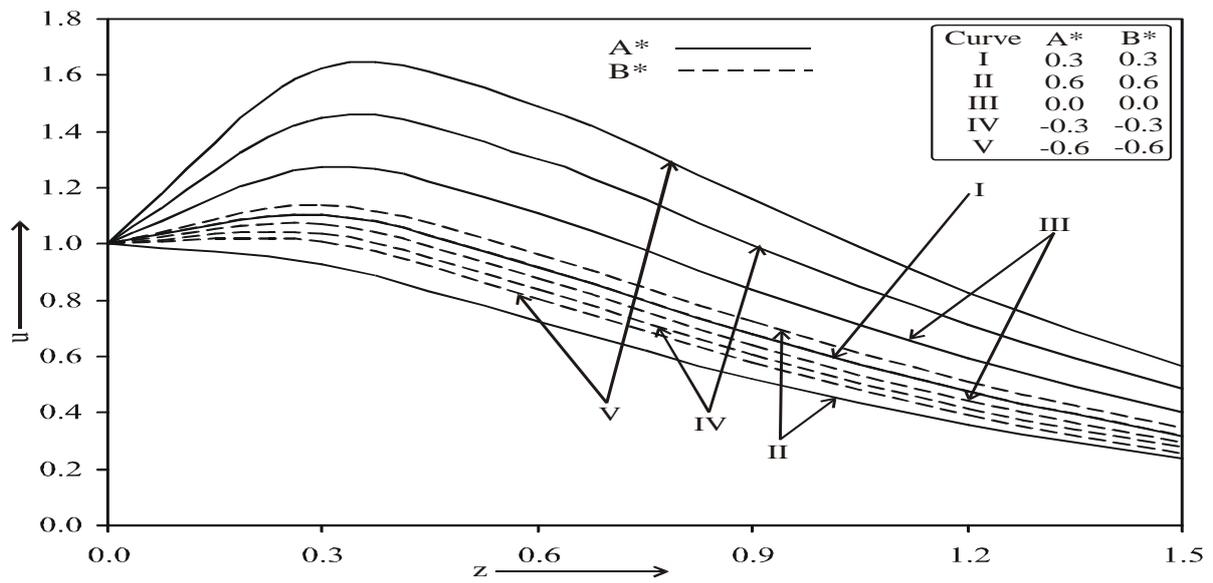


Fig-3: Effect of A^* and B^* on velocity field at $K = 10.0$, $M = 1.0$, $Gr = 14.0$, $Pr = 0.71$, $Ec = 0.01$ and $R = 2.0$

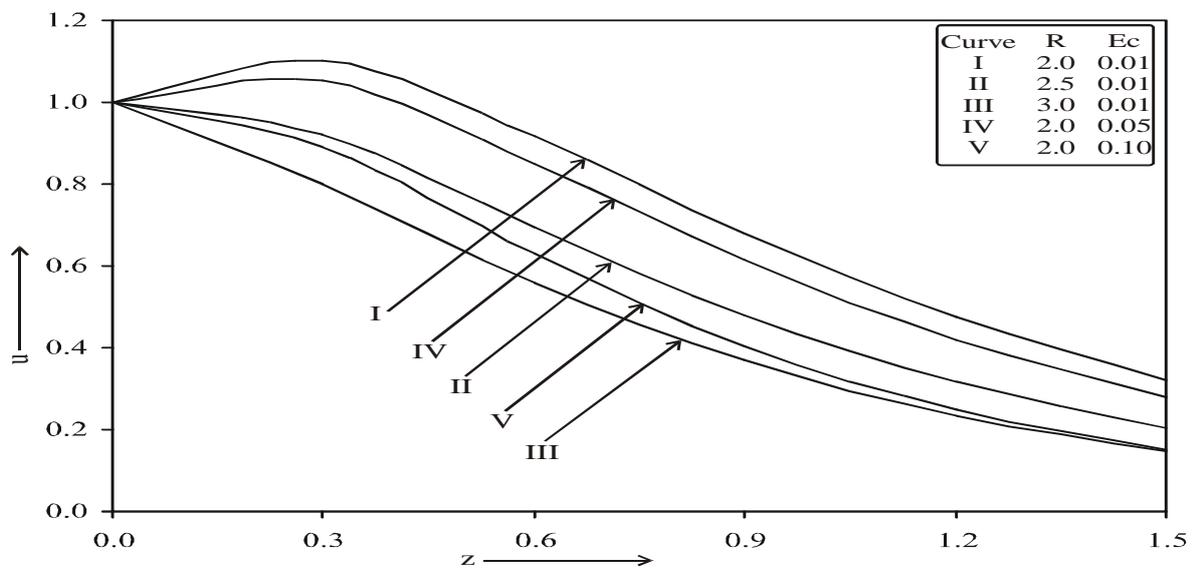


Fig-4: Effect of R and Ec on velocity field at $K = 10.0$, $Gr = 14.0$, $Pr = 0.71$, $M = 1.0$, $A^* = 0.3$ and $B^* = 0.3$

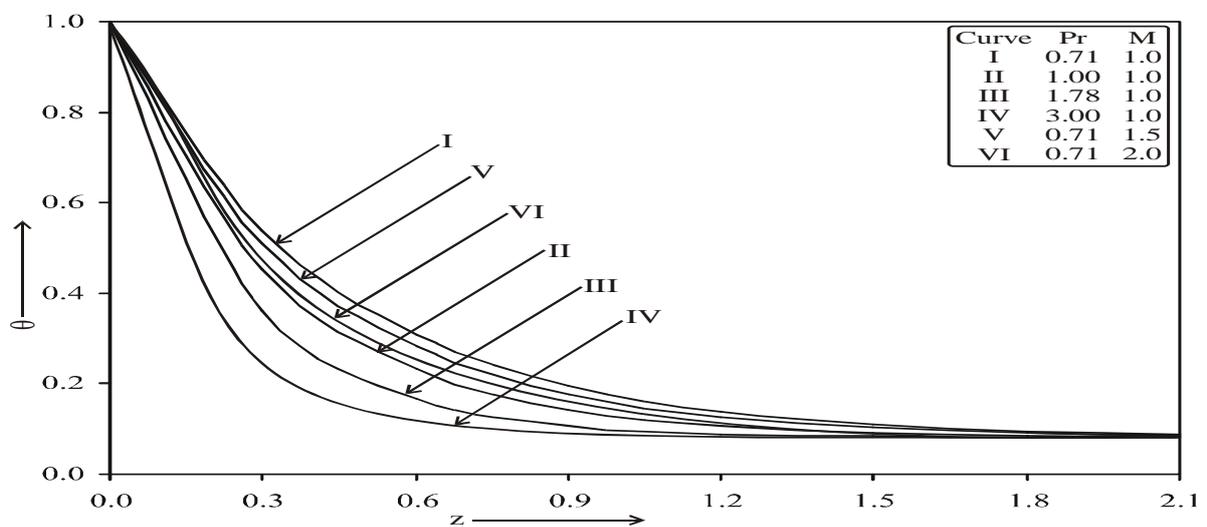


Fig-5: Effect of Pr and M on temperature field at $K = 10.0$, $Gr = 14.0$, $Ec = 0.01$, $R = 2.0$, $A^* = 0.3$ and $B^* = 0.3$

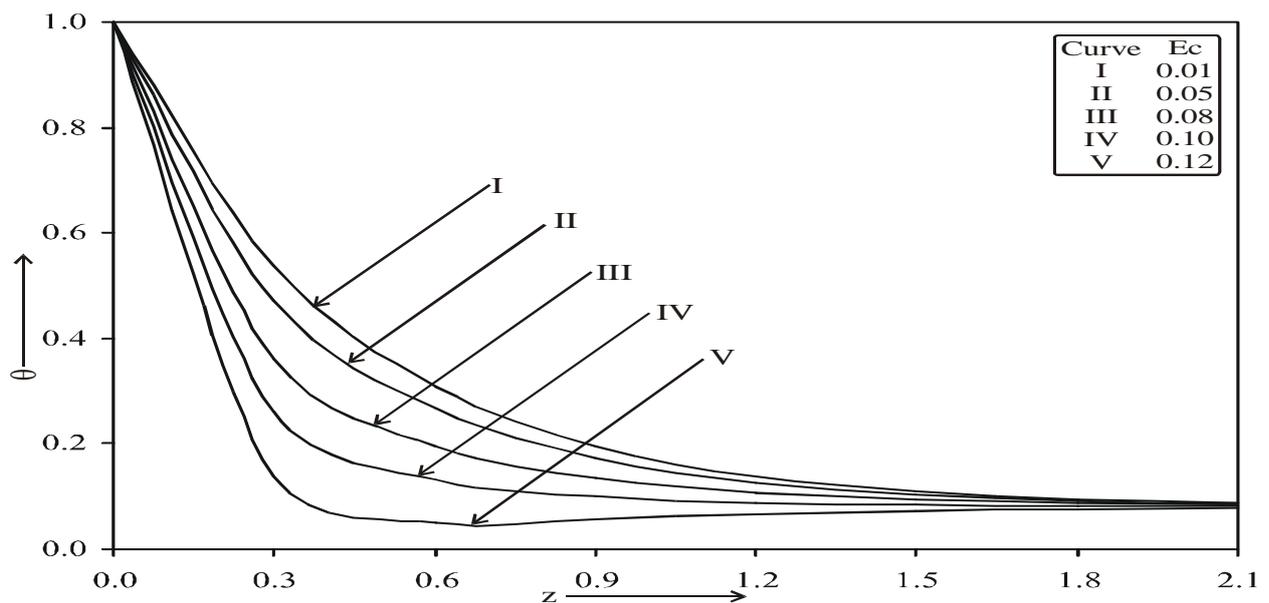


Fig-6: Effect of Ec on temperature field at $K = 10.0$, $R = 2.0$, $Gr = 14.0$, $Pr = 0.71$, $M = 1.0$, $A^* = 0.3$ and $B^* = 0.3$

It is noted that an increase in space dependent heat source ($A^* > 0$) and temperature dependent heat source ($B^* > 0$) parameters decreases the velocity field while an increase in space dependent heat sink ($A^* < 0$) and temperature dependent heat sink ($B^* < 0$) parameters enhances the velocity field. The curve III shows the variation in the velocity field in absence of non-uniform heat source or sink. These results are in good agreement with those of Abel et. al. (2007). Fig.-4 demonstrates the variations in the dimensionless velocity field versus z for different numerical values of radiation parameter (R) and Eckert number (Ec) at the fixed values of $Pr = 0.71$, $K = 10.0$, $Gr = 14.0$, $M = 1.0$, $A^* = 0.3$ and $B^* = 0.3$. It is observed that an increase in radiation parameter or Eckert number decreases the velocity and velocity boundary layer. These results are in excellent agreement with Cogley et. al (1968).

Fig.-5 expresses the variations in temperature field versus z for different numerical values of Prandtl number (Pr) and magnetic parameter (M) at the fixed values of $R = 2.0$, $K = 10.0$, $Gr = 14.0$, $Ec = 0.01$, $A^* = 0.3$ and $B^* = 0.3$. It is observed that a decrease in temperature and temperature

boundary layer exists with increase in Prandtl number and magnetic parameter. It is clear from the curve that the temperature of water at 60°C is more stable in comparison to water at 100°C

Fig.-6 indicates the effect of Eckert number (Ec) on temperature field versus z for fixed values $R = 2.0$, $M = 1.0$, $K = 10.0$, $Pr = 0.71$, $Gr = 14.0$, $A^* = 0.3$ and $B^* = 0.3$. It is clear that the temperature of the fluid uniformly decreases as Eckert number increases.

The variation in the space dependent heat source/sink (A^*) parameter on temperature distribution versus z at $R = 2.0$, $M = 1.0$, $K = 10.0$, $Pr = 0.71$, $Ec = 0.01$, $Gr = 14.0$ and $B^* = 0.3$. For $A^* > 0$ corresponds to internal heat generation, i.e. heat source while $A^* < 0$ correspond to internal heat absorption, i.e., heat sink. It is noted that an increase in space dependent heat source ($A^* > 0$) parameter increases the temperature and temperature boundary layer while reverse effect is noted for an increase in space dependent heat sink ($A^* < 0$) parameter. The curve III shows the variation in the temperature field in absence of non-uniform space dependent heat source or sink. In fact $A^* > 0$

implies that the thermal boundary layer generates the energy, which causes the temperature of the fluid to increase with increase in $A^* > 0$ (heat source) whereas for $A^* < 0$ (heat absorption) the temperature decrease with increase in the value of $A^* < 0$.

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