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Convective flow past an accelerated porous plate in rotating system in presence of magnetic field

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ABSTRACT

Investigation on hydromagnetic convective flow of an incompressible homogeneous viscous liquid over an accelerated porous plate with suction/injection is presented using Laplace transform technique. The whole system is in a state of solid body rotation with constant angular velocity about z'-axis normal to the plate. The boundary conditions of the problem are of physical significance and thus the problem may have some important and interesting characteristic features of hydromagnetic spin up flows. The effects of suction/injection parameter on the velocity field and of Prandtl number on temperature field are graphically shown.

1. Introduction

The study of convective flow through porous media in rotating system is of immense importance and continuing interest due to their applications in many industrial, geothermal, geophysical, technological and engineering applications. Such a study is important in the design of turbines and turbo mechanics, in estimating the flight path of rotating wheels and spin-stabilized missiles. In addition, such flows are of significance importance to petroleum engineers to observe the movement of oil and gas through the reservoir; to the hydrologists to study the migration of underground water and to aero-dynamists to control drag in aero-dynamical problems. Also rotating heat exchangers are extensively used by the chemical and automobile industries.

Early investigations of flow and heat transfer in rotating system are given by Hickman [1], Sparrow and Gregg [2] and Hartnett [3]. The influence of the Prandtl number on the heat transfer on rotating non-isothermal disks and cones was investigated by Hartnett and Deland [4]. The effect of the axial magnetic field on the flow and heat transfer over a rotating disk was considered by Sparrow and Cess [5]. Kreith [6] investigated the flow and heat transfer in rotating systems considering various physical situations.

Greenspan [7] has introduced pioneer work on the theory of rotating fluids. Thornely [8] theoretically investigated Stokes and Rayleigh layers in rotating systems while Gupta [9] obtained an exact solution of three-dimensional Navier Stokes steady state equations for the flow past a plate with uniform suction/injection in rotating system. Debnath [10,11] has studied magnetohydrodynamic boundary layer flow and hydromagnetic boundary layer flow induced by tortional oscillations of a disk, respectively. In addition, Debnath and Mukherjee [12] have presented an analysis on unsteady multiple boundary layers on a porous plate in rotating system considering elliptic harmonic oscillations of the plate. Kishore et al. [13] have reviewed the problem of Debnath and Mukherjee [12] under different boundary conditions wherein the plate is accelerated with a time dependent oscillatory velocity while Kumar and Varshney [14] have extended the problem of Kishore et al. [13] for the fluid saturated porous medium under the same boundary conditions.

Tarek et al. [15] have obtained an asymptotic solution of the flow problem over a rotating disk with a weak axial magnetic field. Bestman and Adjepong [16] studied the unsteady hydromagnetic free convective flow with radiative heat transfer in a rotating liquid but did not consider the effect of heat sink/source, which is of great relevance to astrophysical and aerospace studies. Recently, Chamkha [17] investigated unsteady convective heat and mass transfer past a semi-infinite permeable moving plate with heat absorption, where it was found that increase in solutal Grashof number enhanced the concentration buoyancy effects leading to an increase in the velocity. In another recent study Ibrahim et al. [18] investigated unsteady magnetic hydromagnetic micropolar fluid flow and heat transfer over a vertical porous plate through a porous medium in the presence of thermal and mass diffusion with a constant heat source. More recently, Mbelodogu and Ogulu [19] have obtained analytical closed-form solution of the unsteady hydromagnetic natural convection heat and mass transfer flow of a rotating incompressible fluid.

The object of the present investigations is to discuss convective flow of an incompressible viscous fluid past an accelerated

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Nomenclature

B_0	constant magnetic field
C_p	specific heat at constant pressure (W m^{-1} K^{-1})
E	rotation parameter
g	acceleration due to gravity (m s^{-2})
H	non-dimensional heat source
K'_T	thermal conductivity (W m^{-1}K)
M	magnetic parameter
Pr	Prandtl number
Q'_0	Constant heat source (W m^{-2})
S	non-dimensional suction/injection parameter
t	non-dimensional time
T	non-dimensional temperature
t'	time (s)
T'	temperature (°C)
T'_w	temperature at the porous plate (°C)
T'_∞	temperature of the fluid far away from the plate (°C)
u, v, w	velocity component in x, y, z directions
u', v', w'	velocity component in x', y', z' directions (m s^{-1})
w'_0	suction velocity (m s^{-1})
x', y', z'	coordinate system (m)
x, y, z	non-dimensional coordinate system

Greak symbols

Ω	uniform angular velocity (m s^{-1})
σ	electrical conductivity of the liquid
ϑ	kinematic viscosity coefficient (m^2 s^{-1})
ρ	density (kg m^{-3})

oscillating porous plate embedded in a highly porous medium subjected to uniform suction/injection under the influence of uniform magnetic field of low magnetic Reynolds number applied normal to the flow region. It is considered that the whole system is in the state of a rigid body rotation normal to the plate. The solutions for velocity and temperature fields are obtained in terms of complementary error function [Mclachlan [20]] and discussed with the help of graphs. Since the rotation increases magnitude of the secondary flow and the magnetic field decreases it, the magnetic field plays an important role in retarding the growth of the secondary flow as well as in reducing the heat transfer rate.

2. Formulation of the problem

In Cartesian coordinate system (x', y', z'), we consider unsteady laminar, non-dissipative, incompressible boundary layer heat transfer by convective axisymmetric flow of an electrically conducting and heat generating or absorbing fluid past an accelerated oscillating porous plate in porous medium. The x'-axis and y'-axis are in the plane of the plate and z'-axis normal to it with velocity component (u', v', w') in these directions, respectively. The whole system is in a rigid body rotation about z'-axis, i.e., normal to the plate with uniform angular velocity Ω. Initially, when time $t' \leqslant 0$, the plate and the fluid are at rest and at the same temperature T'_∞. At time $t' > 0$, the plate is accelerated with a velocity $Kt'^m e^{i\omega' t'}$, such that a non-tortional oscillation of a given frequency ω' is imposed on the plate for generation of unsteady flow and the temperature of the plate is instantaneously raised to T'_w and thereafter maintained constant so that the temperature T'_w is independent with the distance x. Since uniform suction is normal and acts towards the plate, $w' = -w_0$ so that $w_0 > 0$ for suction and $w_0 < 0$ for injection. A uniform magnetic field of strength B_0 is applied in the z'-direction (normal direction). The magnetic Reynold number ($Re_m = \mu_e \sigma VL << 1$, where μ_e and σ are the magnetic permeability and the electrical conductivity and V, L are the characteristic velocity and length, respectively) is assumed to be small so that the induced magnetic field is negligible in comparison to the applied magnetic field. Since there is no applied or polarization voltage imposed on the flow field, the electric field $\vec{E} = \vec{0}$, hence Maxwells' equations are uncoupled from the Navier–Stokes equations [Cramer and Pai [21]] and the only contribution of the magnetic field is the Lorentz force in the absence of Hall effect.

Under the present configuration and ignoring Boussinesq approximation, the equations governing the flow are:

Momentum equations:

$$\frac{\partial u'}{\partial t'} - w'_0 \frac{\partial u'}{\partial z'} - 2\Omega v' = \vartheta \frac{\partial^2 u'}{\partial z'^2} - \frac{\vartheta}{k'} u' - \frac{\sigma B_0^2}{\rho} u' \tag{1}$$

$$\frac{\partial v'}{\partial t'} - w'_0 \frac{\partial v'}{\partial z'} + 2\Omega u' = \vartheta \frac{\partial^2 v'}{\partial z'^2} - \frac{\vartheta}{k'} v' - \frac{\sigma B_0^2}{\rho} v' \tag{2}$$

Energy equation:

$$\frac{\partial T'}{\partial t'} - w'_0 \frac{\partial T'}{\partial z'} = \frac{K'_T}{\rho C_p} \frac{\partial^2 T'}{\partial z'^2} - \frac{Q'_0}{\rho C_p} (T' - T'_\infty) \tag{3}$$

The initial and boundary conditions relevant to the problem are:

$$\begin{aligned} t' \le 0: &\quad u' = 0, \quad v' = 0, \quad T' = T'_\infty \quad \text{for all } z' \\ t' > 0: &\quad u' = U_0 t'^m (1 + \in e^{i\omega' t'}), \\ &\quad v' = 0, \quad T' = T'_w \quad \text{at} \quad z' = 0 \\ &\quad u' \to 0, \quad v' \to 0, \quad T' \to T'_\infty \quad \text{as} \quad z \to \infty \end{aligned} \tag{4}$$

We now introduce the following non-dimensional quantities:

$$u = \frac{u'}{U_0} \quad v = \frac{v'}{U_0}, \quad z = \frac{z' U_0}{\vartheta}, \quad t = \Omega t', \quad \omega = \frac{\omega'}{\Omega},$$

$$M_1 = M + k'K = \Omega^{-m}, \quad T = \frac{T' - T'_\infty}{T'_w - T'_\infty}$$

Introducing above mentioned non-dimensional quantities and using $q = u + iv$, the Eqs. (1)–(3) transform to following form:

$$\frac{\partial^2 q}{\partial z^2} + S \frac{\partial q}{\partial z} - (M_1 + iE) q = \frac{E}{2} \frac{\partial q}{\partial t} \tag{5}$$

$$Pr \frac{E}{2} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial z^2} + PrS \frac{\partial T}{\partial z} - \frac{HEPr}{2} T \tag{6}$$

The non-dimensional initial and boundary conditions (4) transform to:

$$\begin{aligned} t \le 0: &\quad q = 0, \quad T = 0 \quad \text{for all} \quad z \\ t > 0: &\quad q = K e^{iwt} t^m, \quad T = 1 \quad \text{at } z = 0 \\ &\quad q \to 0, \quad T \to 0 \quad \text{as } z \to \infty. \end{aligned} \tag{7}$$

Where

$$S = \frac{w'_0}{U_0} (\text{Suction parameter}), \quad E = \frac{2\Omega\vartheta}{U_0^2} (\text{Rotation parameter}),$$

$$H = \frac{Q'_0}{\rho C_p \Omega} (\text{Heat sink parameter}), \quad Pr = \frac{\mu C_p}{K'_T} (\text{Prandtl number}) \quad \text{and}$$

$$M = \frac{B_0}{U_0} \sqrt{\frac{\sigma\vartheta}{\rho}} (\text{Magnetic parameter})$$

3. Solution of the problem

Laplace transform of Eqs. (5), (6) yield:

$$\frac{d^2\bar{q}}{dz^2}+S\frac{d\bar{q}}{dz}-\left(iE+M_1+\frac{pE}{2}\right)\bar{q}=0 \quad (8)$$

$$\frac{d^2\overline{T}}{dz^2}+SPr\frac{d\overline{T}}{dz}-\left(\frac{HEPr}{2}+\frac{pEPr}{2}\right)\overline{T}=0 \quad (9)$$

where $\bar{q}(z,p)=\int_0^\infty e^{-pt}q(z,t)dt$ and $\overline{T}(z,p)=\int_0^\infty e^{-pt}T(z,t)dt$.

Laplace transform of boundary conditions (7) yield:

$$\bar{q}(z,p)=\frac{K\sqrt{(m+1)}}{(p-iw)^{m+1}},\quad \overline{T}=\frac{1}{p}\quad \text{at } z=0$$
$$\bar{q}(z,p)=0,\quad \overline{T}=0\quad \text{as } z\to\infty \quad (10)$$

Solutions of (4) and (5) satisfying the boundary conditions (10) are:

$$\bar{q}(z,p)=\frac{K\sqrt{(m+1)}}{(p-iw)^{m+1}}exp\left[\frac{-zS}{2}-z\sqrt{\frac{E}{2}}\left(p+\frac{S^2+4iE+4M_1}{2E}\right)^{1/2}\right] \quad (11)$$

$$\overline{T}(z,p)=\frac{1}{p}exp\left[\frac{-zSPr}{2}-z\sqrt{\frac{EPr}{2}}\left(p+\frac{S^2Pr^2+2HEPr}{2HEPr}\right)^{1/2}\right] \quad (12)$$

Inverting Eq. (11) by Fourier–Mellin inversion integral, we obtain:

$$q(z,t)=K\sqrt{(m+1)}exp\left(-\frac{zS}{2}\right)\frac{1}{2\pi i}\times\int_{\lambda-i\infty}^{\lambda+i\infty}exp\left[pt-z\sqrt{\frac{E}{2}\left(p+\frac{S^2+4(iE+M_1)}{2E}\right)}\right]\frac{dp}{(p-i\omega)^{m+1}} \quad (13)$$

Introducing $X=z\sqrt{\frac{E}{2}}$, $X_1=\sqrt{p+\frac{S^2+4(M_1+iE)}{2E}}$ and $\alpha=i\omega+\frac{S^2+4(M_1+iE)}{2E}$ in (13) we obtain:

$$q(z,t)=K\sqrt{(m+1)}exp\left(-\frac{zS}{2}\right)F(X_1,\alpha,m) \quad (14)$$

where $F(X_1,t,\alpha,m)=\frac{1}{2\pi i}\int_{Br_2}exp\left[\left\{X_1^2-\frac{S^2+4(M_1+iE)}{2E}\right\}t-XX_1\right]\frac{2X_1}{(X_1^2-\alpha)^{m+1}}dX_1$ and the path Br_2 is Bromwich path defined in Mclachlan [20].

To obtain the value of $F(X_1,t,\alpha,m)$ for different values of m, let

$$G(\alpha)=F(X_1,\alpha,0)=\frac{1}{2\pi i}\int_{Br_2}exp\left[\left\{X_1^2-\frac{S^2+4(M_1+iE)}{2E}\right\}t-XX_1\right]\times\frac{2X_1}{\left(X_1^2-\alpha\right)}dX_1 \quad (15)$$

Differentiating (15) with respect to α, we get:

$$F(X_1,t,\alpha,1)=\frac{dG(\alpha)}{d\alpha}+tG(\alpha)=\frac{d}{d\alpha}[F(X_1,t,\alpha,0)]+tF(X_1,t,\alpha,0) \quad (16)$$

Differentiating (16) successively $(m-1)$ times with respect to α, we get:

$$F(X_1,t,\alpha,m)=\frac{d}{d\alpha}[F(X_1,t,\alpha,m-1)]+tF(X_1,t,\alpha,m-1) \quad (17)$$

which gives $F(X_1,t,\alpha,m)$ for different integral values of m.

Using Mclachlan [20], (15) yields:

$$F(X_1,t,\alpha,0)=\frac{1}{2}exp(i\omega t)\left[exp(X_1\sqrt{\alpha})erfc\left(\frac{X_1}{2\sqrt{t}}+\sqrt{\alpha t}\right)\right]+\frac{1}{2}exp(i\omega t)\left[exp(-X_1\sqrt{\alpha})erfc\left(\frac{X_1}{2\sqrt{t}}-\sqrt{\alpha t}\right)\right] \quad (18)$$

Introducing (18) in (16), we obtain:

$$F(X_1,t,\alpha,1)=\frac{1}{2}exp(i\omega t)\left[exp(X_1\sqrt{\alpha})erfc\left(\frac{X_1}{2\sqrt{t}}+\sqrt{\alpha t}\right)\left(\frac{X_1}{2\sqrt{\alpha}}+1\right)\right]+\frac{1}{2}exp(i\omega t)\left[exp(-X_1\sqrt{\alpha})erfc\left(\frac{X_1}{2\sqrt{t}}-\sqrt{\alpha t}\right)\left(\frac{X_1}{2\sqrt{\alpha}}-1\right)\right] \quad (19)$$

Similarly we can obtain $F(X_1,t,\alpha,2)$ and in general $F(X_1,t,\alpha,m)$.

Using Mclachlan [20], the inverse Laplace transform of (12) in terms of complementary error function is:

$$T(z,t)=G(Z_1,Z_2,Z_3,Z_4) \quad (20)$$

where $G(Z_1,Z_2,Z_3,Z_4)=exp\left(\frac{-zSPr}{2}\right)\left[\frac{1}{2}exp(Z_1\sqrt{Z_2Z_3})erfc\left(\frac{Z_1Z_2}{2\sqrt{Z_4}}+\sqrt{Z_3Z_4}\right)+\frac{1}{2}exp(-Z_1\sqrt{Z_2Z_3})erfc\left(\frac{Z_1Z_2}{2\sqrt{Z_4}}-\sqrt{Z_3Z_4}\right)\right]$

$$Z_1=z\sqrt{\frac{EP_r}{2}},\quad Z_2=1,\quad Z_3=\frac{S^2Pr^2+2HE}{2HE}\quad \text{and}\quad Z_4=t$$

4. Discussion and conclusions

The problem of convective heat transfer to unsteady hydromagnetic flow involving heat source/sink past a porous plate in rotating system is addressed in this study. Solution of the equation of complex velocity (5) is obtained by the use of Laplace transform followed by Fourier–Mellin integral (Mclachlan [20]), while solution of the energy Eq. (6) is obtained by Laplace and inverse Laplace transform technique. Numerical calculations have been carried out for variations in non-dimensional complex velocity and temperature distribution due to change in any one parameter for fixed values of the remaining parameters. The effects of magnetic parameter (M), rotation parameter (E), suction–injection parameter (S) and permeability parameter (k) are observed on complex velocity and also the effects of rotation parameter (E), heat source/sink parameter (H), suction/injection parameter (S) and Prandtl number (Pr) are noted on temperature distribution. Since the solution obtained for velocity is complex, only the real part of the complex quantity is invoked for numerical discussion following Abramovitz and Stegun [22]. Values of the frequency of oscillation (ω) and time (t) are fixed and non-zero; so in all cases, a non-tortional oscillation of a given frequency imposed on the accelerated porous plate is studied throughout the flow regime. To be realistic, the numerical values of Prandtl number (Pr) are chosen to be $Pr = 0.71$, $Pr = 7.0$ and $Pr = 11.4$, which, respectively, correspond to air, water at 20 °C and water at 4 °C and one atmospheric pressure. The numerical values of the remaining parameters, although chosen arbitrarily, are in agreement with the researchers of the field. In rotating system, the fluid near the axis of rotation is forced outward in the vertical direction due to the action of the centrifugal force. The fluid is then replaced by the fluid moving in the axial direction. Thus the axial velocity in rotating system is more than that in stationary system. This increase in the axial velocity enhances the convective heat transfer. As such, this principle has been used to develop practical systems for increasing heat transfer, e.g., the utility of rotating condensers for two sea-water distillation and space-craft power plants in a zero-gravity environment [Hickman [1], Sparrow and Cess [5]].

Fig. 1 illustrates variations in the representative velocity profiles versus z for various values of suction ($S > 0$) and injection ($S < 0$) parameter in the range ($-2.0 \leqslant S \leqslant 2.0$) for fixed values of $M = 0.0$, $E = 0.0$, $K = 10$, $T = 1.0$ and $\omega = 1.0$. The curve I represents velocity for no suction, i.e., when $S = 0.0$. As suction is increased from $S = 0$ to $S = 2.0$ (curve I, curve III) via $S = 1.0$ (curve I), the velocity is decreased, but as injection is increased from $S = 0.0$ to

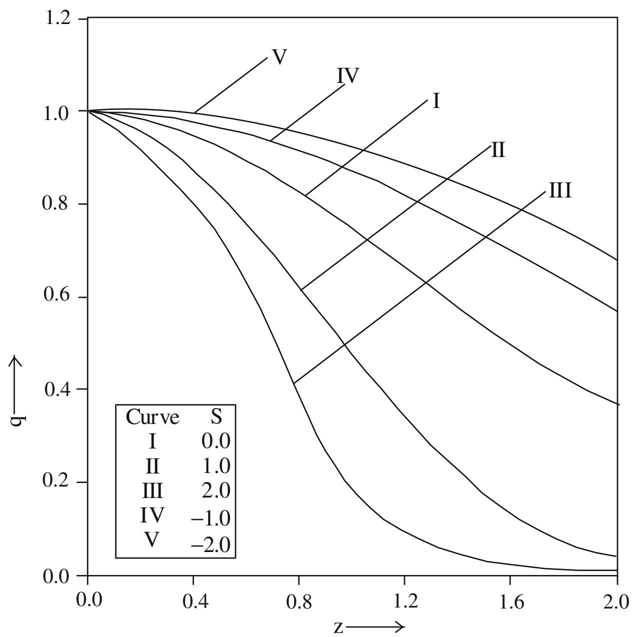

Fig. 1. Velocity profiles showing the effect of suction/injection.

$S = -2.0$ (curve I, curve V) via $S = -1.0$ (curve IV), the velocity is increased. A decreasing trend in the velocity occurs as z increases. Hence, suction/injection has dominant effect in controlling the velocity. This result is consistent with the study of Debnath [10,11].

Fig. 2 depicts variations in velocity versus distance z for various values of magnetic parameter (M) in the range ($0.0 \leqslant M \leqslant 1.5$) for $S = 0.0$, $E = 0.0$, $K = 10$, $T = 1.0$ and $\omega = 1.0$ fixed values. Curve I shows the representative velocity profile for $M = 0$, i.e., when no magnetic field is present. As M is increased from $M = 0$ to $M = 1.5$ (curve I, curve III), the velocity decreases. Since there is no applied or polarization voltage imposed on the flow field, the only contribution of the magnetic field is the Lorentz force in the absence of Hall effect. Hence, the hydromagnetic drag, embodied in the term $-M_1Q$ in Eq. (5), retards the velocity, consistent with many other studies [Tarek et al. [15]].

Fig. 3 shows variations in velocity versus z-coordinate for various values of rotation parameter (E) in the range ($0.0 \leqslant E \leqslant 3.0$) for fixed values of $S = 0.0$, $M = 0.0$, $K = 10$, $T = 1.0$ and $\omega = 1.0$. Curve I represents the velocity when there is no rotation. As E is increased from $E = 0$ to $E = 3.0$ (curve I, curve IV) through $E = 1.0$ and $E = 2.0$ (curve II, curve III), the velocity is increased rising from $z = 0$ to a peak approximately at $z = 0.5$, and then smoothly decreasing towards the z-axis. Clearly, the fluid near the surface of the plate is forced outward due to the action of the centrifugal force produced by the rotation; so that the velocity of the fluid is increased in the vicinity of the plate. This finding is in agreement with Kreith [6] and Kishore et al. [13].

In Fig. 4, the profiles for velocity versus z have been plotted for various values of permeability parameter (k) and for fixed $S = 0.0$, $E = 0.0$, $M = 0.0$, $T = 1.0$ and $\omega = 1.0$ values. Obviously, as permeability parameter (k) is increased from $K = 10$ to $K = 100$ via $K = 50$, the velocity u increases. This explains the fact that as k increases; the resistance of the porous medium is lowered, which increases the momentum development of the flow regime, which in turn enhances the velocity field.

Fig. 5 depicts the temperature distribution versus span wise coordinate z for $Pr = 0.71$ (air), $Pr = 0.025$ (mercury), $Pr = 1.0$ (electrolyte solution), $Pr = 7.0$ (water at room temperature and $Pr = 11.4$ (water at 4 °C) and one atmospheric pressure for $S = 0.0$, $E = 0.0$, $H = 0.0$, $T = 1.0$ and $\omega = 1.0$ fixed values. The temperature is observed to decrease steeply and exponentially away from the porous plate. This observation agrees with Kim [23], where it is observed that this decrease in the temperature and temperature boundary layer is accompanied with a more uniform temperature distribution across the boundary layer.

Fig. 6 represents the temperature profiles for various values of the suction ($S > 0$) and injection ($S < 0$) parameters against z ($-2.0 \leqslant S \leqslant 2.0$) for fixed values of $Pr = 0.71$, $E = 0.0$, $H = 0.0$, $T = 1.0$ and $\omega = 1.0$. Curve I represents the temperature profile when no suction/injection exists in the flow field. It is noted that suction retards the temperature (curve II, curve III), while injection increases the temperature (curve IV, curve V).

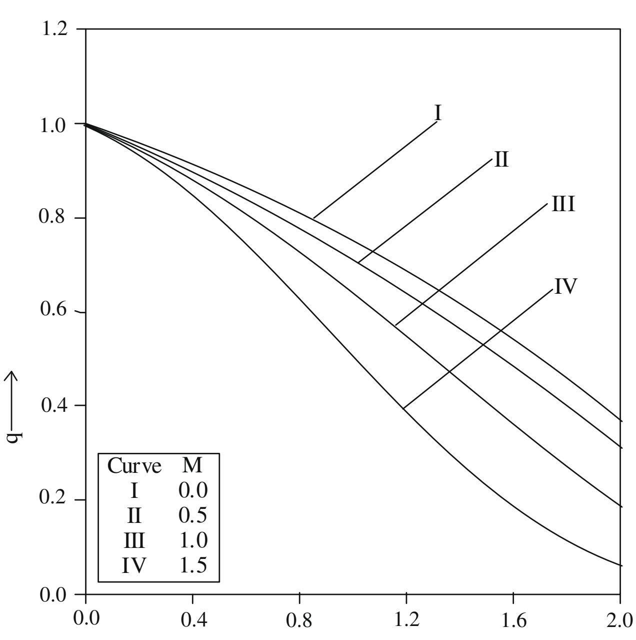

Fig. 2. Velocity profiles showing the effect of magnetic parameter.

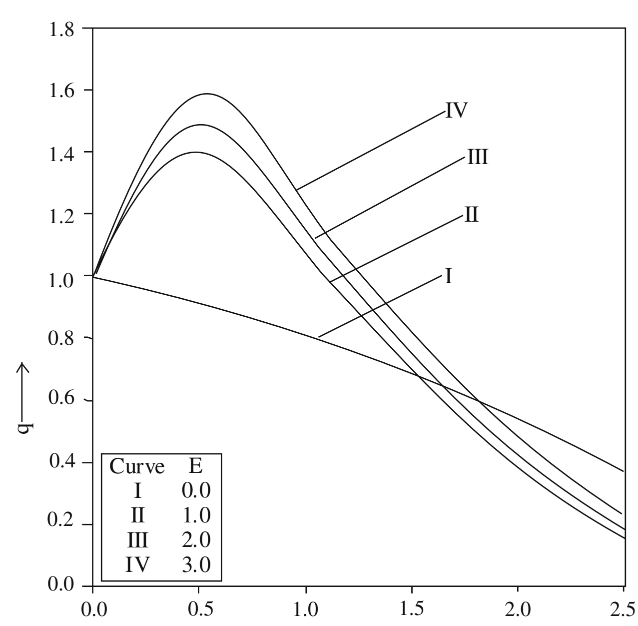

Fig. 3. Velocity profiles showing the effect of rotation parameter.

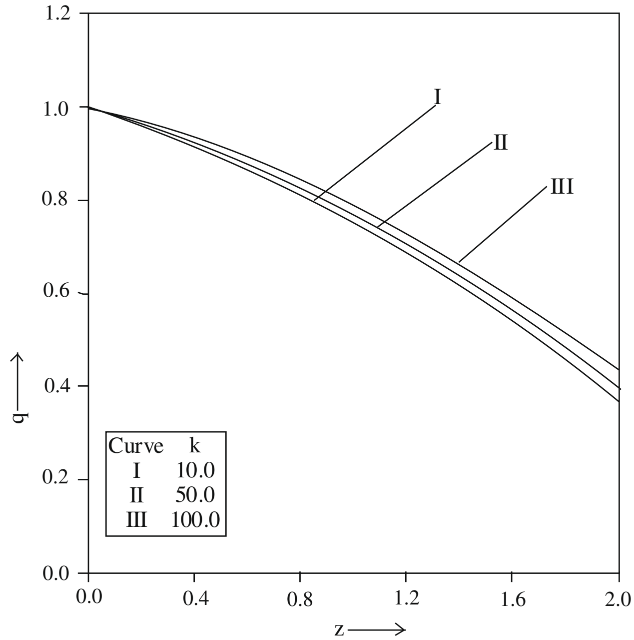

Fig. 4. Velocity profiles showing the effect of permeability parameter.

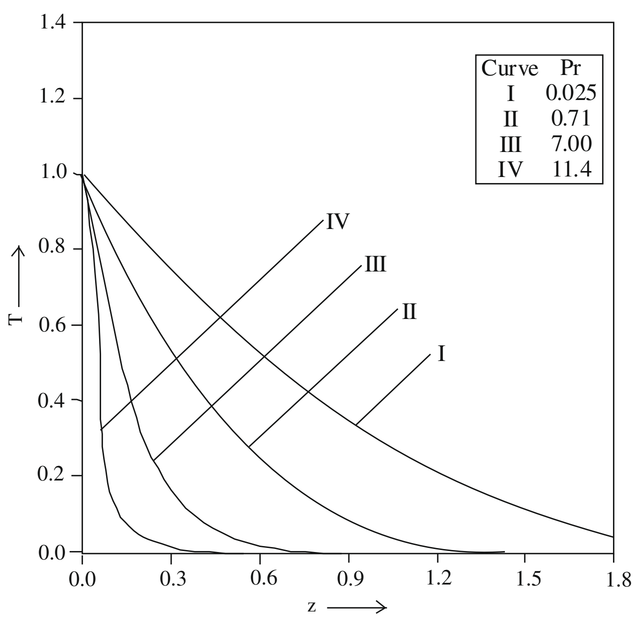

Fig. 5. Temperature field showing the effect of Prandtl number.

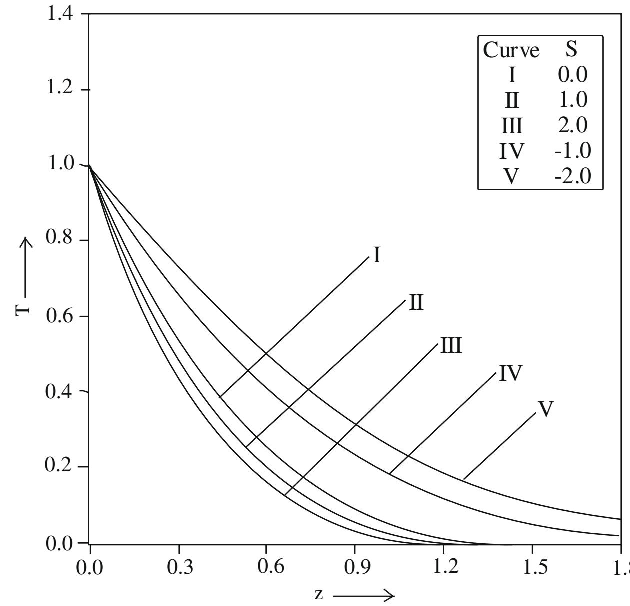

Fig. 6. Temperature field showing the effect of suction/injection parameter.

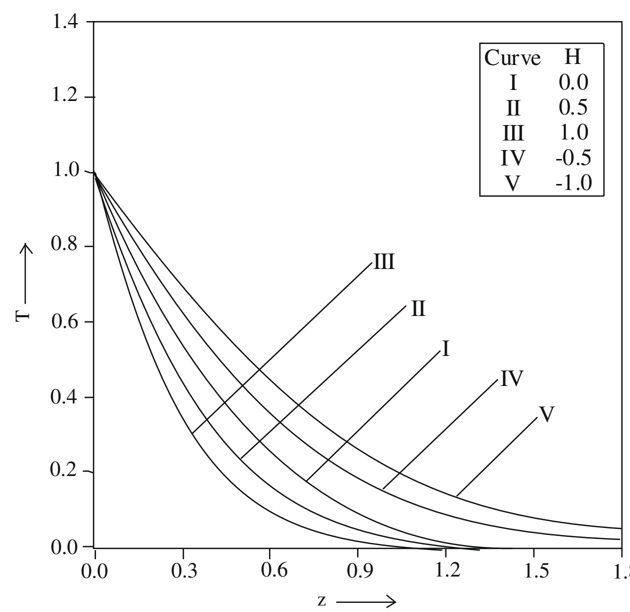

Fig. 7. Temperature field showing the effect of heat sink/source parameter.

Fig. 7 illustrates the profiles of temperature distribution for various values of heat sink ($H > 0$) and heat source ($H < 0$) parameters in the range ($-1.0 \leqslant H \leqslant 1.0$) for fixed $Pr = 0.71$, $E = 0.0$, $S = 0.0$, $T = 1.0$ and $\omega = 1.0$. Curve I shows the profile of temperature distribution in absence of heat sink/source. Heat sink (source) physically implies absorption (evolution) of heat from the surface, which decreases (increases) the temperature in the flow field. Therefore, as heat sink parameter is increased, the temperature decreases steeply and exponentially from the plate but heat source parameter enhances it.

Finally, Fig. 8 shows variations in the temperature field for various values of the rotation parameter (E) for fixed $Pr = 0.71$, $H = 0.0$, $S = 0.0$, $T = 1.0$ and $\omega = 1.0$. It is noted that as rotation is increased, the temperature is increased in the vicinity of the plate and then decreases smoothly. However, higher values of the rotation parameter decreases the temperature more rapidly in comparison to the lower values.

The conclusions of the study are as follows:

(i) An increase in suction decreases the velocity field while injection increases the velocity.
(ii) An increase in magnetic field decreases the velocity field.
(iii) An increase in rotation parameter increases the velocity.
(iv) An increase in permeability parameter increases the velocity field.
(v) An increase in Prandtl number decreases the temperature field.
(vi) An increase in rotation parameter increases the temperature field
(vii) An increase in heat sink parameter decreases the temperature field, while heat source enhance it.

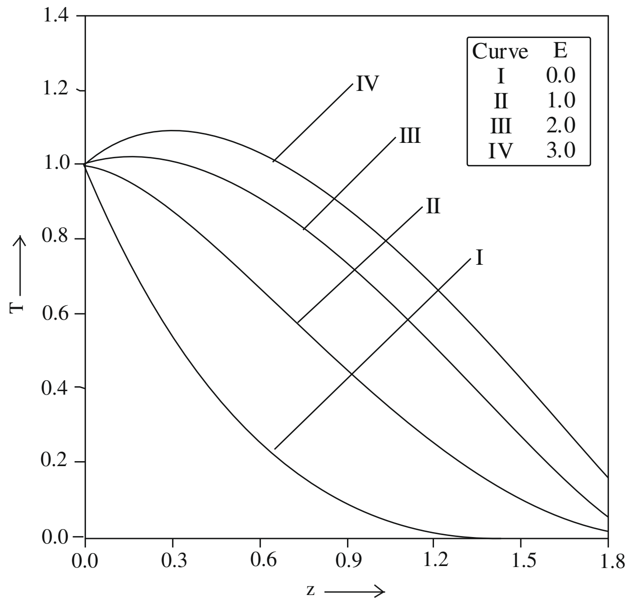

Fig. 8. Temperature field showing the effect of rotation parameter.

(viii) An increase in suction decreases the velocity field, while injection increases it.

(ix) An increase in suction parameter results in a reduction in the temperature field, while injection up lifts it.

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