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Hydromagnetic free convection flow of a viscous liquid in rotating system past an infinite plate with jump in temperature

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Abstract
Hydromagnetic free convection laminar flow of an incompressible viscous, conducting fluid through a porous medium past an isothermal porous vertical plate in rotating system with suction/injection at the plate is studied considering jump in temperature. Approximate solutions for primary and secondary velocity of the liquid and temperature field are obtained using single parameter perturbation technique. Expressions for skin-frictions due to primary and secondary velocities and rate of heat transfer are also derived. The results obtained are numerically discussed with the help of tables and graphs.

Keywords: convection, liquid, rotating, hydromagnetics, incompressible

1. Introduction

In recent years,
free convection flow through porous medium has attracted the attention of a number of researchers in view of its applications to geo-physics, astrophysics, meteorology, physiology, aerodynamics, boundary layer control and so on. In addition, convective flow through porous medium have applications in the field of engineering; for filtration and purification processes, in the field of agricultural engineering; to study the underground water resources, in petroleum industries; to study the movement of natural gases, oil and water through the reservoirs, in metal industry; to study the flow pattern of the melted solids at different temperatures. The development of aeronautical, chemical, mechanical and computer engineering during last few decades on the one hand and finding oil wells in the oceans on the other hand have added stimuli to the study of convection flow of viscous fluids.
Ahmadi and Manvi [1971] [1] derived the equation of motion of viscous flow through a rigid porous medium. Gersten and Gross [1974] [2] applied these equations to study the effects of transverse sinusoidal suction velocity on flow and heat transfer along an infinite porous wall. Raptis [1983] [3] investigated the unsteady flow through a porous medium bounded by an infinite porous plate subjected to a variable plate temperature and constant suction velocity. Raptis and Perdikis [1985] [4] further studied oscillatory flow through porous medium by presence of free convection flow.
Senger *et al*. [1987], Singh and Tripathi [1988], Agrawal [1988], Hartnett and Minkowycz [1989] [5], Jha [1991], Shrivastava [1992], Shrivastava and Sharma [1992], Kulshrestha and Singh [1993] [6], Sattar and Alam [1995], Singh *et al*. [1999] have studied free convection / mass transfer flow in rotating system under various boundary conditions. Singh *et al*. [2000] [7] have analysed MHD free convection and mass transfer flow of a dusty viscous liquid in rotating system. Recently, Singh and Singh [2004] [8] have studied free convection effects in unsteady MHD flow of an incompressible viscous fluid in a rotating system past an isothermal vertical plate under constant suction velocity. More recently, Khandewal and Jain [2005] have studied unsteady hydromagnetic flow of a stratified fluid through a porous medium over a moving plate with slip boundary condition for velocity and jump in temperature. In the present paper, an attempt is made to study hydromagnetic free convection flow in rotating system with jump in temperature. The solutions of the equations are obtained using perturbation technique. In addition, the expressions for skin-friction due to primary velocity, secondary velocity and rate of heat transfer are also derived. The results of the study are discussed with the help of graphs and tables.

2. Formulation of the problem

We consider the unsteady free convection flow of an incompressible, electrically conducting, viscous liquid through a porous medium past an infinite, vertical porous plate. A cartesian coordinate (x, y, z) system rotating uniformly with the liquid in a rigid state of rotation is considered and a constant angular velocity $(0, 0, \Omega)$ is taken into account about *z*-axis. The vertical porous plate is considered in the plane of *z*-axis is chosen normal to the plate pointing towards the flow medium. Besides, the plate is subjected to a time dependent suction velocity $v = -v_0\left(1+\varepsilon e^{-nt}\right)$ normal to the plate where w_0 and *n* are positive real numbers. In this problem we assume

$$\rho = \rho_0 e^{-\beta y}, \quad \mu = \mu_0 e^{-\beta y} \text{ and } k = k_0 e^{-\beta y} \tag{1}$$

The variable magnetic field is considered as follows:

$$B = B_0 e^{-\beta y/2} \tag{2}$$

Under the above stated restrictions and usual Boussinesq's approximation, the equations governing the flow are:

$$\frac{\partial v}{\partial y} = 0 \tag{3}$$

$$\rho\left(\frac{\partial u}{\partial t} - v\frac{\partial u}{\partial y}\right) - 2\Omega v = \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) + g\beta\rho\left(T - T_\infty\right) - \sigma\mu_e B^2 u - \frac{\mu}{k}u \tag{4}$$

$$\rho\left(\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial y}\right) + 2\Omega u = \frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right) - \sigma\mu_e B^2 v - \frac{\mu}{k}v \tag{5}$$

Now using $q = u + iv$ in the equations (4)-(5), we get :

$$\rho\left(\frac{\partial q}{\partial t} + v\frac{\partial q}{\partial y}\right) + 2i\Omega q = g\beta\rho\left(T - T_\infty\right) + \frac{\partial}{\partial y}\left(\frac{\partial q}{\partial y}\right) - \frac{\mu}{k}u - \sigma B^2 q \tag{6}$$

The energy equation is:

$$C_p\left(\frac{\partial T}{\partial t} + v\frac{\partial T}{\partial y}\right) = \frac{1}{\rho}\frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\mu}{\rho}\left(\frac{\partial q}{\partial y}\right)^2 \tag{7}$$

where g is the acceleration due to gravity, β is the volumetric coefficient of the thermal expansion, σ is the electrical conductivity of the liquid, ρ is the density of the liquid, B is the constant magnetic field, C_p is the specific heat, T is the temperature and the other symbols have their usual meaning.
The boundary conditions relevant to the problem are:

$$q = 0,\quad T = T_w + \varepsilon A\left(T_w - T_\infty\right)e^{-nt} + L_2\frac{\partial T}{\partial y} \quad \text{at} \quad y = 0$$

$$q \to 0,\ T \to 0 \quad \text{as} \quad y \to \infty \tag{8}$$

Where $L_1 = \left(\frac{2-m}{m}\right)L$ and $L_2 = \frac{(2-S)}{S}\left(\frac{1.996}{\tau+1}\right)\frac{L}{P_r}$

We introduce the following non-dimensional quantities and parameters:

$$u^* = \frac{u}{U_0},\quad v^* = \frac{v}{U_0},\quad T^* = \frac{T - T_\infty}{T_w - T_\infty},\quad y^* = \frac{v_0 y}{\vartheta},$$

$$k^* = \frac{k v_0^2}{\vartheta^2},\quad t^* = \frac{t v_0^2}{\vartheta},\quad n^* = \frac{n\vartheta}{v_0^2},\quad h = \frac{L_2 v_0}{\vartheta},$$

$S = \frac{\beta\vartheta}{v_0}$ (Stratification parameter), $M = \frac{B_0}{v_0}\sqrt{\frac{\sigma\vartheta}{\rho_0}}$ (Magnetic parameter),

$$P_r = \frac{\rho_0 \vartheta C_p}{K_0} \text{ (Prandtl number)}, \qquad E_c = \frac{U_0^2}{C_p\left(T_w - T_\infty\right)} \text{ (Eckert Number)}$$

Introducing above non-dimensional quantities and variables, the equations (1)-(4), after ignoring the stars over them, reduce to:

$$\frac{\partial q}{\partial t} - \left(1 - S + A\varepsilon e^{-nt}\right)\frac{\partial q}{\partial y} = \frac{\partial^2 q}{\partial y^2} - \left(M_1^2 + 2iE\right)q + G_r T \tag{9}$$

$$P_r \frac{\partial T}{\partial t} = \left(\frac{\partial^2 T}{\partial y^2} - S\frac{\partial T}{\partial y^2}\right) + P_r \frac{\partial T}{\partial y} + P_r A\varepsilon e^{-nt}\frac{\partial T}{\partial y} + E_c P_r \left(\frac{\partial q}{\partial y}\right)^2 \tag{10}$$

The boundary conditions (8) are transformed to:

$$q = 0, \qquad T = 1 + A\varepsilon e^{-nt} + h\frac{\partial T}{\partial y} \quad \text{at} \quad y = 0$$

$$q \to 0,\ T \to 0 \text{ as } y \to \infty \tag{11}$$

3. Solution of the Problem

In order to solve the equation (9) and (10), we assume the velocity and temperature in the neighbourhood of the plate in the following form:

$$q(y,t) = \left[1 - F_1(y)\right] + \varepsilon\left[1 - F_2(y)\right]e^{-nt}$$

$$T(y,t) = T_1(y) + \varepsilon T_2(y)e^{-nt} \tag{12}$$

Using the expressions in (12) into (9)-(10), we get the following set of equations:

$$\frac{\partial^2 F_1(y)}{\partial y^2} + (1-S)\frac{\partial F_1(y)}{\partial y} - \left(M_1^2 + 2iE\right)F_1(y) = -\left(M_1^2 + 2iE\right) + G_r T_1(y) \tag{13}$$

$$\frac{\partial^2 F_2(y)}{\partial y^2} + (1-S)\frac{\partial F_2(y)}{\partial y} - \left(M_1^2 + 2iE - n\right)F_2(y)$$

$$= -A\frac{\partial F_1(y)}{\partial y} - \left(M_1^2 + 2iE - n\right) + G_r T_2(y) \tag{14}$$

$$\frac{\partial^2 T_1(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_1(y)}{\partial y} = -E_c P_r \left(\frac{\partial F_1(y)}{\partial y}\right)^2 \tag{15}$$

$$\frac{\partial^2 T_2(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_2(y)}{\partial y} + nP_r T_2(y)$$

$$= -P_r A\left(\frac{\partial T_1(y)}{\partial y}\right) - 2E_c P_r \left(\frac{\partial F_1(y)}{\partial y}\right)\left(\frac{\partial F_2(y)}{\partial y}\right) \tag{16}$$

Using (12) in boundary conditions (11) are transformed to:

$$F_1 = F_2 = 1,\ T_1 = 1 + h\frac{\partial T_1}{\partial y},\ T_2 = A + h\frac{\partial T_2}{\partial y} \text{ at } y = 0$$

$$F_1 = F_2 = 1,\ T_1 = T_2 \to 0 \text{ as } y \to \infty \tag{17}$$

Now we assume

$$F_1(y) = F_{10}(y) + E_c F_{11}(y) \tag{18}$$

$$F_2(y) = F_{20}(y) + E_c F_{21}(y) \tag{19}$$

$$T_1(y) = T_{10}(y) + E_c T_{11}(y) \tag{20}$$

$$T_2(y) = T_{20}(y) + E_c T_{21}(y) \tag{21}$$

Introducing (18) – (21) in (13)-(16), we get:

$$\frac{\partial^2 F_{10}(y)}{\partial y^2} + (1-S)\frac{\partial F_{10}(y)}{\partial y} - M^2 F_{10}(y) = -M^2 + G_r T_{10}(y) \tag{22}$$

$$\frac{\partial^2 F_{11}(y)}{\partial y^2} + (1-S)\frac{\partial F_{11}(y)}{\partial y} - M^2 F_{11}(y) = G_r T_{11}(y) \tag{23}$$

$$\frac{\partial^2 F_{20}(y)}{\partial y^2} + (1-S)\frac{\partial F_{20}(y)}{\partial y} - \left(M^2 - n\right) F_{20}(y)$$

$$= -A\frac{\partial F_{10}(y)}{\partial y} - \left(M^2 - n\right) + G_r T_{20}(y) \tag{24}$$

$$\frac{\partial^2 F_{21}(y)}{\partial y^2} + (1-S)\frac{\partial F_{21}(y)}{\partial y} - \left(M^2 - n\right) F_{21}(y)$$

$$= -A\frac{\partial F_{11}(y)}{\partial y} + G_r T_{21}(y) \tag{25}$$

$$\frac{\partial^2 T_{10}(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_{10}(y)}{\partial y} = 0 \tag{26}$$

$$\frac{\partial^2 T_{11}(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_{11}(y)}{\partial y} = -P_r\left(\frac{\partial F_{10}(y)}{\partial y}\right)^2 \tag{27}$$

$$\frac{\partial^2 T_{20}(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_{20}(y)}{\partial y} + nP_r T_{20}(y) = -P_r A\left(\frac{\partial T_{10}(y)}{\partial y}\right) \tag{28}$$

$$\frac{\partial^2 T_{21}(y)}{\partial y^2} + \left(P_r - S\right)\frac{\partial T_{21}(y)}{\partial y} + nP_r T_{21}(y)$$

$$= -P_r A\left(\frac{\partial T_{11}(y)}{\partial y}\right) - 2P_r\left(\frac{\partial F_{10}(y)}{\partial y}\right)\left(\frac{\partial F_{20}(y)}{\partial y}\right) \tag{29}$$

Using (12) in boundary conditions (11) are transformed to:

$$F_{10} = F_{20} = 1,\ F_{11} = F_{21} = 0,\ T_{10} = 1 + h\frac{\partial T_{10}}{\partial y},\ T_{11} = h\frac{\partial T_{11}}{\partial y},\ T_{20} = 1 + h\frac{\partial T_{20}}{\partial y},\ T_{21} = h\frac{\partial T_{21}}{\partial y} \text{ at } y = 0$$

$$F_{10} = F_{20} \to 0,\ F_{11} = F_{21} \to 0\ T_{10} = T_{20} \to 0,\ T_{11} = T_{21} \to 0 \text{ as } y \to \infty \tag{30}$$

The solutions of above equations satisfying the boundary conditions (30), we obtain:

$$T_{10}(y) = C_1 e^{-S_1 y} \tag{31}$$

$$F_{10}(y) = 1 + K_1\left(e^{-S_1 y} - e^{-m_1 y}\right) \tag{32}$$

$$T_{20}(y) = C_3 e^{-m_2 z} + K_2 e^{-S_1 y} \tag{33}$$

$$F_{11}(y) = C_5 e^{-m_1 y} + K_6 e^{-S_1 y} - K_7 e^{-2m_1 y}$$
$$+ K_8 e^{-2S_1 y} + K_9 e^{-(m_1 + S_1)y} \tag{34}$$

$$T_{11}(y) = C_4\, e^{-S_1 z} - K_3 e^{-2m_1 y} - K_4 e^{-2S_1 y} + K_5 e^{-(m_1 + S_1)y} \tag{35}$$

$$F_{20}(y) = C_6 e^{-m_3 z} + K_{10} e^{-m_1 y} + K_{11} e^{-S_1 y} + 1 \tag{36}$$

$$T_{21}(y) = C_7 e^{-m_1 y} + K_{12} e^{-S_1 y} + K_{13} e^{-2m_1 y} - K_{14} e^{-2S_1 y}$$
$$+ K_{15} e^{-(S_1 + m_1)y} - K_{16} e^{-(S_1 + m_3)y} + K_{17} e^{-(m_1 + m_3)y} \tag{37}$$

$$F_{21}(y) = C_8 e^{-m_3 y} + K_{18} e^{-m_1 y} + K_{19} e^{-S_1 y} + K_{20} e^{-2m_1 y}$$
$$+ K_{21} e^{-2S_1 y} + K_{22} e^{-(S_1 + m_1)y}$$
$$+ K_{23} e^{-(S_1 + m_3)y} + K_{24} e^{-(m_1 + m_3)y} \tag{38}$$

On substituting (31)-(38) in (12), we get

$$q(y,t) = K_1\left(e^{-m_1 y} - e^{-S_1 y}\right) - E_c\left\{C_5 e^{-m_1 y} + K_6 e^{-S_1 y} - K_7 e^{-2m_1 y} + K_9 e^{-(m_1 + S_1)y} + K_8 e^{-2S_1 y}\right\}$$
$$-\varepsilon e^{-nt}\left[C_6 e^{-m_3 y} + K_{10} e^{-m_1 y} + K_{11} e^{-S_1 y} + E_c\left\{C_8 e^{-m_3 y} + K_{18} e^{-m_1 y} + K_{19} e^{-S_1 y} + K_{20} e^{-2m_1 y}\right.\right.$$
$$\left.\left.+ K_{23} e^{-(S_1 + m_3)y} + K_{22} e^{-(S_1 + m_1)y} + K_{21} e^{-2S_1 y}\right\}\right] \tag{39}$$

$$T(y,t) = C_1 e^{-S_1 y} + E_c\left\{C_4\, e^{-S_1 y} + K_5 e^{-(m_1 + S_1)y} - K_4 e^{-2S_1 y} - K_3 e^{-2m_1 y}\right\}$$
$$+\varepsilon e^{-nt}\left[C_3 e^{-m_1 y} + K_2 e^{-S_1 y} + E_c\left\{C_7 e^{-m_1 y} + K_{17} e^{-(m_1 + m_3)y}\right.\right.$$
$$- K_{16} e^{-(S_1 + m_3)y} + K_{15} e^{-(S_1 + m_1)y} - K_{14} e^{-2S_1 y}$$
$$\left.\left.+ K_{13} e^{-2m_1 y} + K_{12} e^{-S_1 y}\right\}\right]$$

(40)

Hence primary velocity $u(z,t)$ and secondary velocity $v(z,t)$ are:

$$u(y,t) = u_0(y) - \varepsilon u_1(y) e^{-nt} \tag{41}$$

$$v(y,t) = v_0(y) - \varepsilon v_1(y) e^{-nt} \tag{42}$$

Where $u_0(y) = \left(P_1 \cos B_1 y + Q_1 \sin B_1 y\right) e^{-A_1 y} - P_1 e^{-S_1 y} - E_c \left\{ P_6 e^{-S_1 y} \right.$

$+\left(P_{26} \cos B_1 y + Q_{26} \sin B_1 y\right) e^{-A_1 y} + \left(P_7 \cos 2B_1 y + Q_7 \sin 2B_1 y\right) e^{-2A_1 y}$

$\left. +\left(P_9 \cos B_1 y + Q_9 \sin B_1 y\right) e^{-\left(A_1 + S_1\right) y} + P_8 e^{-2S_1 y} \right\}$

$u_1(y) = \left(P_{27} \cos B_2 y + Q_{27} \sin B_2 y\right) e^{-A_2 y} + \left(P_{10} \cos B_1 y + Q_{10} \sin B_1 y\right) e^{-A_1 y}$

$-P_{11} e^{-S_1 y} + E_c \left\{ P_{19} e^{-S_c y} + \left(P_{29} \cos B_2 y + Q_{29} \sin B_2 y\right) e^{-A_2 y} \right.$

$+\left(P_{18} \cos B_1 y + Q_{18} \sin B_1 y\right) e^{-A_1 y} + \left(P_{20} \cos 2B_1 y + Q_{20} \sin 2B_1 y\right) e^{-2A_1 y}$

$+\left(P_{22} \cos B_2 y + Q_{22} \sin B_2 y\right) e^{-\left(S_1 + A_2\right) y} + \left(P_{23} \cos B_2 y + Q_{23} \sin B_2 y\right) e^{-\left(A_1 + S_1\right) y}$

$\left. +\left(P_{24} \cos\left(B_1 + B_2\right) y + Q_{24} \sin\left(B_1 + B_2\right) y\right) e^{-\left(A_1 + S_1\right) y} + P_{21} e^{-2S_1 y} \right\}$

$v_0(y) = \left(Q_1 \cos B_1 y - P_1 \sin B_1 y\right) e^{-A_1 y} - Q_1 e^{-S_1 y} - E_c \left\{ Q_6 e^{-S_1 y} \right.$

$+\left(Q_{26} \cos B_1 y - P_{26} \sin B_1 y\right) e^{-A_1 y} + \left(Q_7 \cos 2B_1 y - P_7 \sin 2B_1 y\right) e^{-2A_1 y}$

$\left. +\left(Q_9 \cos B_1 y - P_9 \sin B_1 y\right) e^{-\left(A_1 + S_1\right) y} + Q_8 e^{-2S_1 y} \right\}$

$v_1(y) = \left(Q_{27} \cos B_2 y - P_{27} \sin B_2 y\right) e^{-A_2 y} + \left(Q_{10} \cos B_1 y - P_{10} \sin B_1 y\right) e^{-A_1 y}$

$-Q_{11} e^{-S_1 y} + E_c \left\{ Q_{19} e^{-S_c y} + \left(Q_{29} \cos B_2 y - P_{29} \sin B_2 y\right) e^{-A_2 y} \right.$

$+\left(Q_{18} \cos B_1 y - P_{18} \sin B_1 y\right) e^{-A_1 y} + \left(Q_{20} \cos 2B_1 y - P_{20} \sin 2B_1 y\right) e^{-2A_1 y}$

$+\left(Q_{22} \cos B_2 y - P_{22} \sin B_2 y\right) e^{-\left(S_1 + A_2\right) y} + \left(Q_{23} \cos B_2 y - P_{23} \sin B_2 y\right) e^{-\left(A_1 + S_1\right) y}$

$\left. +\left(Q_{24} \cos\left(B_1 + B_2\right) y - P_{24} \sin\left(B_1 + B_2\right) y\right) e^{-\left(A_1 + S_1\right) y} + Q_{21} e^{-2S_1 y} \right\}$

4. Skin-friction and Rate of Heat Transfer

The skin-friction (τ_p) due to primary velocity and skin-friction (τ_s) due to secondary velocity at the plate are obtained as follows:

$$\tau_p = \left(\frac{\partial u}{\partial y}\right)_{y=0} = P_{30} + E_c P_{31} + \varepsilon\left\{P_{32} + E_c P_{33}\right\} e^{-nt} \quad (43)$$

$$\tau_s = \left(\frac{\partial v}{\partial y}\right)_{y=0} = Q_{30} + E_c Q_{31} + \varepsilon\left\{Q_{32} + E_c Q_{33}\right\} e^{-nt} \quad (44)$$

The rate of heat transfer in terms of Nusselt number (N_u) at the plate is:

$$N_u = \left(\frac{\partial T}{\partial y}\right)_{y=0} = -C_1 S_1 - E_c P_{34} - \varepsilon\left(P_{35} + E_c P_{36}\right) e^{-nt} \quad (45)$$

Table 1: Variations of skin-friction due to primary velocity (τ_p) (at $t = 1.0$, $n = 0.2$, $E_c = 0.3$ and $\varepsilon = 0.01$)

P_r	**S**	**E**	**M**	**K**	G_r	τ_p
0.71	0.5	1.0	0.5	20.0	10.0	0.57864
7.00	0.5	1.0	0.5	20.0	10.0	0.12487
0.71	1.0	1.0	0.5	20.0	10.0	0.63729
0.71	0.5	1.5	0.5	20.0	10.0	0.54745
0.71	0.5	1.0	1.5	20.0	10.0	0.32468
0.71	0.5	1.0	0.5	50.0	10.0	0.58673
0.71	0.5	1.0	0.5	20.0	15.0	1.24867

Table 2: Variations of skin-friction due to secondary velocity (τ_s) (at $t = 1.0$, $n = 0.2$, $E_c = 0.3$ and $\varepsilon = 0.01$)

P_r	**S**	**E**	**M**	**k**	G_r	τ_s
0.71	0.5	1.0	0.5	20.0	10.0	-0.68287
7.00	0.5	1.0	0.5	20.0	10.0	-0.41463
0.71	1.0	1.0	0.5	20.0	10.0	-0.67752
0.71	0.5	1.5	0.5	20.0	10.0	-0.63837
0.71	0.5	1.0	1.5	20.0	10.0	-0.57382
0.71	0.5	1.0	0.5	50.0	10.0	-0.83946
0.71	0.5	1.0	0.5	20.0	15.0	-1.25814

Table 3: Variations of rate of heat transfer in terms of Nusselt number (N_u) (at $t = 1.0$, $n = 0.2$, $E_c = 0.3$ and $\varepsilon = 0.01$)

P_r	**S**	**E**	**M**	**k**	G_r	N_u
0.71	0.5	1.0	0.5	20.0	10.0	0.47835
7.00	0.5	1.0	0.5	20.0	10.0	2.36843
0.71	1.0	1.0	0.5	20.0	10.0	0.47536
0.71	0.5	1.5	0.5	20.0	10.0	0.43784
0.71	0.5	1.0	1.5	20.0	10.0	0.47168
0.71	0.5	1.0	0.5	50.0	10.0	0.49737
0.71	0.5	1.0	0.5	20.0	15.0	0.58761

5. Discussion and Conclusions

Numerical calculations are carried out to observe the effects of the Prandtl number (P_r), Stratification parameter (*S*), Rotation parameter (*E*), Magnetic parameter (*M*), Permeability parameter (*k*) and Grashof number (G_r) on primary velocity field, secondary velocity field and temperature distribution. These effects are shown in graphs. Numerical calculations are also carried out to observe the effects of the above stated parameters on non-dimensional skin-friction factor. These effects are numerically presented in tables. The cases of most common interest viz. symmetric cooling of the plate ($G_r > 0$) is considered to observe the effects of the above stated parameters on primary velocity field, secondary velocity field and skin-friction at $t = 1.0$, $n = 0.2$, $E_c = 0.3$ and $\varepsilon = 0.01$. To be realistic, the value of the Prandtl number (P_r) is chosen for air ($P_r = 0.71$) and water ($P_r = 7.0$) at 20^0C and one atmospheric pressure. The values of the remaining parameters are chosen arbitrarily following the researchers of the field.

Fig. 1 shows the effects of the Prandtl number (P_r), Stratification parameter (*S*), Rotation parameter (*E*), Magnetic parameter (*M*), Permeability parameter (*k*) and Grashof number (G_r) on primary velocity field while Fig. 2 depict the effects of the Prandtl number (P_r), Stratification parameter (*S*), Rotation parameter (*E*), Magnetic parameter (*M*), Permeability parameter (*k*) and Grashof number (G_r) on secondary velocity field. The effects of above stated parameters on temperature distribution are numerically presented in Fig. 3. Table-1 and Table-2 represents the numerical values of the skin-friction due to primary and secondary velocities for the change of P_r , *S, E, M, k* and G_r at $t = 1.0$, $n = 0.2$, $E_c = 0.3$ and $\varepsilon = 0.01$.

The conclusions drawn from the observations of the Figures and Tables of the study are as follows:

1. The primary velocity increases rapidly near the plate and attaining a maximum value it decreases as *y* increases and ultimately tending to zero.
2. The primary velocity decreases with an increase in *E, M* or P_r while an increase in G_r , *S* or *k* increases the primary velocity.
3. The secondary velocity decreases rapidly near the plate and attaining a minimum value it increases as *y* increases and ultimately tending to zero.
4. The secondary velocity increases with an increase in *E, M* or P_r while an increase in G_r , *S* or *k* decreases the secondary velocity.
5. An increase in G_r or *k* increases the temperature field.
6. An increase in *E, S, M* or P_r decreases the temperature filed.
7. An increase in *S, k* or G_r increases the skin-friction due to primary velocity (τ_p) while an increase in P_r , *E* or *M* decreases the skin-friction due to primary velocity (τ_p).
8. An increase in *k* or G_r increases the skin-friction due to secondary velocity (τ_s) while an increase in P_r , *S, E* or *M* decreases the skin-friction due to secondary velocity (τ_s).
9. An increase in P_r , *k* or G_r increases the rate of heat transfer in terms of Nusselt number (N_u) while an increase in *S, E* or *M* decreases the rate of heat transfer in terms of Nusselt number (N_u).

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