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Numerical investigation of slip flow effects on unsteady hydromagnetic flow over a stretching surface with thermal radiation

Research Article

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Abstract: This paper investigates the slip flow effects on unsteady hydromagnetic flow over a stretching surface with thermal radiation heat transfer. Governing equations of the problem are a system of nonlinear partial differential equations is obtained and transformed to ordinary differential equations by using similarity transformation and are solved numerically by applying Nachtsheim Swigert shooting iteration technique together with Runge Kutta fourth order integration scheme. Resulting non dimensional velocity and temperature profiles are then presented graphically for different values of the parameters involved. The analysis of the results obtained shows that the flow field is influenced appreciably by the Unsteadiness parameter (A), Magnetic interaction parameter (M^2), Velocity slip parameter (h_1), Thermal jump parameter (h_2), Radiation parameter (R_d) and Prandtl number (Pr). Results for skin friction coefficient and the non dimensional rate of heat transfer are also obtained and are discussed in detail.

MSC: 76Wxx • 80Axx

Keywords: Boundary layer flow • Stretching surface • MHD • Unsteady • Slip flow • Radiation

1. Introduction

In recent years, considerable attention has been devoted to the study of boundary layer flow behavior and heat transfer characteristic over a stretching surface. The boundary layer flow over a stretching surface has wide and variety of application in industrial manufacturing processes such as paper production, the aerodynamic extrusion of plastic sheet, glass blowing and metal spinning. The quality of the final product mainly depends on the rate of heat transfer at the stretching surface.

In his pioneering work, Sakiadis [1, 2] studied the boundary layer behavior on continuous solid surfaces and boundary layer equation for two dimensional, asymmetric flows. Flow and heat transfer in the boundary layer on a continuous moving surface was investigated by Tsou [3]. Followed by that, Crane [4] investigated the flow past a stretching sheet. Grubka and Bobba [5] studied the heat transfer characteristics of a continuous, stretching surface with variable temperature. Chen and Char [6] analysed the heat transfer of a continuous, stretching surface with suction or blowing. The problem of stretching surface with constant surface temperature was considered and analysed by Noor [7].

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The boundary layer flow past a stretching surface in the presence of a magnetic field has much practical relevance in polymer processing and in other several industrial processes. Along with this, a new dimension is added to the study of flow and heat transfer effects over a stretching surface by considering the effect of thermal radiation. Thermal radiation effects may play an important role in controlling heat transfer in industry where the quality of the final product depends to a great extend on the heat controlling factors and the knowledge of radiative heat transfer in the system can perhaps lead to a desired product with sought qualities. High temperature plasmas, cooling of nuclear reactors and liquid metal fluids are some important applications of radiative heat transfer. The radiative flow of an electrically conducting fluid with high temperature in the presence of a magnetic field are encountered in electrical power generation, astrophysical flows, solar power technology, space vehicle re-entry, nuclear engineering applications and in other industrial areas.

Radiation effect on a certain MHD free convection flow was presented by Ghaly [8]. Raptis [9] analysed the effect of thermal radiation on MHD flow. Radiation effects on heat transfer from a stretching surface in a porous medium was investigated by Rashed [10]. The radiation effect is considered by Bataller [11] in the study of boundary layer flow over a static flat plate (Blasius flow) and Cortell [12] in the study of boundary layer flow over a moving flat plate (Sakiadis flow) in a quiescent fluid. Abbas et al. [13] considered the radiation effects on MHD flow in a porous space. The problem of Bataller and Cortell has been extended by Ishak [14] and he found the existence of dual solutions. Anjali Devi and Kayalvizhi [15] presented the analytical solutions of MHD flow with radiation over a stretching surface embedded in a porous medium. Recently, Siti et al. [16] studied the hydromagnetic boundary layer flow over stretching surface with thermal radiation.

The technological application of the hydromagnetic flow with slip flow effects has become the centre of attraction of many scientists, engineers and researchers. Beaver and Joseph [17] proposed a slip flow condition at the boundary. Of late, there has been a revival of interest in the flow problems with partial slip. Martin et al. [18] presented the Blasius boundary layer solution with slip flow conditions. Wang [19] undertook the study of the flow of a Newtonian fluid past a stretching sheet with partial slip and purportedly gave an exact solution. Slip flow past a stretching surface was analysed by Andersson [20]. Martin et al. [21] analysed the momentum and heat transfer in a laminar boundary with slip flow. Wang [22] carried out the stagnation slip flow and heat transfer on a moving plate. Matthews et al. [23] gave a note on the boundary layer equations with linear slip boundary conditions. Abbas et al. [24] analysed the slip effects and heat transfer effects of a viscous fluid over an oscillatory stretching surface. Fang et al. [25] gave an exact solution of the slip MHD viscous flow over a stretching sheet. Wang [26] carried out an analysis of viscous flow due to a stretching sheet with surface slip and suction. Recently, the effects of slip conditions on stretching flow with ohmic dissipation and thermal radiation was given by Qasim [27].

All the above works dealt with the fluid flow problems of steady case. The unsteady heat transfer problem over a stretching surface which is stretched with a velocity that depends on time is considered by Andersson [28]. Elbashbeshy and Bazid [29] presented an exact similarity solution for unsteady momentum and heat transfer flow whose motion is caused solely by the linear stretching of a horizontal stretching surface. Ishak et al. [30] analysed the heat transfer over an unsteady stretching surface with prescribed heat flux. Homotopy analysis of unsteady boundary layer flow adjacent to permeable stretching surface in a porous medium was carried out by Ali et al. [31]. Tsai et al. [32] studied the non uniform heat source effect on the flow and heat transfer from an unsteady stretching sheet through a quiescent fluid medium extending to infinity. El Aziz [33] investigated the radiation effect on the flow and heat transfer over an unsteady stretching sheet. Effects of slip and heat transfer analysis of flow over an unsteady stretching surface was investigated by Mukhopadhyay [34]. Unsteady MHD flow and heat transfer over a stretching plate was studied by Ishak [35]. Radiation effect on unsteady MHD flow over a stretching surface was presented by Yusof et al. [36].

2. Author's contribution

So far no attempt has been made to investigate the slip flow effects on the unsteady hydromagnetic flows over a stretching surface with thermal radiation heat transfer. Motivated by the applications mentioned, this paper is mainly devoted to the study of thermal radiation and slip flow effects on an unsteady hydromagnetic flow over a stretching surface. The governing partial differential equations are transformed to ordinary differential equations using suitable similarity transformations and are solved numerically. In the absence of the applied variable magnetic field and radiation the results obtained are in good agreement with the results of Swati Mukhopadhyay and Andersson [34].

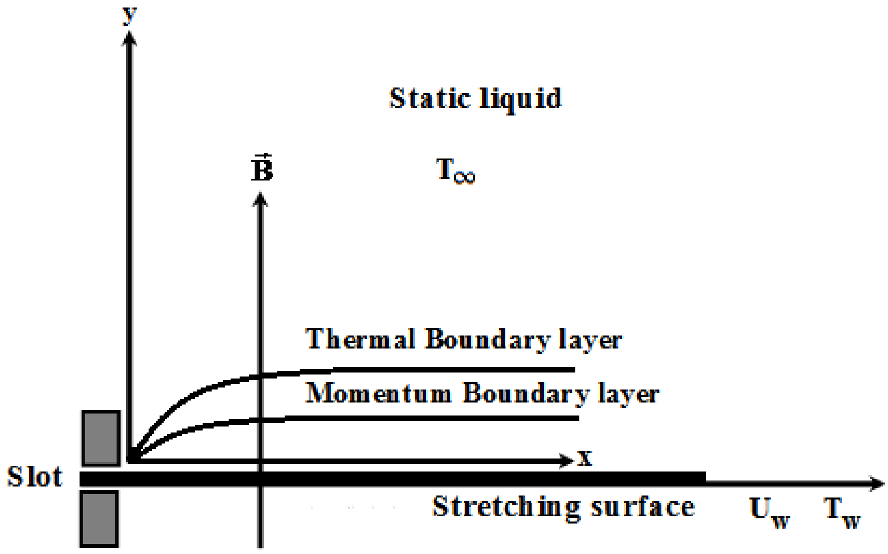

Fig. 1. Schematic representation of the problem

3. Formulation of the problem

Consider a two dimensional, unsteady boundary layer flow of an incompressible, viscous, radiating, electrically conducting fluid over a stretching surface with velocity $U_w(x,t) = \frac{bx}{1-\beta t}$ and with temperature $T_w(x,t) = T_\infty + T_0(\frac{bx^2}{2\nu})(1-\beta t)^{-3/2}$, where both b and β are constants and the constant β has the dimension reciprocal to time. T_w is the temperature of the wall, T_∞ is the main stream temperature, T_0 is the reference temperature and ν is the kinematic viscosity of the ambient fluid. The x-axis is chosen along the stretching surface and points in the direction of motion. The y-axis is perpendicular to the surface and the fluid flow. A variable magnetic field $\vec{B}(x,t)$ is applied in the direction parallel to y-axis and can be expressed as $\vec{B}(x,t) = B_0 x^{\frac{m-1}{2}}(1-\beta t)^{-1/2}\,\vec{j}$, where B_0 is the strength of the magnetic field, m is the positive integer with m=1 and β is the constant. The magnetic Reynolds number is assumed to be very small and hence the induced magnetic field is assumed to be negligible.
Under all these assumptions, the governing equations of the problem is given as follows

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} - \frac{\sigma B^2 u}{\rho} \tag{2}$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} - \frac{1}{\rho C_p}\frac{\partial q_r}{\partial y} \tag{3}$$

where u, v are the velocity components along x and y direction respectively, ν is the kinematic viscosity of the fluid, σ is the electrical conductivity of the fluid, ρ is the density of the fluid, B is the magnetic field applied, T is the fluid temperature, $\alpha = \frac{K}{\rho C_p}$ is the thermal diffusivity with K as the thermal conductivity and C_p as the heat capacity at constant pressure and q_r is the radiative heat flux. Here the fluid is considered to be grey, absorbing, emitting but a non scattering medium and hence the Rosseland's approximation is used to describe the radiative heat flux. Therefore the radiative heat flux q_r under the Rosseland's approximation has the form

$$q_r = -\frac{4\sigma^*}{3k_1}\frac{\partial T^4}{\partial y} \tag{4}$$

where σ^* is the Stefan Boltzman constant and k_1 is the mean absorption coefficient. It is assumed that the temperature difference within the flow is sufficiently small such that T^4 may be expressed as a linear function of temperature. This can be done by expanding T^4 in a Taylor series expansion about T_∞ and neglecting the higher order terms, thus

$$T^4 \cong 4T_\infty^3 - 3T_\infty^4 \tag{5}$$

Using (4) and (5), equation (3) will become

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{16\sigma^* T_\infty^3}{3k_1\rho C_p}\frac{\partial^2 T}{\partial y^2} \tag{6}$$

The corresponding boundary conditions are given by

$$\left.\begin{array}{llll} u=U_w(x,t)+N_1\nu\frac{\partial u}{\partial y}; & v=0; & T=T_w(x,t)+D_1\frac{\partial T}{\partial y} & \text{at} \quad y=0 \\ u\to 0; & T\to T_\infty & & \text{as} \quad y\to\infty \end{array}\right\} \tag{7}$$

here $N_1=N_0\left(1-\beta t\right)^{1/2}$ is the velocity slip factor which changes with time, N_0 is the initial values of the velocity slip factor,$D_1=D_0\left(1-\beta t\right)^{1/2}$ is the thermal jump factor. It also changes with time, D_0 is the initial value of the thermal jump factor. The essential slip factor N_1 and D_1 have the dimension as $(\text{velocity})^{-1}$ and length respectively.

4. Method of solution

The mathematical analysis of the problem is simplified by introducing the following similarity transformations and dimensionless variables.

$$\eta=\left(\frac{b}{\nu}\right)^{1/2}(1-\beta t)^{-1/2}y \tag{8}$$

$$\Psi=(b\nu)^{1/2}(1-\beta t)^{-1/2}xf(\eta) \tag{9}$$

where Ψ is the physical stream function which is chosen in such a way that it automatically satisfies the equation of continuity given by (3). $\theta=\frac{T-T_\infty}{T_w-T_\infty}$ that is $T=T_\infty+T_0\frac{bx^2}{2\nu}(1-\beta t)^{-3/2}\theta(\eta)$, where θ is the dimensionless temperature. The relations for the velocity components are readily obtained as

$$u=\frac{\partial\Psi}{\partial y}=U_w f'(\eta); \qquad v=-\frac{\partial\Psi}{\partial x}=-(b\nu)^{1/2}(1-\beta t)^{-1/2}f(\eta) \tag{10}$$

By using the above similarity transformation and the dimensionless variables, the governing equations defined in (2) and (6) are then transformed into a set of the following nonlinear ordinary differential equations

$$f'''-A\left(\frac{\eta}{2}-f'\right)-f'^2+ff''-M^2f'=0 \tag{11}$$

$$(3R_d+4)\theta''+3R_dPr\left(f\theta'-2f'\theta-\frac{A}{2}(\eta\theta'+3\theta)\right)=0 \tag{12}$$

The corresponding boundary conditions are

$$\left.\begin{array}{llll} f'(\eta)=1+h_1f''(\eta); & f(\eta)=0; & \theta(\eta)=1+h_2\theta'(\eta) & \text{as} \quad \eta=0 \\ f'(\eta)\to 0; & & \theta(\eta)\to 0 & \text{as} \quad \eta\to\infty \end{array}\right\} \tag{13}$$

where $A=\frac{\beta}{b}$ is the unsteadiness parameter, $M^2=\frac{\sigma B_0^2}{\rho b}$ is the magnetic interaction parameter, $R_d=\frac{Kk_1}{4\sigma^* T_\infty^3}$ is the radiation parameter, $Pr=\frac{\nu}{\alpha}$ is the Prandtl number, $h_1=N_0(b\nu)^{1/2}$ is the velocity slip parameter and $h_2=D_0\left(\frac{b}{\nu}\right)^{1/2}$ is the thermal jump parameter. The other quantities of physical interest in this problem are the local skin friction coefficient and the local Nusselt number which are defined as

$$C_{fx}=\frac{2\tau_w}{\rho U_w^2}=2Re_x^{-1/2}f''(0) \tag{14}$$

$$Nu_x=\frac{xq_w}{K(T_w-T_\infty)}=-\theta'(0)Re_x^{1/2}\left(1+\frac{4}{3R_d}\right) \tag{15}$$

respectively, where $Re_x=\frac{U_wx}{\nu}$ is the local Reynolds number. The surface shear stress τ_w and the net surface heat flux q_w are given by

$$\tau_w=\mu\left(\frac{\partial u}{\partial y}\right)_{y=0} \tag{16}$$

$$q_w=\left(-K\frac{\partial T}{\partial y}+q_r\right)_{y=0} \tag{17}$$

Table 1. Non dimensional rate of heat transfer when A = 1.2, $M^2 = 1.0$, Pr = 0.71, $h_1 = 0.4$, $h_2 = 0.5$ and $R_d = 5.0$

A	M^2	Pr	h_1	h_2	R_d	$-\theta'(0)\left(1+\frac{4}{3R_d}\right)$
0.0	1.0	0.71	0.4	0.5	5.0	0.73889
0.6						0.81923
1.2						0.93161
1.8						1.01364
2.4						1.07900
1.2	0.0	0.71	0.4	0.5	5.0	0.95406
	1.0					0.93161
	3.0					0.90452
	5.0					0.88810
	7.0					0.87681
1.2	1.0	0.71	0.4	0.5	5.0	0.93161
		1.0				1.04257
		1.5				1.17780
		2.3				1.32157
		7.0				1.67635
1.2	1.0	0.71	0.2	0.5	5.0	0.95633
			0.4			0.93161
			0.6			0.91418
			0.8			0.90109
			1.0			0.89085
1.2	1.0	0.71	0.4	0.1	5.0	1.31993
				0.3		1.09227
				0.5		0.93161
				0.7		0.81215
				0.9		0.71984
1.2	1.0	0.71	0.4	0.5	0.5	1.80961
					1.0	1.37561
					2.0	1.11332
					5.0	0.93161
					10^9	0.79561

5. Numerical solution of the problem

Eqs. (11) and (12) along with the boundary conditions given by (13) constitutes a nonlinear boundary value problem and it is difficult to solve them as such. Hence it is solved by converting them to an initial value problem by employing an efficient shooting method such as Nachtsheim Swigert integration scheme along with Runge Kutta shooting method. The suitable guess value for $f''(0)$ and $\theta'(0)$ are obtained using Nachtsheim Swigert iteration scheme and later solutions of the initial value problems are obtained using Runge Kutta fourth order method. The convergence criterion of the problem mainly depends on how good the guess values are for $f''(0)$ and $\theta'(0)$.

6. Results and discussion

Inorder to analyse the results, numerical computations have been carried out for various values of the parameters such as Unsteadiness parameter (A), Magnetic interaction parameter (M^2), Prandtl number (Pr), Radiation parameter (R_d), Velocity slip parameter (h_1) and Thermal jump parameter (h_2). For illustrations of the results, numerical values are plotted in the figures. In the absence of the magnetic field and the radiation effects the results are in good agreement with that of Swati Mukhopadhyay and Andersson [34]. This is shown through Fig. 2.

Fig. 3 presents the non dimensional velocity for variation of the unsteadiness parameter. It is seen that the velocity along the sheet decreases with the increase in the unsteadiness parameter A and this implies an accompanying reduction of the momentum boundary layer thickness. The variation in velocity with the changes in the magnetic interaction parameter is shown in Fig. 4. It shows that the rate of transport is considerably reduced with the increase in magnetic interaction parameter. It clearly indicates that the transverse magnetic field opposes the transport phenomena. This is due to the fact that the variation of M^2 leads to the variation of Lorentz force due to magnetic field and it produces more resistance to the transport phenomena. Fig. 5 is the graphical representation of the dimensionless velocity for different values of the velocity slip parameter. With the increasing values of the velocity slip parameter, the fluid velocity decreases. When slip occurs (for the non zero values of h_1) the flow velocity near the surface is no longer equal to the surface stretching velocity, as the velocity slip exists. Furthermore increasing the values of h_1 will decrease the flow velocity because under the slip condition the pulling of the stretching sheet

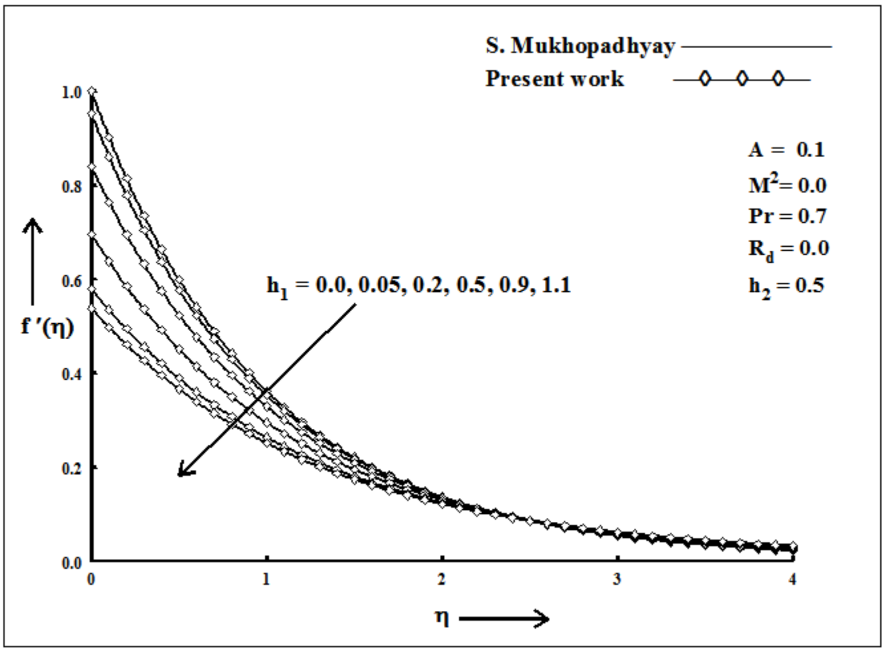

Fig. 2. A comparative study of velocity profiles for various values of h_1

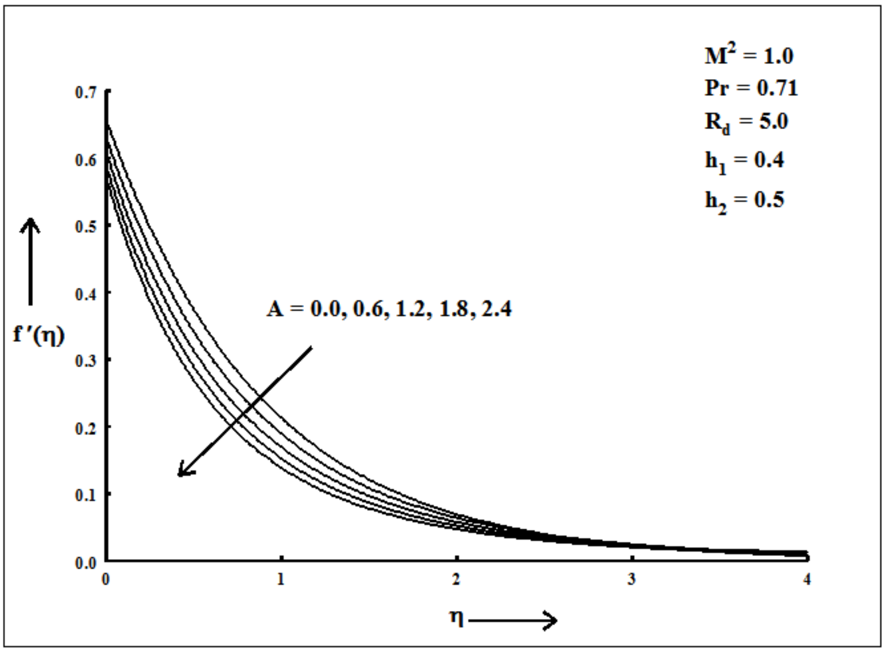

Fig. 3. Velocity profiles for various A

can be only partially transmitted to the fluid. It is readily seen that h_1 has a substantial effect on the solution.

Figs. 6 to 11 show the variation in the temperature boundary layer caused by various parameters involved in the study. For the increasing values of the unsteadiness parameter, the dimensionless temperature is found to decrease monotonically with the distance η from the surface. The impact of the unsteadiness parameter is more pronounced over the temperature distribution than on the velocity. This can be clearly shown in Figs. 6 . Figs. 7 gives the dimensionless temperature for various values of M_2. The thermal boundary layer becomes thicker with

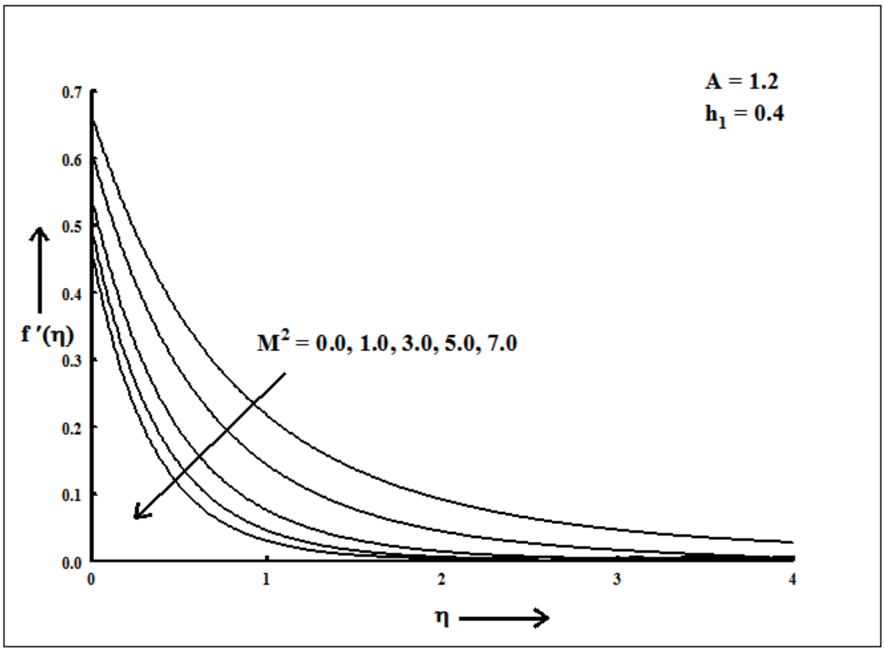

Fig. 4. Velocity profiles for various M^2

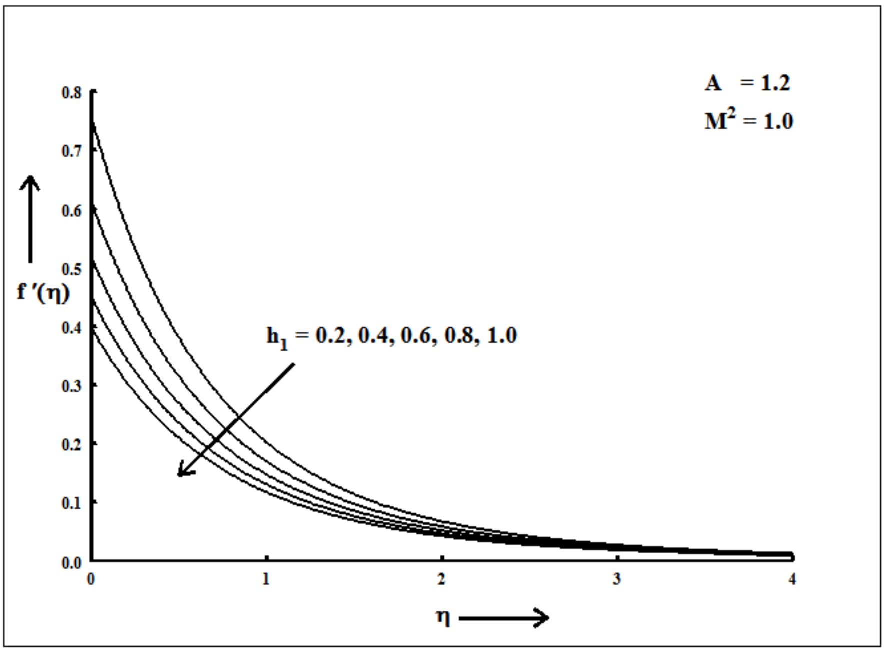

Fig. 5. Velocity profiles for various h_1

the increasing values of the magnetic interaction parameter. Similarly the velocity slip parameter has an increasing effect over the dimensionless temperature distribution. This is elucidated through Figs. 8. As the thermal jump parameter increases, less heat is transferred from the surface to the fluid. Hence the thermal jump parameter for its higher values decreases the dimensionless temperature of the fluid. Figs. 9 shows clearly that the thermal boundary layer thickness becomes thinner as the thermal jump parameter takes higher values.

Figs. 10 portrays the dimensionless temperature distribution for various values of the radiation parameter where

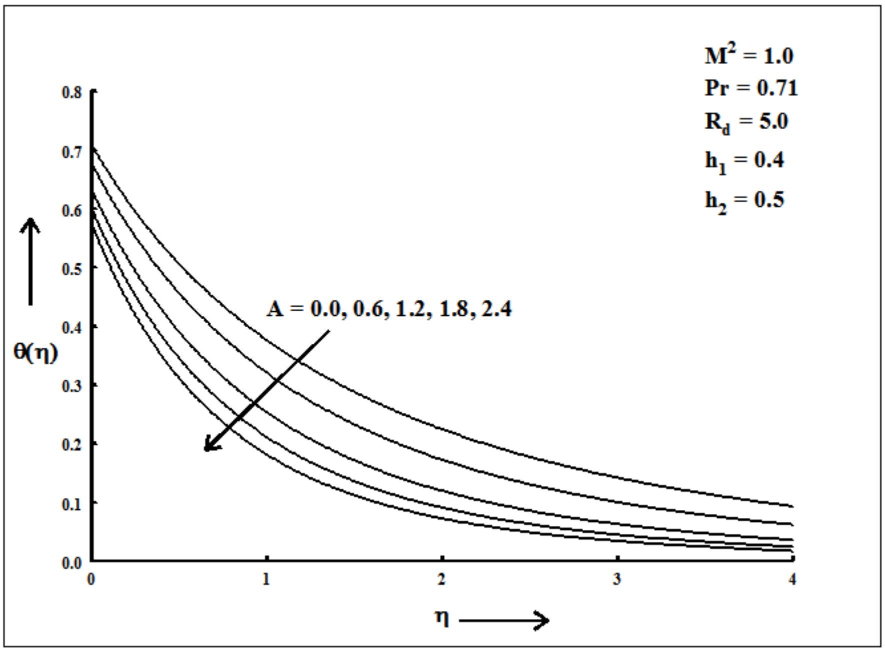

Fig. 6. Temperature profiles for various A

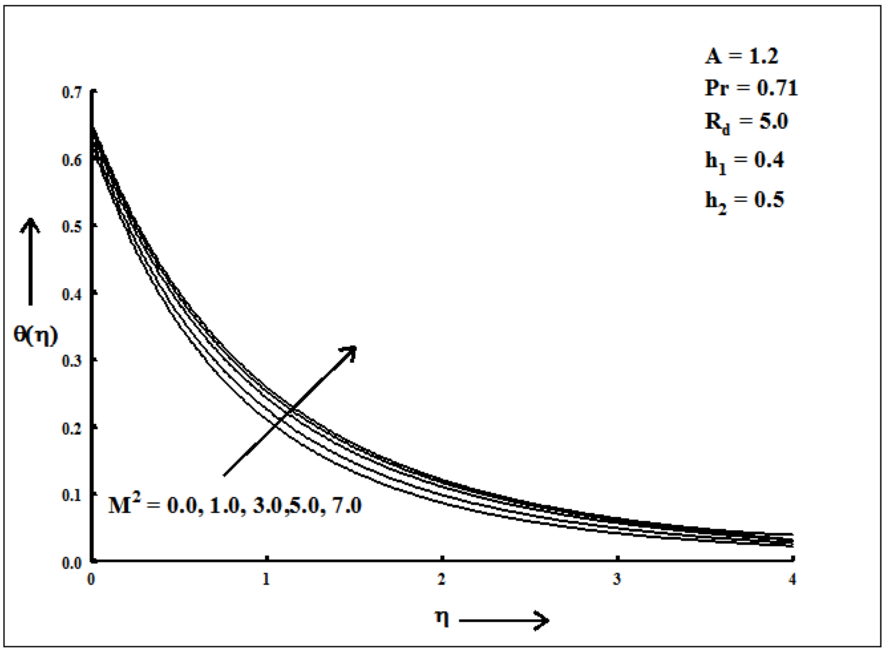

Fig. 7. Temperature profiles for various M^2

all the other parameter values are fixed. It shows that as the radiation parameter increases the thermal boundary layer thickness declines. Fluids having high Prandtl number will have thin thermal boundary layer. This can be illustrated through Figs. 11. As the Prandtl number increases the thermal boundary layer becomes thinner.

Figs. 12 and 13 gives the representation of local skin friction coefficient variations for various values of the unsteadiness parameter and the magnetic interaction parameter. In both the cases it is noted that the local skin friction coefficient reduces for increasing values of both the parameters.

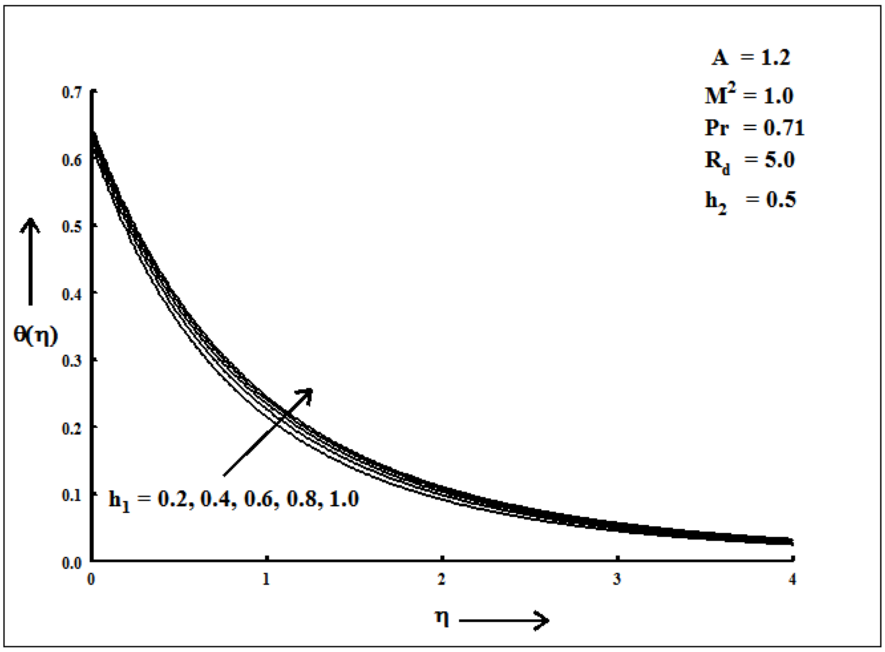

Fig. 8. Temperature profiles for various h_1

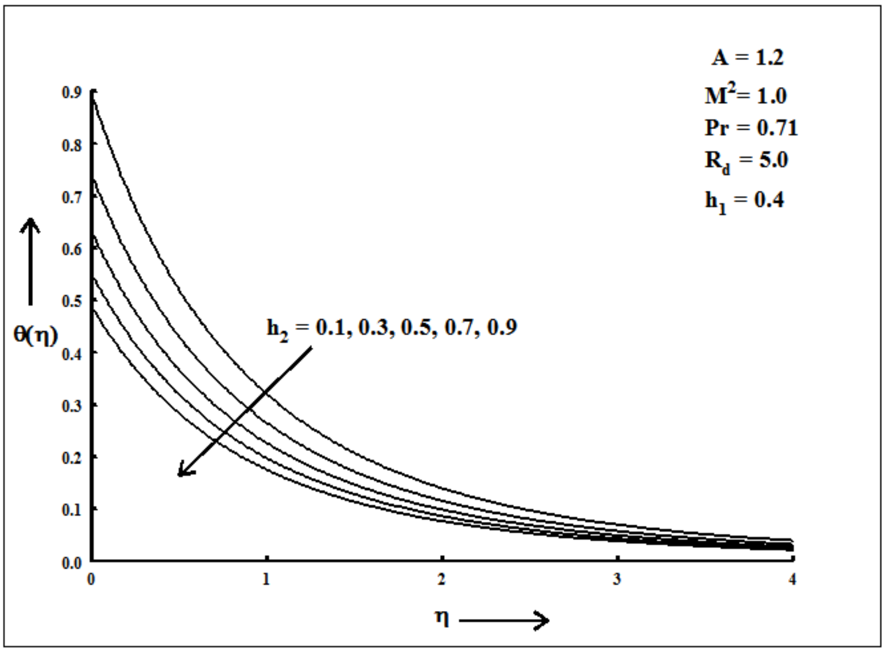

Fig. 9. Temperature profiles for various h_2

The effect of various parameters involved over the non dimensional rate of heat transfer is shown through Table 1. It is known from the table that the non dimensional rate of heat transfer is reduced for the higher values of the magnetic interaction parameter, velocity slip parameter, thermal jump parameter and the radiation parameter. The unsteadiness parameter and the Prandtl number enhances the non dimensional rate of heat transfer.

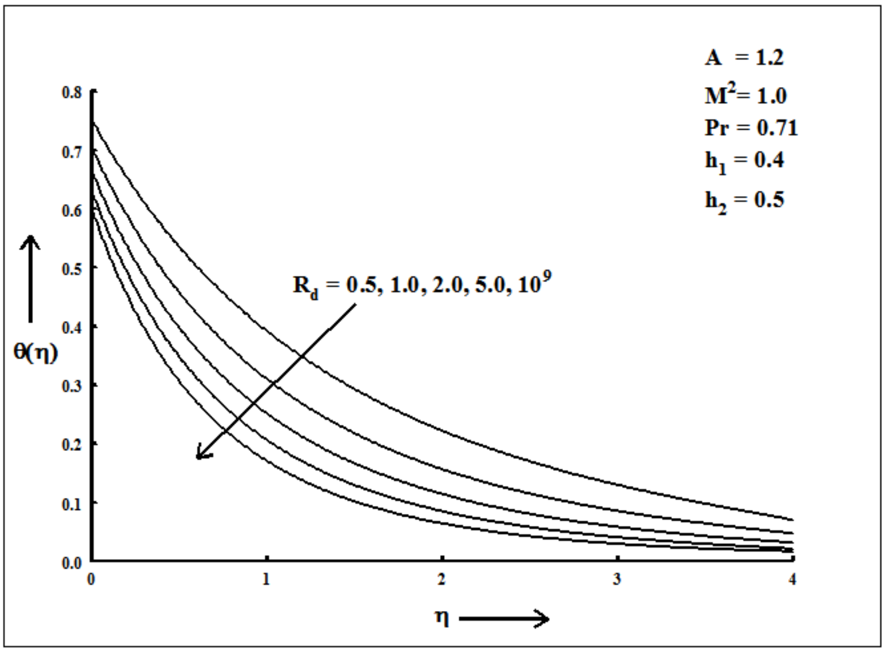

Fig. 10. Temperature profiles for various R_d

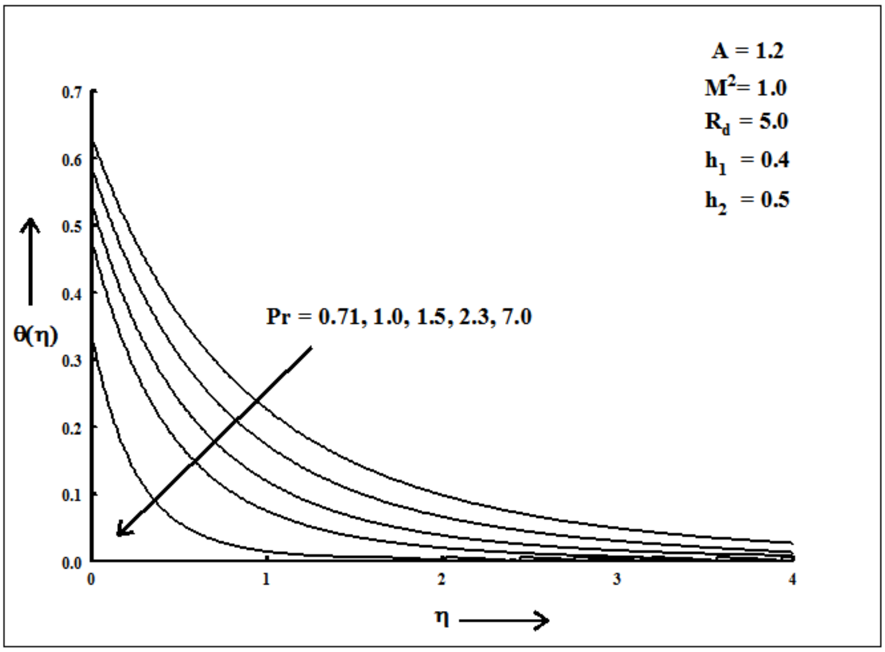

Fig. 11. Temperature profiles for various Pr

7. Conclusion

The present paper have numerically analysed the slip flow effects on unsteady hydromagnetic flow over a stretching surface along with thermal radiation heat transfer. Numerical solutions for the governing equations were given and a detailed study on the effects of various physical parameters involved over the dimensionless velocity, temperature, local skin friction coefficient and the local Nusselt number were carried out and discussed briefly. For the validation of the results obtained, a comparative study has been carried out in the absence of magnetic field and radiation and

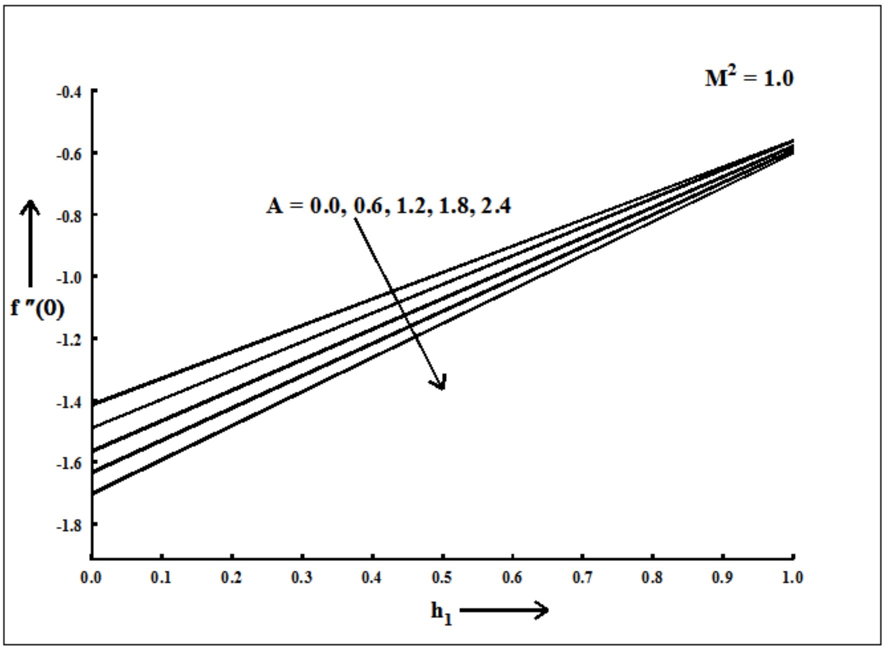

Fig. 12. Skin friction coefficient for various A

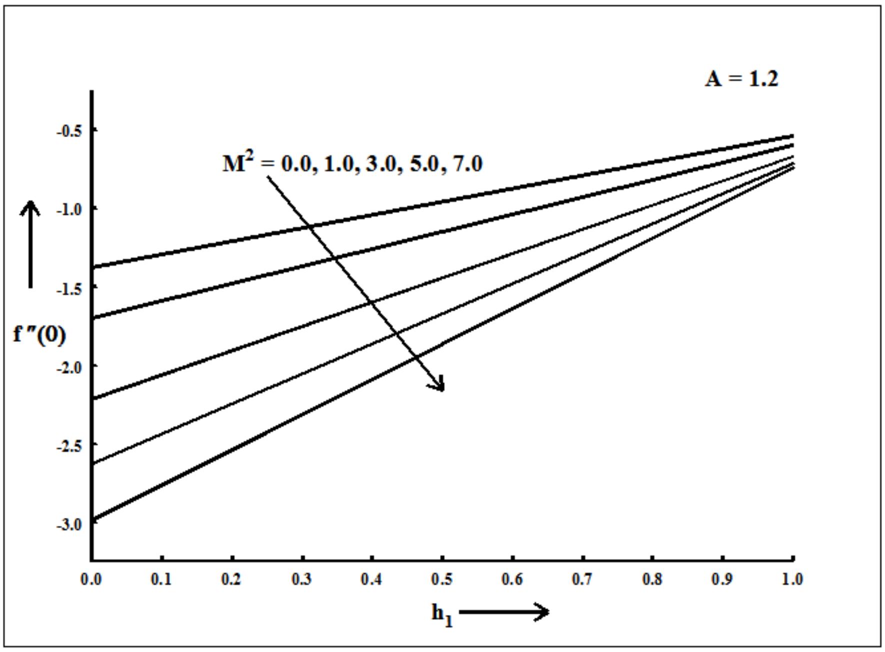

Fig. 13. Skin friction coefficient for various M^2

it is found that the results go in hand with that of the results found by Swati Mukhopadhyay and Andersson [34]. The summary of the results obtained are presented as follows

- The Unsteadiness parameter A decreases the dimensionless velocity, dimensionless temperature and the local skin friction coefficient whereas it enhances the rate of heat transfer.
- The Magnetic interaction parameter M^2 has a decreasing effect over the dimensionless velocity, local skin friction coefficient and local Nusselt number but it increases the thermal boundary layer thickness.

- The effect of Radiation parameter R_d and the Prandtl number Pr is to decline the dimensionless temperature. The non dimensional rate of heat transfer is enhanced by the Prandtl number whereas the Radiation parameter suppress the non dimensional rate of heat transfer.
- The Velocity slip parameter h_1 has a decreasing effect over the dimensionless velocity but the same increases the dimensionless temperature.
- The effects of the Thermal jump parameter h_2 is to reduce the thermal boundary layer thickness and to suppress the rate of heat transfer.

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