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STEADY MHD SLIP FLOW OVER A PERMEABLE STRETCHING CYLINDER WITH THERMAL RADIATION

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ABSTRACT

Aim of the paper is to investigate the effects of thermal radiation and velocity slip on steady MHD slip flow of viscous incompressible electrically conducting fluid over a permeable stretching cylinder saturated in porous medium in the presence of external magnetic field. The governing nonlinear partial differential equations are transformed into ordinary differential equations by suitable similarity transformation and solved numerically using Runge-Kutta fourth order method with shooting technique. Effect of various physical parameters on fluid velocity, temperature, skin –friction coefficient and Nusselt number are presented through graphs and discussed numerically.

Keywords: Slip Flow; MHD; Radiation; Stretching Cylinder; Heat Source; Porous Medium

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1. INTRODUTION

The investigation of viscous incompressible fluid flow over a stretching/shrinking surface has gained much attention in recent years as it has various applications in both industrial and manufacturing processes. Some of these are MHD power generators, petroleum industries, plasma studies, hot rolling, wire drawing, aerodynamic extrusion of plastic sheets and metal spinning. Crane [Crane (1970)] investigated the flow and heat transfer past a linearly stretching sheet. Gupta and Gupta [Gupta et al. (1977)] extended the work of Crane by introducing mass transfer with suction and blowing. Lin and Shih [Lin and Shih (1980), Lin and Shih (1981)] studied buoyancy effects on laminar boundary layer heat transfer along vertically moving cylinders. Heat transfer characteristics of a continuous stretching surface with power law surface temperature vibration were discussed by Grubka and Bobba [Grubka and Bobba (1985)]. Chen and Char [Chen and Char (1988)] considered heat transfer past a stretching surface with suction or blowing. Wang [Wang (1998)] investigated fluid flow due to stretching cylinder and obtained both exact and asymptotic solution for large Reynolds number. Heat transfer characteristics of a continuous stretching surface were analyzed by Ali [Ali (1994)].

Slip flow means non-adherence of fluid to the boundary wall. The slip flow boundary condition was first introduced by C.L.M.H. Navier more than a century ago. Anderson [Anderson (2002)], Wang [Wang (2002)], Ariel et al. [Ariel et al. (2006)] and Fang et al. [Fang et al. (2009)] obtained closed form solution of Navier-Stokes equations for laminar boundary layer slip flow over a stretching surface. Ganesan and Loganathan [Ganesan and Loganathan (2003)] investigated magnetic field effect on moving vertical cylinder with constant heat flux. Cortell [Cortell (2005)] considered suction/blowing and internal heat generation/absorption in flow and heat transfer of a fluid through porous medium over a stretching surface. Flow and heat transfer in an asymmetric stagnation flow on a cylinder was studied by Elbarbary and Elgazery [Elbarbary and Elgazery (2005)]. Xu, Liao [Xu and Liao (2005)] and Hayat et al. [Hayat et al. (2006)] used homotopy analysis method to study MHD Flow of non-Newtonian and Maxwell fluids over stretching plate.

The flow past a stretching cylinder has many industrial and engineering applications for example in metallurgy and polymer industries such as extraction and manufacture of polymer and rubber sheets glass fiber production etc. Ishak et al. [Ishak et al. (2008), Ishak and Nazar (2009) and Ishak et al. (2008)] examined the boundary layer flow and heat transfer due to stretching cylinder with uniform suction/blowing effect and external magnetic field. Later Mukhopadhyay [Mukhopadhyay (2013), Mukhopadhyay (2011)] extended the work of Ishak by including chemically reactive solute transfer and slip flow along a stretching cylinder. Hayat et al. [Hayat et al. (2018)] discussed convective heat and mass transfer by an inclined stretching cylinder. Stagnation-point flow and heat transfer over an exponentially stretching/shrinking cylinder was studied by Merkin et al. [Merkin et al. (2017)]. Yu et al. [Yu et al. (2018)] investigated effects of thermal buoyancy on flow and heat transfer around a permeable circular cylinder with internal heat generation. In our previous paper [Sinha and Yadav (2021)], the influence of heat source/sink on MHD mixed convective flow along a vertical stretching cylinder saturated in porous medium was investigated.

Aim of the present paper is to investigate the effects of thermal radiation and velocity slip on steady MHD slip flow of viscous incompressible electrically conducting fluid over a permeable stretching cylinder saturated in porous medium in the presence of external magnetic field.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

Consider steady axisymmetric flow of viscous incompressible electrically conductive fluid over a permeable stretching horizontally placed cylinder of radius R in the presence of external magnetic field B_o. The uniform magnetic field B_o is applied normal to the surface of the cylinder which is saturated in porous medium. The x and r axis are taken as the axis of the cylinder and in the radial directions respectively. To neglect the induced magnetic field, it is assumed that the magnetic Reynolds number is very small. The governing equations of continuity, motion and energy are as follows:

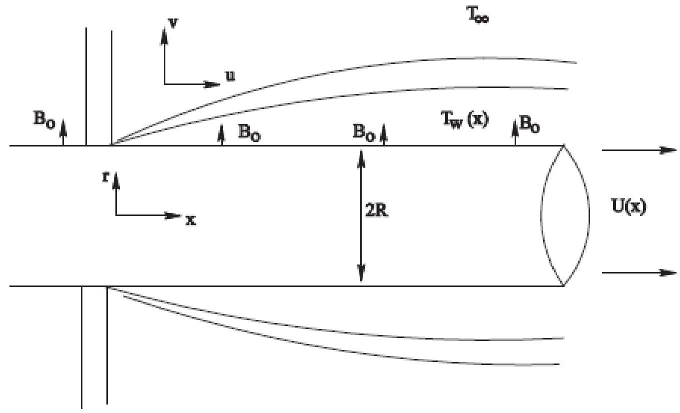

Figure 1 Physical model of the problem

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=\frac{\vartheta}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)-\frac{\sigma {B_o}^2 u}{\rho}-\frac{\vartheta u}{K_o} \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}=\frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{\rho C_p r}\frac{4\sigma}{3\kappa^*}\frac{\partial}{\partial r}\left(r\frac{\partial T^4}{\partial r}\right)+\frac{Q}{\rho C_p}(T-T_\infty) \tag{3}$$

Where u and v are the velocity components in x and r directions, $\vartheta(=\frac{\mu}{\rho})$ is the kinematic viscosity, ρ is density of the fluid, μ is the coefficient of viscosity, σ is the electrical conductivity, $K_o$is permeability of the porous medium, T is temperature of the fluid, α is thermal diffusivity and Q is external volumetric heat source/sink.For the radiated heat flux Rosseland approximation is used and $T^4$is approximated by truncated Taylor series about $T_\infty i.e. T^4 \cong 4T_\infty^3 T - 3T_\infty^4$.

Corresponding boundary conditions are given by

$$\left.\begin{array}{l} u = U(x) + S_{v1}\vartheta\frac{\partial u}{\partial r}; v = v_w \;; T = T_w(x); at\ r = R \\ \text{and } u \to 0;\ \ T \to T_\infty\ as\ r \to \infty \end{array}\right\} \tag{4}$$

Where $U(x) = U_o\frac{x}{L}$ is the stretching velocity, $T_w(x) = T_\infty + T_o\left(\frac{x}{L}\right)^N$ is the prescribed wall temperature, U_o and T_o are the reference velocity and temperature respectively, T_∞ is ambient temperature, L is characteristic length, S_{v1} is velocity slip and N is temperature exponent.

3. METHOD OF SOLUTION

In order to get solution of equation (1) to (3) with boundary conditions (4), introducing the following similarity variable, stream function and dimensionless functions

$$\eta = \frac{r^2-R^2}{2R}\left(\frac{U}{\vartheta x}\right)^{\frac{1}{2}}, \psi = (U\vartheta x)^{\frac{1}{2}} R f(\eta),\ \theta(\eta) = \frac{T-T_\infty}{T_w-T_\infty} \tag{5}$$

Where $u = \frac{1}{r}\frac{\partial\psi}{\partial r}$ and $v = -\frac{1}{r}\frac{\partial\psi}{\partial x}$so that the equation of continuity is automatically satisfied. Equations (2) to (4) reduce to

$$(1+2\omega\eta)f''' + 2\omega f'' + ff'' - f'^2 - M^2 f' - \frac{1}{K}f' = 0 \tag{6}$$

$$(1+2\omega\eta)\left(1+\frac{4}{3}R_d\right)\theta'' + 2\omega\left(1+\frac{4}{3}R_d\right)\theta' + Pr\left(f\theta' - N\theta f'\right) + \delta.Pr.\theta = 0 \tag{7}$$

$$\left.\begin{array}{l} f' = 1 + S_v f''; f = S; \theta = 1; at\ \eta = 0 \\ f' \to 0; \quad \theta \to 0; \quad as \quad \eta \to \infty \end{array}\right\} \tag{8}$$

Where prime denotes differentiation with respect to η, $\omega\left(=\left(\frac{\vartheta L}{R^2 U_o}\right)^{\frac{1}{2}}\right)$ is the curvature parameter, $K\left(=\frac{K_o U_o}{\vartheta L}\right)$ is the permeability parameter, $M^2\left(=\frac{\sigma {B_o}^2 L}{\rho U_o}\right)$ is the magnetic parameter, $\delta\left(=\frac{QL}{\rho C_p U_o}\right)$ is the heat source/sink parameter, $Pr\left(=\frac{\vartheta}{\alpha}\right)$ is the Prandtl number, $R_d\left(=\frac{4T_\infty^3}{\kappa k^*}\right)$ is the radiation parameter, $S_v\left(=S_{v1}(\frac{U_o\vartheta}{L})\right)$ is the slip parameter and $S\left(=\left(\frac{U_o L}{\vartheta}\right)^{1/2}\right)$ is suction/injection parameter.

The physical quantities of interest are the skin friction coefficient $\left(C_f\right)$ and local Nusselt number (Nu_x) defined as

$$C_f = \frac{\tau_w}{\rho U_\infty^2}, Nu_x = \frac{xq_w}{\kappa(T_w-T_\infty)} \tag{9}$$

The wall shear stress τ_w and the heat flux at the wall q_w are given by

$$\tau_w = \mu\left(\frac{\partial u}{\partial r}\right)_{r=R},\ q_w = -\kappa\left(\frac{\partial T}{\partial r}\right)_{r=R}$$

Where μ and κ are the coefficient of viscosity and thermal conductivity of the fluid respectively.

Using similarity transformation (5) in (9), the skin friction coefficient and local Nusselt number reduce to

$$C_f Re_x^{1/2} = f''(0),\ Nu_x Re_x^{-1/2} = -\theta'(0).$$

Since equations (6) and (7) are highly nonlinear, these equations with boundary conditions (8) are converted into system of first order differential equations as given below

$$f_1' = f_2;\; f_2' = f_3\,;\; f_3' = \left(\frac{1}{K}f_2 + M^2 f_2 + {f_2}^2 - f_1 f_3 - 2\omega f_3\right)/(1+2\omega\eta)\,;\quad f_4' = f_5\,;$$

$$f_5' = -\left[2\omega\left(1+\tfrac{4}{3}R_d\right)f_5 + \Pr(f_1 f_5 - N f_4 f_2) + \delta Pr f_4\right]/(1+2\omega\eta)\left(1+\tfrac{4}{3}R_d\right) \tag{10}$$

with boundary conditions

$$\left.\begin{array}{l} f_1(0) = S;\; f_2(0) = 1 + S_v f_3(0);\; f_4(0) = 1; \\ \text{and }\; f_2 \to 0;\quad f_4 \to 0\;\; as\;\; \eta \to \infty \end{array}\right\} \tag{11}$$

4. RESULTS AND DISCUSSIONS

Effects of various physical parameters e.g., curvature parameter, magnetic parameter, velocity slip parameter, temperature exponent, radiation parameter, Prandtl number, permeability parameter, heat source/sink parameter and suction/injection parameter on fluid velocity and temperature are shown through figures 2 to 9. Skin friction coefficient and Nusselt number for different values of these parameters are tabulated and discussed through Table 1.

Effect of magnetic parameter on fluid velocity and temperature are shown through Figure 2(a) and Figure 2 (b).

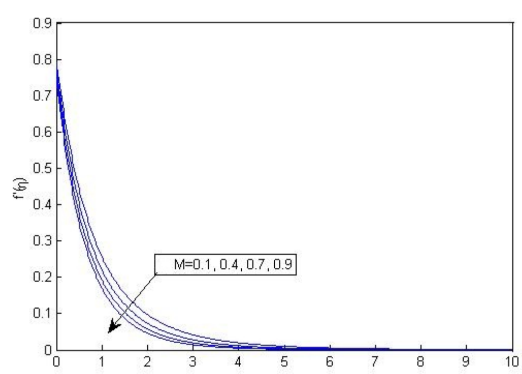

Figure 2 (a) Variation of velocity f'(η) with η for various values of magnetic parameter (M) when ω=0.25, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

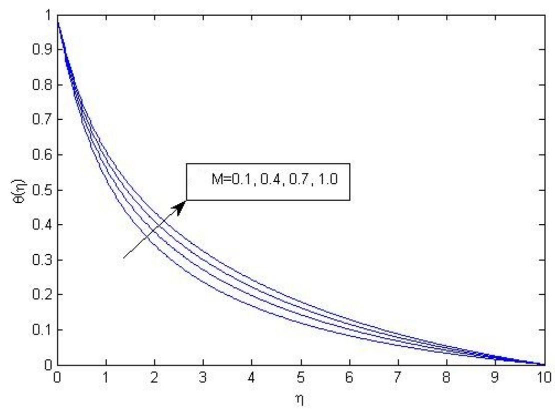

Figure 2 (b) Variation of temperature θ(η) with η for various values of magnetic field parameter (M) when ω=0.25, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

When magnetic field increases, a resistive force (Lorentz force) works against the flow of the fluid which results in decreasing fluid velocity and increasing fluid temperature. It is consistent with the data given in Table 1 which shows that skin friction decreases with decreasing fluid velocity while Nusselt number increases with increasing temperature difference. Figure 3(a) and Figure 3 (b) represent that both fluid velocity and temperature increase with enhancing values of velocity slip parameter. This is because there is a jump in velocity of the fluid layers adjacent to the wall due to increasing velocity slip parameter.

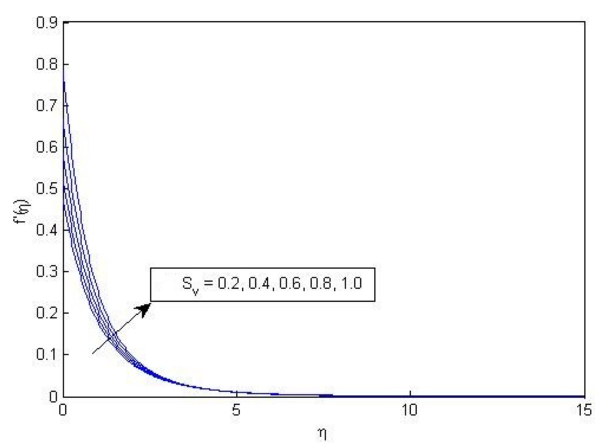

Figure 3 (a) Variation of velocity f'(η) with η for various values of slip parameter (S_v) when ω=0.25, M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1 and K=10

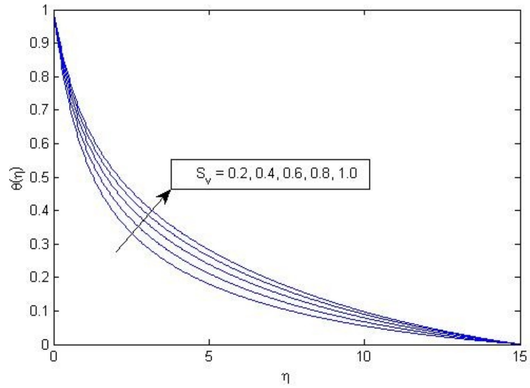

Figure 3 (b) Variation of temperature θ(η) with η for various values of slip parameter (S_v) at ω=0.25, M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1 and K=10.

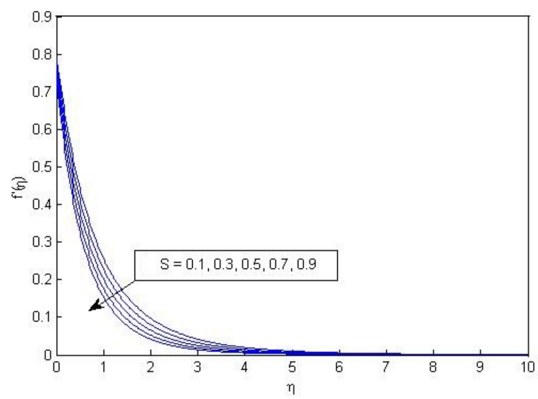

Figure 4 (a) Variation of velocity f'(η) with η for various values of suction/injection parameter (S) when ω=0.25, M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S_v=0.2 and K=10.

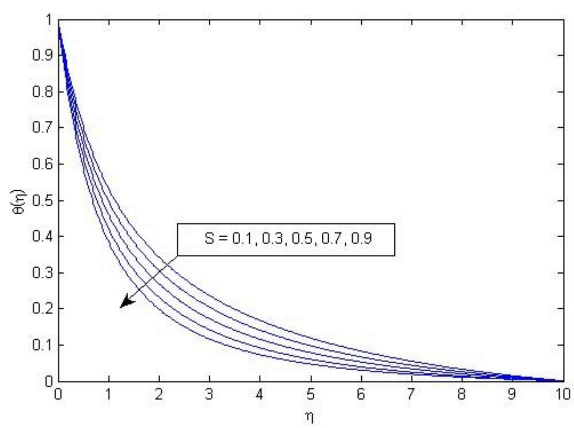

Figure 4(b) Variation of temperature θ(η) with η for various values of suction/injection parameter (S) when ω=0.25, M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S_v=0.2 and K=10.

Fluid velocity and temperature decrease with increasing suction parameter as depicted in Figure 4 (a) and Figure 4 (b). The physics behind this is when suction parameter increases some amount of fluid is sucked by the wall. Also, due to decreasing fluid velocity and temperature skin friction decreases while Nusselt number increases which can be verified from Table 1. Effect of permeability parameter on fluid velocity and temperature are shown through Figure 5 (a) and Figure 5 (b). When permeability parameter increases fluid velocity increases while temperature decreases. This is because increasing permeability parameter shows more assistance to the fluid flow and as a result fluid temperature decrease.

Figure 6(a) and Figure 6 (b) represent that both fluid velocity and temperature decrease with increasing curvature parameter.

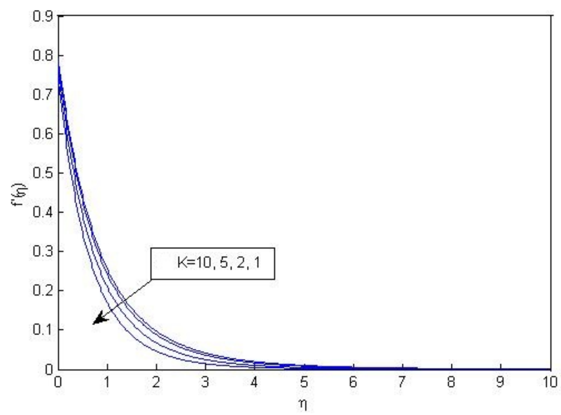

Figure 5 (a) Variation of velocity f'(η) with η for various values of permeability parameter (K) when ω=0.25, M=0.1, Pr=1,R_d=0.1, N=1, δ=0.1, S=0.1 and S_v=0.2.

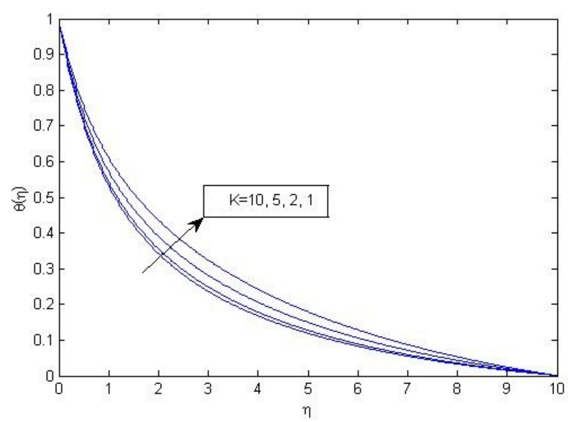

Figure 5 (b) Variation of temperature θ(η) with η for various values of permeability parameter (K) when ω=0.25, M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1 and S_v=0.2.

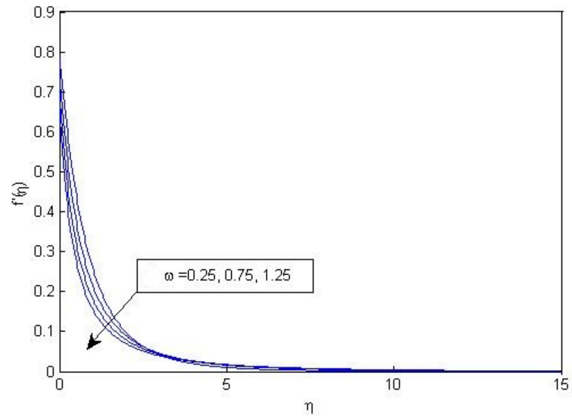

Figure 6 (a) Variation of velocityf'(η) with η for various values of curvature parameter (ω)when M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

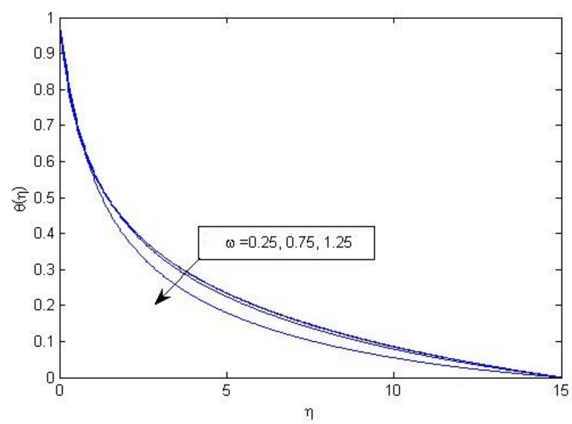

Figure 6 (b) Variation of temperature θ(η) with η for various values of curvature parameter (ω) when M=0.1, Pr=1, R_d=0.1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

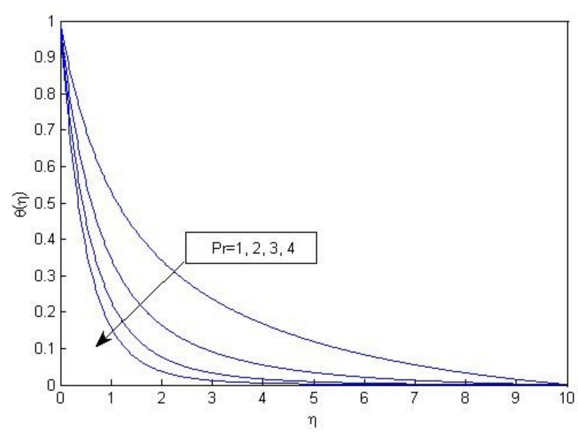

Figure 7 Variation of temperature θ(η) with η for various values of Prandtl number (Pr) when ω=0.25, M=0.1, R_d=0.1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

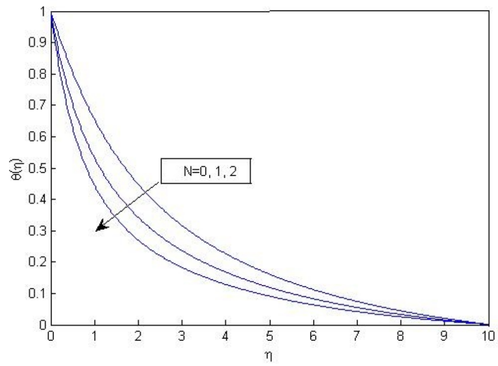

Figure 8 Variation of temperature θ(η) with η for various values of temperature exponent (N) when ω=0.25, M=0.1, Pr=1, R_d=0.1, δ=0.1, S=0.1, S_v=0.2 and K=10.

Figure 7 and Figure 8 depict that fluid temperature decreases with increasing Prandtl number or temperature exponent, while Figure 9 shows that temperature increases with increasing radiation parameter. When radiation parameter increases fluid elements consumes the radiated heat and get energized and as a result fluid temperature increases and Nusselt number decreases.

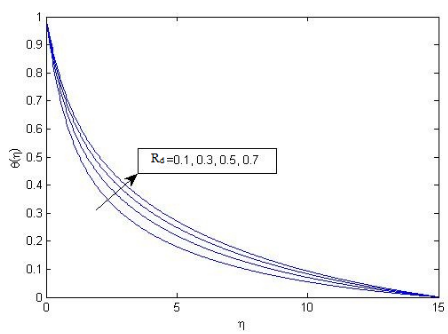

Figure 9 Variation of temperature θ(η) with η for various values of radiation parameter (R_d) when ω=0.25, M=0.1, Pr=1, N=1, δ=0.1, S=0.1, S_v=0.2 and K=10.

Variation in skin friction coefficient $(f''(0))$ and Nusselt number $(-\theta'(0))$ with respect to physical parameters are given in Table 1. The table shows that skin friction coefficient decreases when magnetic parameter, suction parameter or curvature parameters increases while it increases when velocity slip parameter or permeability parameter increases. Moreover, the table illustrate that the Nusselt number of the flow field decreases as the values of magnetic parameter, radiation parameter or velocity slip parameter increases, and it increases as the values of curvature parameter, Prandtl number, temperature exponent, suction parameter or permeability parameter increases.

Table 1 Numerical values of Skin friction coefficient $f''(0)$ and Nusselt number $-\theta'(0)$ for various values of physical parameters when $\delta = 0.1$.

ω	M	Pr	Rd	N	S	S_v	K	$f''(0)$	$-\theta'(0)$
0.25	0.1	1	0.1	1	0.1	0.2	10	-0.99027	0.75980
1.25								-1.41780	0.97500

0.4							-1.075795	0.74510
1.0							-1.213036	0.66515
	1							0.79765
	4							1.99500
		0.3						0.65800
		0.7						0.53800
			1				-0.990850	0.79765
			2				-0.990850	1.09190
				0.3			-1.06145	0.88200
				0.7			-1.21006	1.08500
					0.4		-0.798670	0.68200
					1.0		-0.515815	0.53650
						1	-1.213036	0.66550
						10	-0.990850	0.79765

Table 2 Comparison of numerical values of Nusselt number for different temperature exponents with previously published results when ω=0.0, M= 0.0 and Pr=1.

N	Ishak and Nazar [18]	Grubka and Bobba [Grubka and Bobba (1985) +	S. Mukhopadhyay [21]	Present study
0	0.5820	0.5820	0.5821	0.5720
1	1.0000	1.0000	1.0000	0.9870
2	1.3333	1.3333	1.3332	1.3201

Table 2 shows the comparison of Nusselt number for different values of temperature exponent with previous studies. The numerical results reveal that our results are in an excellent agreement with the results given by Ishak and Nazar [Ishak et al. (2008)], Grubka and Bobba [Grubka and Bobba (1985)], S. Mukhopadhyay [Mukhopadhyay (2013)] in limiting conditions.

5. CONCLUSIONS AND RECOMMENDATIONS

The numerical study has been done to examine the influence of thermal radiation and slip on velocity and heat transfer of MHD boundary layer flow over a stretching cylinder. From the study the following conclusions are drawn:

Fluid velocity and skin friction coefficient increase with increasing velocity slip parameter or permeability parameter.

Fluid velocity and skin friction coefficient decrease with increasing curvature parameter, magnetic parameter or suction/injection parameter.

Fluid temperature increases while Nusselt number decreases with increasing magnetic parameter, velocity slip parameter or radiation parameter.

Fluid temperature decreases while Nusselt number increases with increasing curvature parameter, suction parameter, permeability parameter, temperature exponent or Prandtl number.

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