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Heat and mass transfer by MHD flow near the stagnation point over a stretching or shrinking sheet in a porous medium

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A comprehensive numerical study of a steady two-dimensional stagnation point flow towards a heated linearly stretching or shrinking sheet in a porous medium immersed in viscous, incompressible and electrically conducting fluid in the presence of a uniform transverse magnetic field is presented. Using similarity transformation, the governing boundary layer partial differential equations are converted into non-linear ordinary differential equations and solved by Runge-Kutta fourth order method along with shooting technique. Some significant features of the flow and heat transfer in terms of velocity and temperature for various values of the governing parameters like, stretching or shrinking parameter, Prandtl number, permeability parameter, magnetic parameter and Eckert number are analyzed and presented through graphs while skin-friction coefficient and Nusselt number are shown numerically. Results of shear stress and heat transfer rate are also compared with the results of previous researchers.

Keywords: MHD flow**,** Stagnation point, Stretching sheet, Shrinking sheet, Porous media

1 Introduction

The practical applications of the dynamics of fluid flow over a stretching surface are of utmost importance, for example, extrusion of plastic sheets, glass blowing, paper production, drying of papers and textiles, drawing plastic films, metal spinning, continuous casting and spinning of fibers, etc. Since the quality of final product depends to a large extent on the skin friction coefficient and the surface heat transfer rate, so in all of the above cases, a study of the flow field and heat transfer can be of significant importance. Many researchers have investigated various aspects of this problem, such as consideration of mass transfer, exponentially stretching surface, magnetic field and application to non-Newtonian fluids, and similarity solutions have been obtained. Initially, Sakiadis[1] presented the boundary layer flow on a moving continuous solid surface. Later, Crane[2] studied a closed form solution of the two-dimensional flow over stretching sheet by considering the stretching velocity proportional to the distance from the slot. The problems of the flow through stretching surface have been investigated by Wang[3], Troy *et al*[4]., Vajravelu and Nayfeh[5], Mukhopadhyay and Andersson[6] and Jat and Chaudhary[7] in various conditions. Recently, Makinde and Aziz[8], Mahapatra *et al.*[9] and Chaudhary *et al.*[10] analyzed the flow over stretching surface in different cases.

In comparison to stretching sheet, less work has been done on the flow over a shrinking sheet. The boundary layer flow due to a shrinking surface has a wide area of applications like on a rising shrinking balloon, shrinking film and packaging of bulk products. On the shrinking surface, the generated vorticity is not confined physically within a boundary layer and a steady flow is not possible unless adequate suction is applied at the surface. Goldstein[11] presented the backward boundary layer flow in converging passages. Heat and mass transfer for viscous incompressible flow over shrinking surfaces have been studied by Miklavcic and Wang[12], Fang[13], Fang and Zhang[14] and Lok *et al.*[15]

Stagnation point virtually appears in all flow fields of engineering and science, so stagnation point flow is a topic of significance in fluid mechanics. The stagnation region encounters the highest heat transfer, the highest pressure and the highest rate of mass decomposition. Stagnation point flow has various applications in many manufacturing processes in industry. The applications include the boundary layer along material handling conveyers, the aerodynamic extrusion of plastic sheets, blood flow problems, processes in the textile and paper industries, flow over the tips of rockets, aircrafts, submarines and oil ships.

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The pioneering work in this area was carried out by Heimenz[16] who studied the steady boundary layer flow in the region of a stagnation point on an infinite wall. The extension to the axisymmetric case was presented by Homann[17]. Later, a large number of analytical and numerical studies explaining various physical situations of the boundary layer stagnation point flow are presented by Sparrow *et al.*[18], Chiam[19], Amin and Riley[20], Mahapatra and Gupta[21] and Wang[22]. Most recently, Rosali *et al.*[23], Mahapatra and Nandy[24] and Lok and Pop[25] considered the problem of stagnation point flow in various situations.

Flow through porous media has attracted a lot of attention because these are quite prevalent in nature. Such type of flow finds its applications in a broad spectrum of disciplines including chemical engineering and geophysics. It is also important in many technological processes, geothermal energy usage and in astrophysical problems. Many other applications may also benefit from a better understanding of fundamentals of mass, momentum, and energy transport in porous media, namely, petroleum reservoir operations, food processing, cooling of nuclear reactors, building insulation, underground disposal of nuclear waste, and casting and welding in manufacturing processes. Enhancement of forced convection by the use of a porous substrate has been the subject of several investigations. Comprehensive references on flow in porous media can be found in books by Ingham and Pop[26], Schlichting and Gersten[27], Vafai[28] and Nield and Bejan[29]. Moreover, Vafai and Kim[30] reported a composite system problem involving a relatively thin porous substrate attached to the surface of a flat plate. Thereafter, representative studies dealing with these effects have been studied by researchers such as Huang and Vafai[31], Yih[32], Jat and Chaudhary[33], Chaudhary and Kumar[34] and Khader[35].

In recent years, a number of simple fluid flow problems of viscous incompressible fluid have attained new attention in the more general context of magnetohydrodynamics. The desired properties of the end product and the rate of cooling can be controlled by the use of electrically conducting fluid and applications of magnetic field. The study of magnetohydrodynamic flow through a heated surface has important applications in many technological processes such as exotic lubricants and suspension solutions, magneto-hydrodynamic flight, foodstuff processing, MHD power generators, solidification of liquid crystals, the boundary layer control in aerodynamics, and in the field of planetary magnetosphere. Hydromagnetic boundary layer flow over a stretching surface has attracted attention of many researchers in recent time due to its important applications in metal-working processes and modern metallurgy. It seems that the magnetohydrodynamic flow over a stretching surface was first investigated by Andersson[36]. On the other hand, the problem of MHD stagnation point flow past a stretching sheet was presented by Mahapatra and Gupta[37]. Later, Abel and Mahesha[38], Ramesh *et al.*[39], Singh and Singh[40], Makinde *et al.*[41], Olajuwon and Oahimire[42], and Chaudhary and Kumar[43] analyzed and presented MHD flow problems considering various aspects of the problems.

Inspired by Rosali *et al.*[23], the objective of this present study is to investigate the effects of the magnetic parameter and the Eckert number on the boundary layer magnetohydrodynamic stagnation point flow over a stretching or shrinking surface immersed in a porous medium. It is expected that the obtained results can be served as a complement to previous studies providing useful information for applications.

2 Description of the Problem

Consider a steady, two-dimensional stagnation point flow of a viscous incompressible electrically conducting fluid impinging normally on a stretching or shrinking surface of constant temperature T_w in a porous medium. The stretching or shrinking surface is placed along *x*-axis. The fluid is subjected to a uniform transverse magnetic field of strength B_0 in the direction of *y*-axis, as shown in Fig. 1. The induced magnetic field is assumed to be small compared to the applied magnetic field, so it is negligible. The external flow velocity varies linearly along *x*-axis, i.e., $u_e(x) = ax$, where $a > 0$ is the strength of the stagnation flow and *x* is the coordinate measured along the stretching or shrinking surface. The ambient fluid temperature T_∞ is a constant. It is assumed that the velocity of the stretching or shrinking surface is $u_w(x) = bx$, where b is the stretching rate with $b > 0$ for stretching and $b < 0$ for shrinking. Therefore, with these assumptions the governing boundary layer equations can be expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad \dots (1)$$

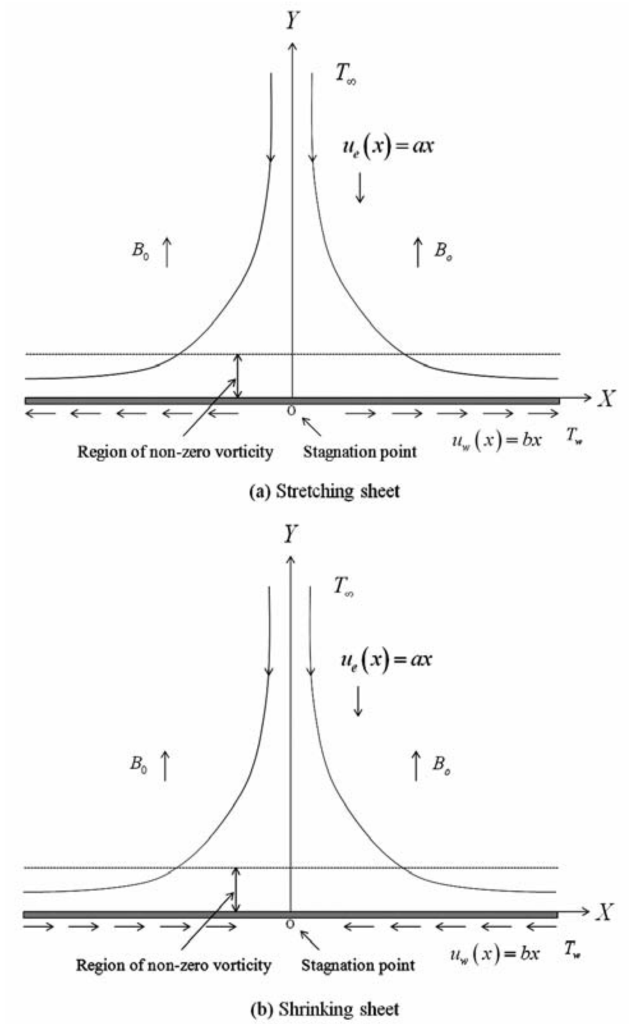

Fig. 1 – Physical model of the problem

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=u_e\frac{du_e}{dx}+\upsilon\frac{\partial^2 u}{\partial y^2}+\frac{\upsilon}{K_1}(u_e-u)+\frac{\sigma_e B_0^2}{\rho}(u_e-u) \quad \ldots (2)$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}+\frac{\mu}{\rho C_p}\left(\frac{\partial u}{\partial y}\right)^2+\frac{\sigma_e B_0^2}{\rho C_p}(u_e-u)^2 \quad \ldots (3)$$

with the appropriate boundary conditions:

$$\begin{aligned} y=0 \;\; &: \quad u=u_w(x)=bx, \quad T=T_w \\ y\to\infty \;\; &: \quad u=u_e(x)=ax, \quad T=T_\infty \end{aligned} \quad \ldots (4)$$

where u and v are the velocity components in the x and y directions, respectively, y is the coordinate measured along normal to the stretching or shrinking surface, υ is kinematic viscosity, K_1 is the permeability of the porous medium, σ_e is the electrical conductivity, ρ is the fluid density, T is the temperature of the fluid, α is the thermal diffusivity, μ is the coefficient of viscosity and C_p is the specific heat at constant pressure.

3 Similarity Solution

To obtain the similarity solution of the Eqs (1)-(3), with the boundary conditions Eq. (4), the stream function and the dimensionless variables can be defined as follows [Rosali *et al.*[23]]:

$$\psi(x,y)=\sqrt{\alpha x u_e}\, f(\eta) \quad \ldots (5)$$

$$\eta=\sqrt{\frac{u_e}{\alpha x}}\, y \quad \ldots (6)$$

$$T=T_\infty+(T_w-T_\infty)\,\theta(\eta) \quad \ldots (7)$$

where $\psi(x,y)$ is the stream function defined as $u = \partial\psi/\partial y$ and $v = -\partial\psi/\partial x$ which automatically satisfy the continuity equation (1), $f(\eta)$ is the dimensionless stream function, η is the similarity variable and $\theta(\eta)$ is the dimensionless temperature.

Substituting Eqs (5)-(7) into the momentum and the energy equations (2) and (3), we obtain the following nonlinear ordinary differential equations:

$$\Pr f'''+ff''-f'^2+K(1-f')+M(1-f')+1=0 \quad \ldots (8)$$

$$\theta''+f\theta'+Ec\left\{\Pr f''^2+M(1-f')^2\right\}=0 \quad \ldots (9)$$

with the transformed boundary conditions:

$$\begin{aligned} \eta=0 \;\; &: \quad f=0, \quad f'=c, \quad \theta=1 \\ \eta\to\infty &: \quad f'\to 1, \quad \theta\to 0 \end{aligned} \quad \ldots (10)$$

where primes denote differentiation with respect to η, $\Pr=\dfrac{\upsilon}{\alpha}$ is the Prandtl number, $K=\dfrac{\upsilon}{aK_1}$ is the permeability parameter, $M=\dfrac{\sigma_e B_o{}^2\upsilon \operatorname{Re}_x}{\rho u_e{}^2}$ is the magnetic parameter, $\operatorname{Re}_x=\dfrac{u_e x}{\upsilon}$ is the local Reynolds number, $Ec=\dfrac{u_e{}^2}{C_p(T_w-T_\infty)}$ is the Eckert number and $c=\dfrac{b}{a}$ is the stretching or shrinking parameter with $c>0$ for stretching and $c<0$ for shrinking.

4 Numerical Procedure

Equations (8) and (9) with the boundary conditions (10), are solved numerically using Runge-Kutta fourth order method along with shooting technique. By converting them into the following simultaneous linear differential equations of first order:

$$p_1' = p_2 \quad \ldots (11)$$

$$p_2' = p_3 \quad \ldots (12)$$

$$p_3' = -\frac{1}{\Pr}\left[p_1 p_3 - p_2^2 + K\left(1-p_2\right) + M\left(1-p_2\right) + 1\right] \quad \ldots (13)$$

And

$$q_1' = q_2 \quad \ldots (14)$$

$$q_2' = -\left[p_1 q_2 + Ec\left\{\Pr p_3^2 + M\left(1-p_2\right)^2\right\}\right] \quad \ldots (15)$$

with the converted boundary conditions:

$$\eta = 0: \quad p_1 = 0,\ p_2 = c,\ q_1 = 1$$
$$\eta \to \infty: \ p_2 \to 1,\ q_1 \to 0 \quad \ldots (16)$$

where $p_1 = f$, $p_2 = f'$, $p_3 = f''$, $q_1 = \theta$ and $q_2 = \theta'$.

To solve Eqs (13) and (15) as an initial value problem, the values of $p_3(0)$ and $q_2(0)$ are required. But no such values are given at the boundary. So the suitable guess values for $p_3(0)$ and $q_2(0)$ are chosen and the fourth order Runge-Kutta method with step size 0.001 is applied to obtain the solution. The computations have been carried out for various values of the stretching or shrinking parameter c, the Prandtl number $\Pr$, the permeability parameter K, the magnetic parameter M and the Eckert number Ec. A sixth decimal place accuracy is restricted for the sake of convergence.

5 Local Skin Friction and Surface Heat Transfer

The physical quantities of interest are the local skin friction coefficient C_f and the surface heat transfer, i.e., local Nusselt number Nu_x, which are defined as:

$$C_f = \frac{\mu\left(\dfrac{\partial u}{\partial y}\right)_{y=0}}{\dfrac{\rho u_e^{\,2}}{2}} \quad \ldots (17)$$

$$Nu_x = \frac{-x\left(\dfrac{\partial T}{\partial y}\right)_{y=0}}{T_w - T_\infty} \quad \ldots (18)$$

Using the similarity variables (5) - (7), we obtain

$$\frac{1}{2} C_f \sqrt{\mathrm{Re}_x} = f''(0) \quad \ldots (19)$$

$$\frac{Nu_x}{\sqrt{\mathrm{Re}_x}} = -\theta'(0) \quad \ldots (20)$$

where the function $f''(0)$ and $\theta'(0)$ present the wall shear stress and the heat transfer rate at the surface respectively.

6 Results and Discussion

The computational results are demonstrated in graphical and tabular form. In order to develop a better understanding of the physical problem, as display the influences of various parameters such as the stretching or shrinking parameter c, the Prandtl number $\Pr$, the permeability parameter K, the magnetic parameter M and the Eckert number Ec on the velocity $f'(\eta)$, the temperature $\theta(\eta)$, the shear stress $f''(0)$ and the heat transfer rate $\theta'(0)$.

Figures 2 and 3, display the effects of the stretching or shrinking parameter c on the velocity $f'(\eta)$ and the temperature $\theta(\eta)$ profiles respectively, while the other parameters are constant. These figures show that the velocity increases with the increasing values of the stretching or shrinking parameter c while the temperature decreases for an increment in the stretching or shrinking parameter c. Thus the actual effect of the stretching or shrinking parameter is to make the temperature distribution more uniform within the boundary layer. So, it can be effectively used for the fast cooling of the sheet.

The velocity $f'(\eta)$ and temperature $\theta(\eta)$ distribution for various values of the Prandtl number $\Pr$ are shown in Figs 4 and 5 respectively, keeping other parameters constant. From these figures it is evident that the velocity decreases with the increasing values of the Prandtl number $\Pr$ while in the same

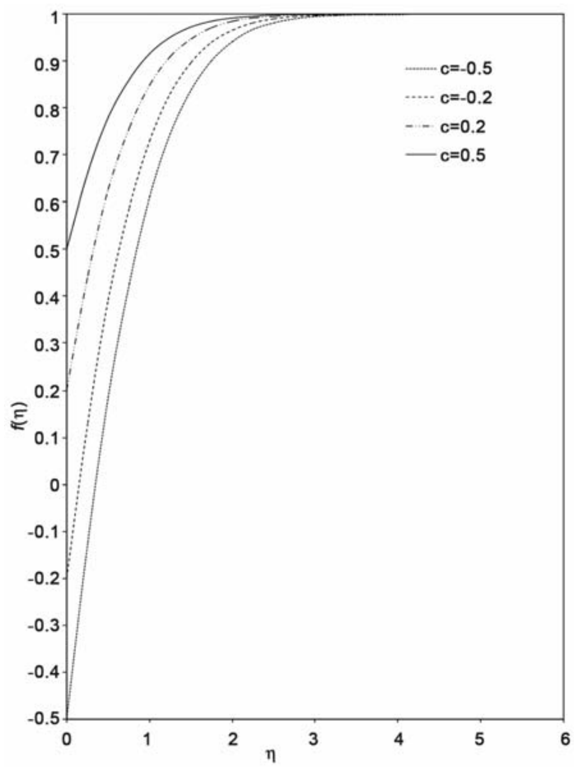

Fig. 2 – Effects of c on the velocity distribution for $\mathrm{Pr}=1.0,\ K=0.1$ and $M=0.1$

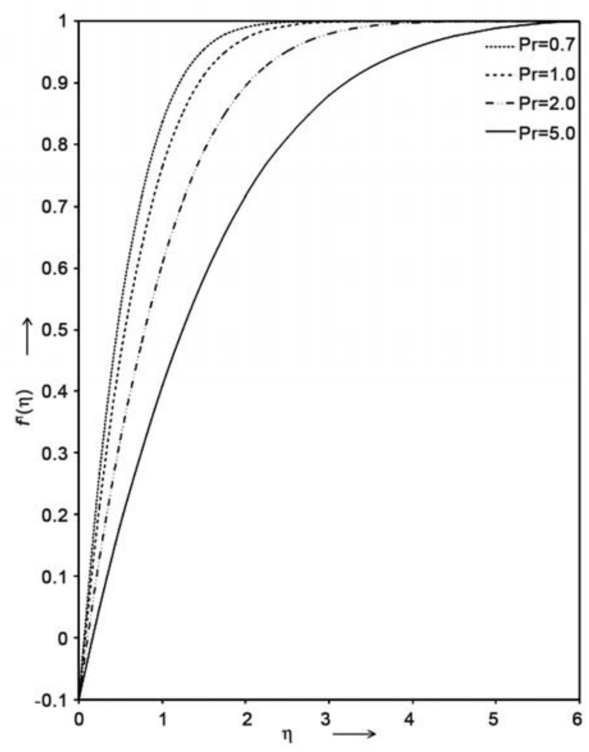

Fig. 4 – Effects of Pr on the velocity distribution for $c=-0.1, K=0.1$ and $M=0.1$

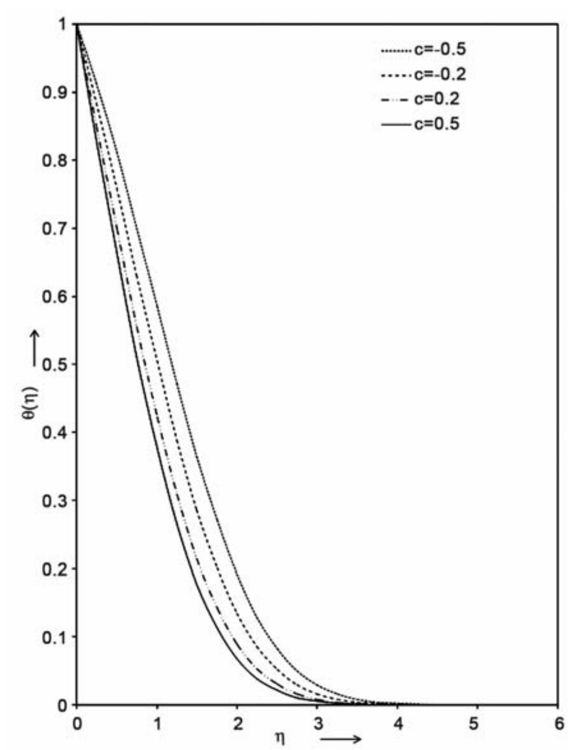

Fig. 3 – Effects of c on the temperature distribution for $\mathrm{Pr}=1.0,\ K=0.1,\ M=0.1$ and $Ec=0.1$

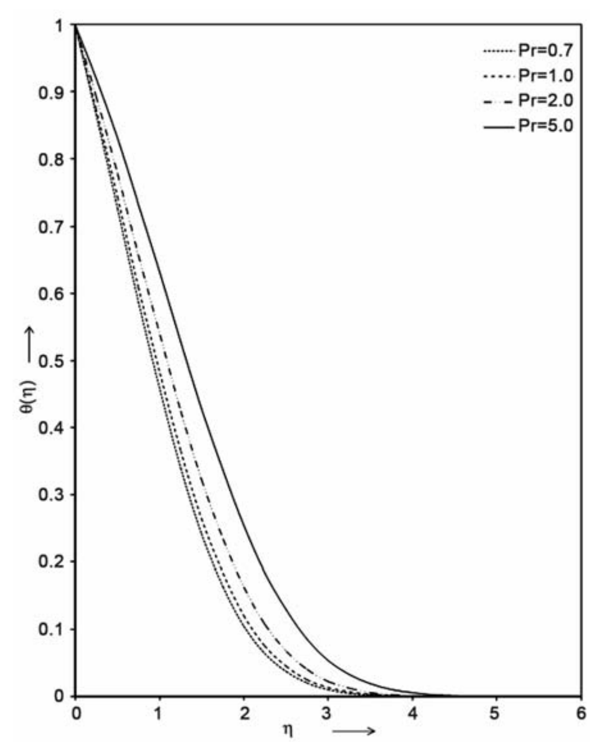

Fig. 5 – Effects of Pr on the temperature distribution for $c=-0.1, K=0.1,\ M=0.1$ and $Ec=0.1$

case the temperature increases accordingly. This is due to the fact that the increasing values of the Prandtl number reduce the thermal boundary layer thickness. It can be noticed that the temperature distribution asymptotically approaches to zero in the free stream region. So, in heat transfer problems the Prandtl number controls the relative thickness of flow and thermal boundary layers, and can be used to increase the cooling rate.

Figures 6 and 7 plotted the influences of the permeability parameter K on the velocity $f'(\eta)$ and the temperature $\theta(\eta)$ profiles respectively, taking other parameters constant. From these figures it can be seen that the velocity increases with the increasing values of the permeability parameter K but the reverse is true for the temperature distribution. For higher values of the permeability parameter the velocity profile is nearly uniform in which the velocity boundary layer is confined within a very thin region. This phenomenon occurs for the assumption of pure Darcy flow. It is also clear that the velocity is more sensitive to the permeability parameter than the temperature profiles, as compared in these figures.

The influence of different values of the magnetic parameter M on the velocity $f'(\eta)$ and the temperature $\theta(\eta)$ distribution are presented in Figs 8 and 9 respectively, where the other parameters are kept constant. These figures indicate that the velocity increases with the increasing values of the magnetic parameter M but the opposite behavior is true for the temperature distribution. From a physical point of view, this can be explained by the fact that the application of a uniform magnetic field normal to the flow direction gives rise to a force which is known as Lorentz force. This force is positive and consequently as the magnetic parameter M increases, the force also increases and hence accelerates the flow and decelerates its temperature.

Figure 10 exhibits the temperature $\theta(\eta)$ profiles for the variation in the Eckert number Ec keeping other parameters constant. In this case, it is noteworthy that the Eckert number Ec has an increasing effect on the temperature profiles. This is a consequence of the fact that for higher values of the Eckert number, there is significant generation of heat due to viscous dissipation near the sheet. Therefore, viscous dissipation in a flow through porous surface is beneficial for gaining the temperature.

Table 1 shows the effects of the stretching or shrinking parameter c, the Prandtl number $\Pr$, the

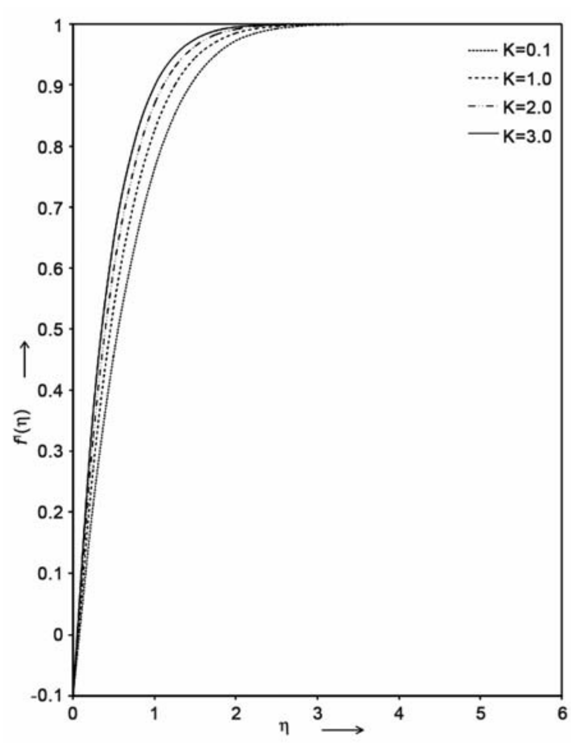

Fig. 6 – Effects of K on the velocity distribution for $c=-0.1, \Pr=1.0$ and $M = 0.1$

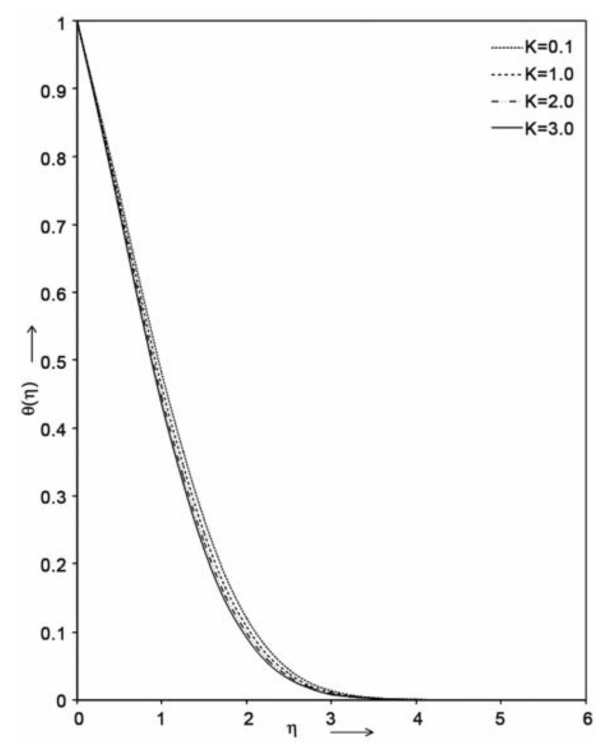

Fig. 7 – Effects of K on the temperature distribution for $c=-0.1, \Pr=1.0$, $M=0.1$ and $Ec = 0.1$

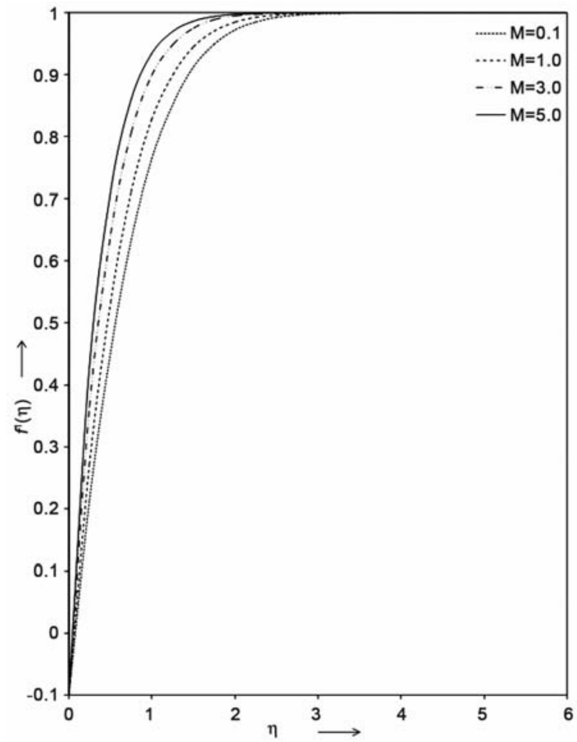

Fig. 8 – Effects of M on the velocity distribution for $c=-0.1, \mathrm{Pr}=1.0$ and $K=0.1$

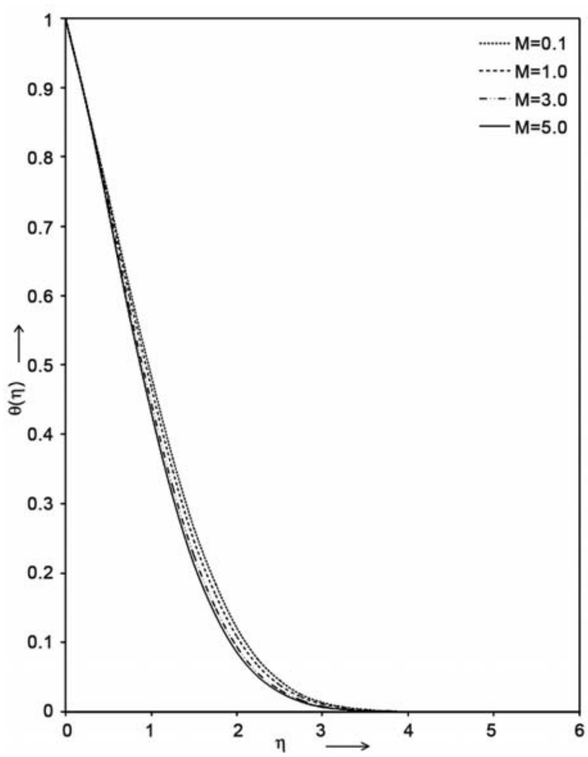

Fig. 9 – Effects of M on the temperature distribution for $c=-0.1, \mathrm{Pr}=1.0,\ K=0.1$ and $Ec=0.1$

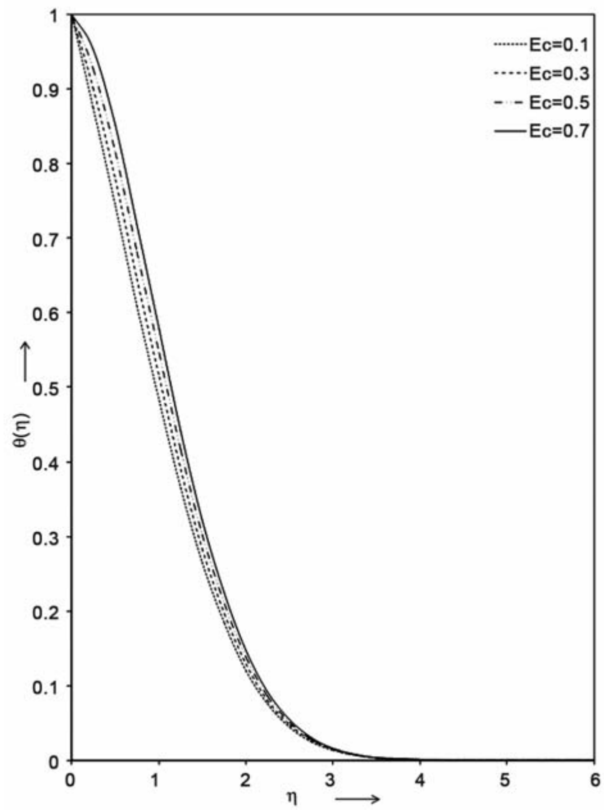

Fig. 10 – Effects of Ec on the temperature distribution for $c=-0.1, \mathrm{Pr}=1.0,\ K=0.1$ and $M=0.1$

Table 1 – Numerical values of $f''(0)$ for different values of c, Pr, K and M

c	Pr	K	M	$f''(0)$
- 0.5	1.0	0.1	0.1	1.640077
- 0.2				1.474584
0.2				1.109737
0.5				0.747083
- 0.1	0.7	0.1	0.1	1.670304
	1.0			1.397476
	2.0			0.988166
	5.0			0.625275
- 0.1	1.0	1.0	0.1	1.742807
		2.0		2.060220
		3.0		2.335104
- 0.1	1.0	0.1	1.0	1.742807
			3.0	2.335104
			5.0	2.805457

permeability parameter K and the magnetic parameter M on the wall shear stress $f''(0)$. It is seen that the wall shear stress $f''(0)$ decreases with the increasing values of the stretching or shrinking parameter c and the Prandtl number Pr when other parameters are constant while a reverse phenomenon occurs for the permeability parameter K and the magnetic parameter M. From physical point of view, positive sign of skin friction coefficient means the fluid exerts a drag force on the surface while the negative sign means the opposite.

The variation of the reduced Nusselt number $\theta'(0)$ for several values of the stretching or shrinking parameter c, Prandtl number $\Pr$, the permeability parameter K, the magnetic parameter M and the Eckert number Ec are presented in Table 2. It is numerically seen that the heat transfer rate $\theta'(0)$ decreases with the increasing values of the stretching or shrinking parameter c and the permeability parameter K but an opposite behavior is noted in the case of the Prandtl number $\Pr$, the magnetic parameter M and the Eckert number Ec, taking other parameters constant. Moreover it is quite evident that the values of the heat transfer rate $\theta'(0)$ are always negative for all the values of physical parameters considered. Practically, negative sign of Nusselt number means that there is a heat flow from the surface.

Table 2 – Numerical values of $\theta'(0)$ for different values of $c, \Pr, K, M$ and Ec

c	$\Pr$	K	M	Ec	$-\theta'(0)$
- 0.5	1.0	0.1	0.1	0.1	0.314390
- 0.2					0.437600
0.2					0.583240
0.5					0.676620
- 0.1	0.7	0.1	0.1	0.1	0.511050
	1.0				0.476115
	2.0				0.401936
	5.0				0.291996
- 0.1	1.0	1.0	0.1	0.1	0.484310
		2.0			0.487360
		3.0			0.487370
- 0.1	1.0	0.1	1.0	0.1	0.457348
			3.0		0.418457
			5.0		0.383180
- 0.1	1.0	0.1	0.1	0.3	0.326960
				0.5	0.177807
				0.7	0.028650

In order to validate the accuracy of computational results obtained in present study, the values of the wall shear stress and the heat transfer rate are compared with the previous results of Sparrow et al.[18], Yih[32] and Lok and Pop[25] in Table 3. From the table it can be seen that the results are in an excellent agreement.

7 Conclusions

The combined effects of the stretching or shrinking parameter, the Prandtl number, the permeability parameter, the magnetic parameter and the Eckert number on two-dimensional boundary layer magnetohydrodynamic stagnation point flow were studied numerically. The governing equations were transferred to a set of ordinary differential equations by using similarity variables and computational results for the velocity, the temperature, the wall shear stress and the heat transfer rate at the surface are made by Runge-Kutta fourth order method in the association with shooting technique. From the results of the problem, it can be concluded that the velocity profile is changing due to the stretching or shrinking parameter, the permeability parameter, the magnetic parameter and the Prandtl number. These changes are revealed by the velocity increases with the increasing values of the stretching or shrinking parameter, the permeability parameter and the magnetic parameter while it decreases with the increase in the Prandtl number. On the other hand, the thermal boundary layer thickness decreases for the increasing values of the stretching or shrinking parameter, the permeability parameter and the magnetic parameter but an opposite behavior occurs for the Prandtl number and the Eckert number. Moreover the local skin friction coefficient decreases with the stretching or shrinking parameter

Table 3 – Comparison of the values of $f''(0)$ and $-\theta'(0)$ with the previous literature results for $\Pr = 1.0$, $K = 0.0$ and $Ec = 0.0$

c	M	$f''(0)$				$-\theta'(0)$		
		Sparrow[18]	Yih[32]	Lok and Pop[25]	Present Study	Sparrow[18]	Yih[32]	Present Study
-0.5	0.0	-	-	1.49567	1.49567000	-	-	-
-0.2		-	-	1.05113	1.05113000	-	-	-
0.5		-	-	0.71329	0.71329500	-	-	-
0.0	0.0	1.231	1.232588	1.23259	1.23258800	0.5705	0.570465	0.5704650
	1.0	1.584	1.585331	-	1.58533100	0.5953	0.595346	0.5953460
	4.0	2.345	2.346663	-	2.34666262	0.6341	0.634132	0.6341319

and the Prandtl number while the reverse phenomenon occurs for the permeability parameter and the magnetic parameter. Finally, the surface heat transfer rate decreases with the stretching or shrinking parameter and the permeability parameter but the reverse behavior is noted for the Prandtl number, the magnetic parameter and the Eckert number.

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