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Similarity Solution on MHD Boundary Layer over Stretching Surface Considering Heat Flux

M. Ferdows*, Tania S. Khaleque and M.Z.I. Bangalee

Research group of Fluid Flow Modeling and Simulation, Department of Applied Mathematics, University of Dhaka, Dhaka-1000, Bangladesh

Email: ferdows@du.ac.bd

ABSTRACT

This article investigates the influence of variable heat flux on the problem of steady two dimensional MHD flow and heat transfer of an electrically conducting fluid along a semi-infinite vertical plate taking into account the effect of viscous dissipation. The governing equations are converted into a system of nonlinear ordinary differential equations via a similarity variable. The resulting system of equations is then solved numerically by using Natchsheim Swigert shooting iteration technique together with sixth order Runge-Kutta integration scheme. Boundary layer velocity and temperature profiles are determined numerically for various values of the ratio of free stream velocity and stretching velocity, the magnetic field parameter, suction/blowing parameter, Brinkman number. Regardless of the flow conditions, the flow velocity and temperature is found significantly affected by the flow parameters.

Keywords: MHD, Stretching surface, Similarity solution, Heat flux.

1. INTRODUCTION

The continuous surface heat and mass transfer has many practical applications in electro-chemistry and polymer processing such as hot rolling, wire drawing, glass blowing, metal spinning, paper production, crystal growing, purification of molten metals from non-metallic inclusion by applying magnetic field, aerodynamic extrusion of plastic sheet, continuous casting, glass fibre production and many more. Sakiadis [1], [2] was the first to study boundary layer flow of a viscous fluid over a stretched surface moving with a constant velocity in an ambient fluid. Erickson et al. [3] and Tsou et al. [4] extended the work of Sakiadis to account for mass transfer in the boundary layer on a continuous moving surface. Chen and Char [5], Elbashbeshy [6] investigated the effects of variable and uniform surface temperature and surface heat flux subject to blowing or suction. Crane [7], Gupta and Gupta [8] studied the boundary layer flow caused by a stretching sheet whose velocity varies linearly with a distance from a fixed point on the surface under different conditions. Magneto-hydrodynamics (MHD) free convection flow has a great significance for the applications in the fields of stellar and planetary magnetospheres, aeronautics and MHD flow and heat transfer problems have become more important industrially. In many metallurgical processes involving the cooling of many continuous strips or filaments by drawing them through an electrically conducting fluid subject to a magnetic field, the rate of cooling can be controlled and final product of desired characteristics can be achieved. Chakrabarti and Gupta [9], Ishak et. al. [10], Kumar et al. [11], Kafoussias and Nanousis [12], Anjali and Kanda [13] investigated MHD flow heat and mass transfer over a stretching sheet in different aspects. Mahapatra and Gupta [14], Chiam [15], Nazar et al. [16], Ostrach [17] and Sparrow and Gregg [18] investigated the stagnation-point flow on a stretching sheet. The problem of natural convection along a vertical isothermal or uniform flux plate is a classical problem that has been solved with the similarity method. In these works the viscous dissipation term in the energy equation has been omitted. Gebhart [19] was the first who studied the problem taking into account the viscous dissipation. Recently, Pantokratoras [20], Hossain et al. [21] studied the effect of viscous dissipation in natural convection in a new way. Hitesh [22] investigated hydromagnetic flow with viscous dissipation, variable heat flux and radiation. Parash and Hazarika [23] studied computationally study of the effects of variable viscosity and thermal conductivity on the MHD flow of micropolar fluid past an accelerated infinite vertical insulated plate. Sharif [24] investigated numerically the effects of heat generation or absorption and thermophoresis on hydromagnetic free convective and mass transfer steady laminar boundary layer flow over an inclined permeable stretching sheet. On the other hand, numerical solution for axisymmetric flow and heat transfer over a stretching cylinder surface subject to a uniform magnetic field and prescribed surface heat flux has been studied by Fazle et al. [25].

In this paper we investigate the effects of viscous dissipation on the steady two-dimensional stagnation-point flow of an incompressible viscous fluid towards a stretching surface subject to variable heat flux and suction/blowing in presence of transverse magnetic field.

2. EQUATION OF MOTION

Let us consider the magneto-hydrodynamic two dimensional steady boundary layer flow of an incompressible viscous and electrically conducting fluid from a vertically moving surface with suction or injection at the surface. Two equal and opposite forces are introduced along the x-axis so that the sheet is stretched, keeping the origin fixed in the fluid of ambient temperature T_∞. It is assumed that the speed of a point on the plate is proportional to its distance from the origin. It is also assumed that the heat flux at the stretching surface varies as the square of the distance from the origin.

In MHD flows, the size of electromagnetic parameters affects the quantitative interaction between the flow and field. The magnetic field vector $\vec{B}=(B_x,B_y)$ is assumed to lie in the xy plane. The electrical field E is assumed to be zero. Hughes and Young [26] have shown that the Lorentz force has two components:

$$F_x=-\sigma\left(uB_y^2-vB_xB_y\right),$$

$$F_y=\sigma\left(uB_xB_y-vB_x^2\right),$$

where u and v are the velocity components in the x and y directions respectively. From an "order of magnitude" analysis, it can be assumed that $B_y=o\left(B_x\right)$. Invoking the boundary layer approximation $\left(u\geq v\right)$, F_x simplifies to $F_x=-\sigma B_y^2u$, where the y-component of the magnetic field may be dependent on both x and y; however, for convenience, it is assumed that B_y varies only with the span-wise coordinate y. So, according to El-Amin [27], if a strong magnetic field B_0 is applied in the y-direction then it gives rise to magnetic forces $F_x=-\sigma B_0^2u$ in x-direction.

For steady-state incompressible viscous fluid environment with constant properties using Boussinesq approximation, the governing equations for convective flow are:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\upsilon\frac{\partial^2 u}{\partial y^2}+u_e\frac{du_e}{dx}+\frac{\sigma B_0^{\,2}}{\rho}\left(u_e-u\right) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{k}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{\upsilon}{c_p}\left(\frac{\partial u}{\partial y}\right)^2 \tag{3}$$

subject to the following boundary conditions:

$$\left.\begin{array}{c} u=u_w=cx,\ v=-v_0,\ \dfrac{\partial T}{\partial y}=Ax^2 \ \text{ at } y=0 \\ u\to u_e(x)=ax, T=T_\infty \text{ as } y\to\infty \end{array}\right\} \tag{4}$$

where u_e is the stagnation-point velocity in the inviscid free stream, T is the fluid temperature, υ is the kinematic viscosity, σ is the electric conductivity, B_0 is the uniform magnetic field strength, ρ is the density of the fluid, k is the thermal conductivity of the fluid, c_p is the specific heat at constant pressure and a, c and A are positive constants. It may be noted that the constant a is proportional to the free stream velocity far away from the stretching surface.

In order to obtain a similarity solution of the problem, we now introduce the following dimensionless variables:

$$\eta=y\sqrt{\frac{c}{\upsilon}},\ \psi=\sqrt{c\upsilon}xf(\eta),\ T=T_\infty+(T_w-T_\infty)\theta(\eta) \tag{5}$$

where ψ is the stream function, η is the dimensionless distance normal to the sheet, f is the dimensionless stream function and θ is the dimensionless fluid temperature. Now

$$u=\frac{\partial\psi}{\partial y}=cxf'(\eta)\ \ v=-\frac{\partial\psi}{\partial x}=-\sqrt{c\upsilon}f(\eta) \tag{6}$$

In order to solve equation (3) we assume

$$T=T_\infty+A\sqrt{\frac{\upsilon}{c}}x^2\theta\left(\eta\right) \tag{7}$$

Using the transformations from equations (6) and (7) in equations (2) and (3), we get the following dimensionless equations:

$$f'''+ff'-(f')^2+\frac{a^2}{c^2}+M(\frac{a}{c}-f')=0 \tag{8}$$

$$\theta''+\Pr(f\theta'-2f'\theta)+B_r(f'')^2=0 \tag{9}$$

The transformed boundary conditions are:

$$\left.\begin{array}{c} f=f_w=\dfrac{v_0}{\sqrt{c\upsilon}},\ f'=1,\theta'=1 \quad at \quad \eta=0 \\ f'=\dfrac{a}{c},\theta=0 \quad as \quad \eta\to\infty \end{array}\right\} \tag{10}$$

where a prime denotes an ordinary differentiation with respect to η, $\frac{a}{c}$ is the ratio of free stream velocity parameter to stretching sheet parameter, $M=\frac{\sigma B_0^2}{\rho c}$ is the magnetic field parameter, $f_w=\frac{v_0}{\sqrt{c\upsilon}}$ is the suction/injection parameter, $\Pr = \frac{\mu c_p}{k}$ is the Prandtl number, $B_r = \Pr Ec$ is the Brinkman number where $Ec = \frac{c^{5/2}}{A c_p \sqrt{\upsilon}}$ is the Eckert number.

Here $f_w > 0$ (i.e. $v_0 > 0$) corresponds to suction and $f_w < 0$ (i.e. $v_0 < 0$) corresponds to blowing and Brinkman number is a dimensionless dissipation parameter arises naturally and it represents the ratio of dissipation effects to fluid conduction effects. A Brinkman number of order unity or greater means that the temperature rise due to dissipation is significant, on the other hand, $B_r = 0.0$ indicates temperature rise due to pure conduction in the fluid (White [28]).

Of special significance in convection problems are the local skin friction coefficient and the local Nusselt number. The shear stress at the stretching surface τ_w is given by $\tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0}$ and skin friction coefficient C_f is defined as $C_f = \frac{\tau_w}{\rho u^2 / 2}$.

The local wall heat flux is given by Fourier's law of conduction: $q_w = -k \left(\frac{\partial T}{\partial y} \right)_{y=0}$ and local Nusselt number is defined as $Nu_x = \frac{x q_w}{k(T_w - T_\infty)}$. Using the non-dimensional variables, we get

$$\frac{1}{2} C_f \operatorname{Re}_x^{1/2} = f''(0) \quad \text{and}$$
$$Nu_x / \operatorname{Re}_x^{1/2} = -\theta'(0) \tag{11}$$

where $\operatorname{Re}_x = ax/\upsilon$ is the local Reynolds number.

3. NUMERICAL METHOD FOR SOLUTION

The numerical solutions of the nonlinear differential equations (8)-(9) under the boundary conditions (10) have been performed by applying a shooting method called Nachtsheim-Swigert iteration technique, Nachtsheim and Swigert [29] along with the sixth order Runge-Kutta-Butcher integration scheme. Thus adopting this numerical technique, a computer program was set up for the solutions of the governing differential equations of our problem. Various groups of parameters $f_w, M, \Pr, B_r, \frac{a}{c}$ were considered in different phases. In all the computations the step-size $\Delta\eta = 0.001$ was selected that satisfied the convergence criterion of 10^{-6} in all cases. The value of η_∞ was found to each iteration loop by $\eta_\infty = \eta_\infty + \Delta\eta$. The maximum value of η_∞ to each group of parameters is determined when the value of the unknown boundary conditions at $\eta = 0$ change to successful loop with error less than 10^{-6}.

4. RESULTS AND DISCUSSION

In Fig.1, we represent the result for the variation of the parameter a/c when $\Pr = 0.7, M = 2.0, f_w = 0.5$ and $B_r = 3.0$ (though velocity profiles does not change with B_r). Two sets of values for a/c, i.e. $a/c < 1$ and $a/c > 1$ are considered. It can be easily observed that the horizontal velocity profiles increase with the increase of non-zero values of a/c. The figure shows that when $a/c > 1$, the flow has a boundary layer structure and the thickness of the boundary layer reduces as a/c increases. For fixed value of c, corresponding to the stretching of the surface, increase in a in relation to c (such that $a/c > 1$) implies increase in straining motion near the stagnation region. Due to this reason the acceleration of the external stream is increased and this leads to thinning of the boundary layer (Layek et al. [30]). On the other hand when $a/c < 1$, the flow has an inverted boundary layer structure. In this case, the stretching velocity (cx) of the sheet exceeds the velocity (ax) of the external stream. It is to be noted that no boundary layer is formed when $a/c = 1$. The figure also shows that the temperature curves increase with the increase of a/c in both the cases of pure conduction (when $B_r = 0.0$ i.e. neglecting viscous dissipation) and the conduction with viscous dissipation ($B_r = 1.0$).

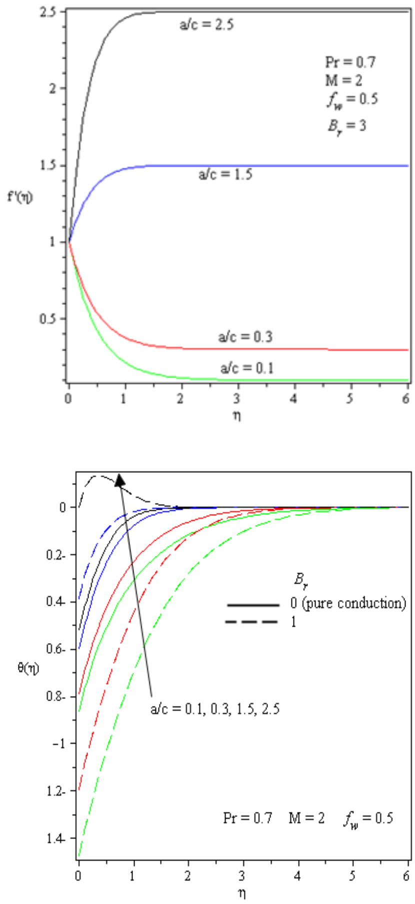

Figure 1. Effect of parameter a/c

In Fig.2, the dimensionless velocity distributions $f'(\eta)$ and temperature distributions $\theta(\eta)$ are plotted against η for different values of Brinkman number B_r. The case of pure conduction is also shown in the figure (i.e. when $B_r = 0.0$). The momentum boundary layer thickness decreases with the increase of B_r. However, the function $f'(\eta)$ is negative for all values of B_r. Contrary to velocity profiles, the temperature profiles increase as the Brinkman number increases.

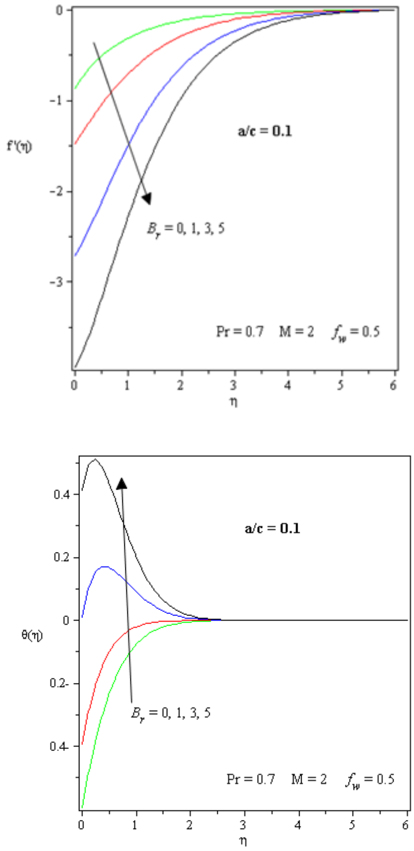

Figure 2. Effect of Brinkman parameter B_r

Fig.3 shows the effect of suction parameter f_w on the boundary layers. It is seen that the velocity profiles decrease monotonically with an increase of suction parameter indicating the usual fact that suction stabilizes the boundary layer growth. Thus sucking the decelerated fluid particles reduces the growth of the fluid boundary layer. However, we observe that the temperature profiles increase with the increase of suction parameter f_w in both the cases where viscous dissipation effect is considered and neglected as is seen by Hitesh Kumar [22].

Fig.4 displays the effect of the variation of Prandtl number Pr on the thermal boundary layers. In both the cases $B_r = 0.0$ and $B_r = 1.0$, the thickness of thermal boundary layers increase with the increase in Prandtl number Pr.

The effect of magnetic field parameter M on the velocity and temperature profiles with $\Pr = 1.0$, $f_w = 0.5$ and $B_r = 3.0$ is shown in Fig.5 and Fig.6 considering two different cases of $a/c = 0.3$ and $a/c = 1.5$. When $a/c = 0.3 < 1$, the velocity curves show that the rate of transport is considerably reduced with the increase of magnetic field parameter M. This is due to the fact that the variation of M leads to the variation of Lorenz force due to magnetic field and the Lorenz force produces more resistance to the transport phenomena.

However, for a fixed value of $a/c = 1.5$ with $a/c > 1$, the velocity curves shows an opposite behaviour with the increase of M. Here, the velocity at a point increases with M. This can be explained by the fact that when $a/c < 1$, the velocity of the stretching sheet exceeds the velocity of the inviscid stream and an inverted boundary layer is formed near the surface. Thus it is expected that the horizontal velocity at a point in this boundary layer increases with increase in M. From Fig.6, we observe that temperature profiles decrease with the increase of magnetic field parameter M in both the cases.

So, for a fixed value of a/c with $a/c < 1$ the transverse velocity at a point decreases with increase in M due to the inhibiting influence of the Lorenz forces.

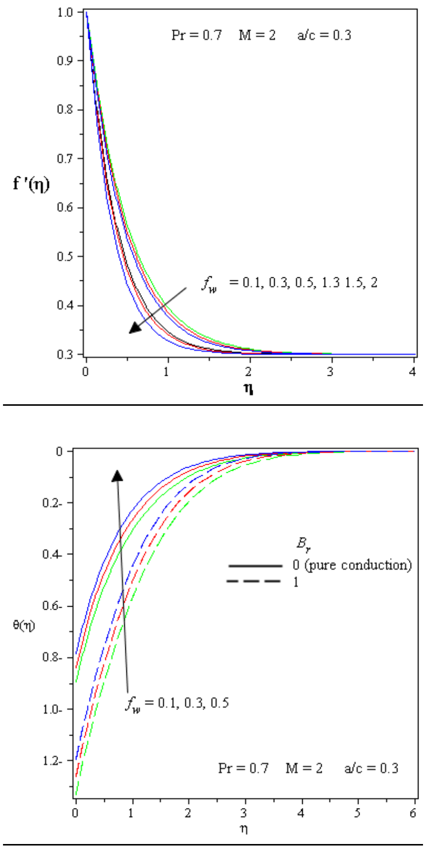

Figure 3. Effect of Suction parameter f_w

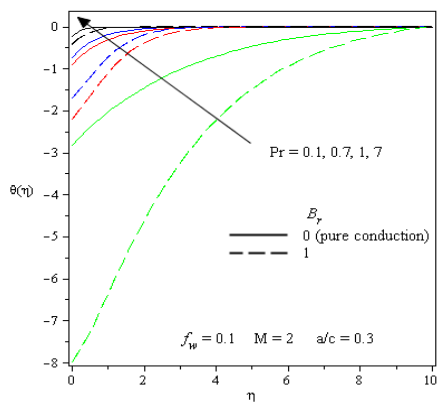

Figure 4. Effect of Prandtl parameter P_r

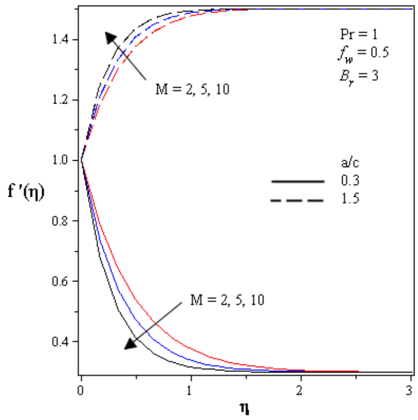

Figure 5. Effect of Magnetic parameter M

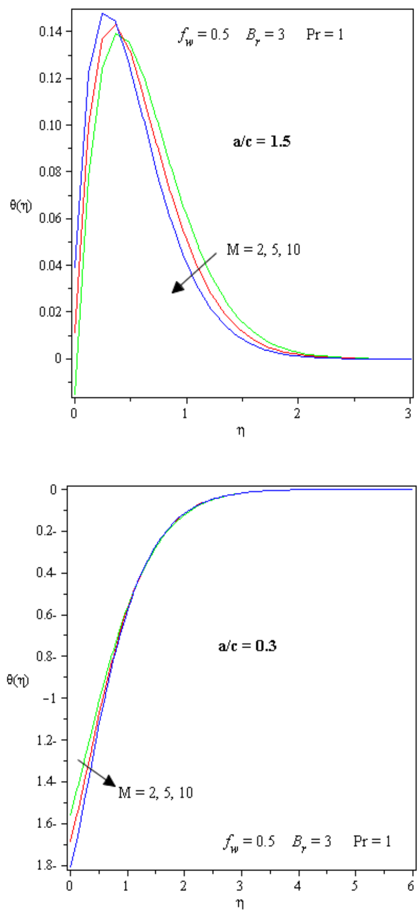

Figure 6. Effect of Magnetic parameter M with a/c

Tables 1 and 2 display the numerical results for $-f''(0)$ and $\theta'(0)$ for different values of a/c, M, f_w, Pr and B_r. Numerical values in Table 1 indicate that an increase of a/c increases the wall shear stress and whereas an increase of M and f_w decreases the wall shear stress. However, rate of heat transfer i.e. Nusselt number (Nu) increases as a/c, f_w increase and Nu decreases as the values of B_r, Pr increase.

Table 1. Values of $-f''(0)$ and $\theta'(0)$ for various values of M, a/c and f_w when $\Pr = 1$ and $B_r = 3$

a/c	M	$-f''(0)$, $f_w = 0.1$	$f_w = 0.3$	$f_w = 0.5$	$\theta'(0)$, $f_w = 0.1$	$f_w = 0.3$	$f_w = 0.5$
0.1	2	1.6441	1.7398	1.840	2.772	2.153	2.0344
	5	2.2778	2.3718	2.469	2.662	2.469	2.2871
	10	2.4694	3.0507	3.050	2.287	3.054	3.0549
0.3	5	1.814	1.887	1.887	1.915	1.797	1.7970
0.5	5	1.3255	1.3783	1.433	1.431	1.347	1.2687
1.3	2	-0.6858	-0.719	-0.753	0.259	0.232	0.2082
	5	-0.8627	-0.895	-0.928	0.234	0.210	0.1897
	10	-1.0956	-1.127	-1.159	0.209	0.189	0.1708
1.5	5	-1.4646	-1.5186	-1.574	0.016	0.001	-0.011
2	5	-3.0588	-3.1675	-3.279	-0.455	-0.454	-0.4525

Table 2. Values of $\theta'(0)$ for various values of Pr and B_r when M=2, a/c=1.5 and $f_w = 1.5$

B_r	Pr = 1	7	10	20
0	-0.36760527	-0.08137867	-0.05935586	-0.03132512
1	-0.23231782	-0.05487682	-0.04027556	-0.02142842
3	0.03825708	-0.00187312	-0.00211495	-0.00163502
5	0.30883197	0.05113057	0.03604565	0.01815838

5. CONCLUSION

From the present study we can make the following conclusions:

1. Both the momentum and thermal boundary layers increase with the increase in parameter a/c, the ratio of the free stream constant to stretching surface constant.
2. Suction stabilizes the boundary layer growth.
3. The boundary layers are highly influenced by Prandtl number *Pr*.
4. The velocity profiles decrease and temperature profiles increase as the viscous dissipation effect i.e. Brinkman number *Br* increases.
5. When $a/c > 1$, the thickness of momentum boundary layers increase with the increase in magnetic field parameter. However when $a/c < 1$, the velocity curves reduce as magnetic field parameter increase due to the inverted boundary layer.

The present investigation has neglected Hall current effects, see Beg et al. [31], [32]. These are of relevance in strong magnetic field ocean generator systems and will be considered imminently.

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