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# Investigation of Heat and Mass Transfer of MHD Flow over the Movable Permeable Plumb Surface Using HAM

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**Abstract:** Analytical solution is presented for the investigation of uniqueness, heat and mass transfer on magnetohydrodynamic (MHD) flow over a movable leaky plumb surface. The temperature of the surface and concentration is not constant. The coupled boundary layer equations are non-linear and they are solved using Homotopy Analysis Method (HAM). A parametric study of all the governing parameters is carried out over the results. The results show that the momentum, heat and mass transfer phenomena depend on magnetic parameter, Prandtl number, Schmidt number, buoyancy ratio and suction or blowing parameter. Numerical and HAM results for the dimensionless velocity profiles, temperature profiles and the concentration profiles are presented for several of important parameters. The velocity profile is reduced as the value of the Hartman number and buoyancy ratio increase. Temperature value is decreased when the magnitude of suction parameter increases as well as blowing parameter increase. Also the concentration magnitude decreases when Schmidt number increases.

**Key words:** Heat and Mass Transfer · MHD Flow · Permeable Surface · Homotopy Analysis Method · Hartman Number

## INTRODUCTION

Most fluid mechanical problems have non-linear behavior inherently. There are few phenomena in different fields of science occurring linearly. A lot of scientific phenomena like heat and mass transfer ones function nonlinearly. These nonlinear equations cannot be solved using the ordinary methods and therefore these equations should be solved using the other methods. Some of them are solved using numerical techniques and some are solved using the analytical and semi analytical methods such as perturbation techniques, ADM, homotopy analysis method (HAM) and etc. In this study HAM is applied for finding the approximate solutions of momentum, heat and mass transfer in MHD flow with free convection on a movable leaky plumb surface. In the analytical perturbation method the small parameter should be exerted in the equation. Therefore, finding the small parameter and exerting it into the equation is important in this method. Homotopy analysis method is one of the well- known methods used to solve wide range of linear and nonlinear differential equations. Also both ordinary as well as partial can be solved by the HAM which was expressed by Liao in [1-4]. The applications of this method and similar methods in different fields of nonlinear equations, in fluid mechanics and heat transfer have been studied by seceral researchers [5-10] and etc. Hydromagnetic incompressible viscous flow has many important engineering applications such as MHD power generator, cooling of reactors and many metallurgical processes involve the cooling of continuous tiles. Sakiadis [11] firstly studied the boundary layer flow over a stretched surface moving with a constant velocity. Liao obtained a proper series solution of unsteady boundary layer flows over an impulsively stretching plate uniformly valid for all non-dimensional times. Cheng and Huang [12] considered the problem of unsteady flows and heat transfer in the laminar boundary layer on a linearly

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accelerating surface with suction or blowing with or without a heat source or sink. Ali [13] presented the heat transfer characteristics of a power law continuous stretched surface without and with suction injection. The free convection effect on MHD coupled heat and mass transfer of a moving vertical surface has been studied by Yih [14]. Anjali Devi and Kandasamy [15] studied the steady MHD laminar boundary layer flow over a wall of the wedge with suction and injection in the presence of species concentration and by considering the mass diffusion. The effects of Dufour and Soret numbers on unsteady MHD free convection and mass transfer flow past an infinite vertical porous plate embedded in a porous medium have been considered by Alam *et al*. [16]. Xu and Liao [17] examined the unsteady MHD flows of a non-Newtonian fluid over a non-impulsively stretching flat sheet and presented an accurate series solution. Abdelkhalek [18] investigated the free convection from a moving vertical surface in a MHD flow using perturbation technique. Recently, Hasanpour *et al*. [19] investigated the MHD mixed convective flow in a lid-driven cavity filled with porous medium using numerical method. They concluded that the fluid circulations within the cavity are reduced by increasing magnetic field strength as well as Darcy number reduction. Ashorynejad *et al*. [20] investigated the MHD free convective flow through a porous medium over a square cavity. The results show that the heat and mass transfer mechanisms and the flow characteristics inside the enclosure depended strongly on the strength of the magnetic field and Darcy number. The main objective of present study is investigation of the momentum, heat and mass transfer in a MHD flow of a movable permeable vertical surface. The system of momentum, heat and mass conservation equations can be reduced to some parametrical problem by introducing suitable transformation variable. By use of scaling transformations, the set of governing equations and the boundary condition are reduced to Non-linear ordinary differential equations with appropriate boundary conditions. Then these transformed governing equations are solved using homotopy analysis method. Characteristic results for the velocity, temperature and concentration profiles are presented for various governing parameters.

## MATERIALS AND METHODS

In this paper the steady, incompressible, two-dimensional MHD Flow with free convection on a movable leaky vertical surface is considered. The fluid properties are assumed to be constant except the density in the buoyancy terms which is approximated according to the Boussinesq's approximation. The variations of surface temperature and concentration are assumed to be linear. No electric field exists and both viscous and magnetic dissipations are neglected. The Hall Effect and the joule heating terms are also neglected when the velocity of the fluid distant from the plate is equal to zero. Under the above assumptions the boundary layer form of the governing equations can be written as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=\xi\frac{\partial^2 u}{\partial y^2}-\frac{\sigma.\mathrm{B}_0^2.u}{\rho} +g\beta_T(T-T_\infty)+g\beta_c(c-c_\infty) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial x}=\alpha\frac{\partial^2 T}{\partial y^2} \tag{3}$$

$$u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial x}=D\frac{\partial^2 c}{\partial y^2} \tag{4}$$

The boundary conditions for Eqs. (1)-(4) are as follows:

$$\begin{cases} y=0, v=-v_w, u=Bx, T=T_\infty+ax, c=c_\infty+bx & (5)\\ y\to\infty, u=0, T=T_\infty, c=c_\infty & (6)\end{cases}$$

Also the following non-dimensional functions and variables are introduced:

$$u=\frac{\partial\varphi}{\partial y}, v=-\frac{\partial\varphi}{\partial x}, \eta=\sqrt{\frac{B}{\xi}}y, F(\eta)=\frac{\varphi}{x\sqrt{B\xi}} \tag{7}$$

$$\theta(\eta)=\frac{T-T_\infty}{T_w(x)-T_\infty}, C(\eta)=\frac{c-c_\infty}{c_w(x)-c_\infty} \tag{8}$$

With a new set of independent and dependent variable defined by Eq. (7), the continuity equation (1) is satisfied automatically and from Eqs. (2) and (4) the following ordinary differential equations can be obtained:

$$F''+FF''-\left(M+F'\right)F'=-\frac{G_{rT}}{\mathrm{Re}^2}\left(\theta+NC\right) \tag{9}$$

$$\theta''+\mathrm{Pr}\left(F\theta'-F'\theta\right)=0 \tag{10}$$

$$C''+Sc\left(FC'-F'C\right)=0 \tag{11}$$

Primes denote differentiation with respect to η and the boundary conditions (Eqs. (5) and (6)) becomes:

$$\begin{cases} F(0)=F_w, F'(0)=1, F'(\infty)=0 & (12)\\ \theta(0)=1, \theta(\infty)=0 & (13)\\ C(0)=1, C(\infty)=0 & (14)\end{cases}$$

In the above equations N is zero for thermal driven flow, infinite for mass driven flow, positive for thermally assisting flow, negative for thermally opposing flow abd $F_w = \frac{v_w}{\sqrt{B\xi}}$ is the suction or injection parameter. For the case of suction, $v_w > 0$ and hence $F_w > 0$. and for the case of blowing, $v_w < 0$ and hence $F_w < 0$.

**Application of HAM:** Homotopy analysis method is used for the solution of the system equations (9-11) by subject to the boundary conditions (12-14). To start with HAM one needs to make the initial guess approximations satisfying the boundary data and to choose suitable linear operators. The initial approximations of F(η) and θ(η), C(η) and the auxiliary linear operators $L$[F(η)], $L$[θ(η)] and $L$[C(η)] are as follows:

$$F_0(\eta) = \eta e^{-\eta} + F_w \tag{15}$$
$$\theta_0(\eta) = e^{-\eta} \tag{16}$$
$$C_0(\eta) = e^{-\eta} \tag{17}$$

and:

$$L_1[F(\eta)] = F''' + 2F'' + F \tag{18}$$
$$L_2[\theta(\eta)] = \theta'' + \theta' \tag{19}$$
$$L_3[C(\eta)] = C'' + C' \tag{20}$$

Which have the following properties:

$$L_1[c_1 + c_2 e^{-\eta} + c_3 \eta e^{-\eta}] = 0 \tag{21}$$
$$L_2[c_1 + c_2 e^{-\eta}] = 0 \tag{22}$$
$$L_3[c_1 + c_2 e^{-\eta}] = 0 \tag{23}$$

Following the Homotopy analysis method, the non-linear operator is defined as:

$$N_1[F(\eta)] = F(\eta,p)F''(\eta,p) - F'^2(\eta,p) + \frac{G_{rT}}{\mathrm{Re}^2}(\theta(\eta,p) + \mathrm{N}(\eta,p)C(\eta,p) \tag{24}$$

$$N_2[\theta(\eta,p)] = \theta''(\eta,p) + \Pr(F(\eta,p)\theta'(\eta,p) - F'(\eta,p)\theta(\eta,p)) \tag{25}$$

$$N_3[\theta(\eta,p)] = C''(\eta,p) + Sc(F(\eta,p)C'(\eta,p) - F'(\eta,p)C(\eta,p)) \tag{26}$$

Using the above description, with assumption $H_1(\eta) = 1$, $H_2(\eta) = 1$, $H_3(\eta) = 1$ the zero-order deformation equation is constructed as:

$$(1-p)L_1[\hat{F}(\eta,p) - F_0(\eta)] = p\hbar N_1[\hat{F}(\eta,p)] \tag{27}$$
$$(1-p)L_2[\hat{\theta}(\eta,p) - \theta_0(\eta)] = p\hbar N_2[\hat{\theta}(\eta,p)] \tag{28}$$
$$(1-p)L_3[\hat{C}(\eta,p) - C_0(\eta)] = p\hbar N_3[\hat{C}(\eta,p)] \tag{29}$$

Obviously for p = 0 and p = 1 the above equations (27-29) change to:

$$\hat{F}(\eta,p) = F_0(\eta) + \sum_{m=1}^{\infty} F_m(\eta)p^m \tag{30}$$

$$\hat{\theta}(\eta,p) = \theta_0(\eta) + \sum_{m=1}^{\infty} \theta_m(\eta)p^m \tag{31}$$

$$\hat{C}(\eta,p) = C_0(\eta) + \sum_{m=1}^{\infty} C_m(\eta)p^m \tag{32}$$

As p increases from 0 to 1, $\hat{F}(\eta,p)$ and $\hat{\theta}(\eta,p)$ vary from $F_0(\eta)$ and $\theta_0(\eta)$ to the exact solutions ($F(\eta)$ and $\theta(\eta)$). Due to Taylor's theorem and Eqs. (30)-(32), the $F(\eta)$ and $\theta(\eta)$ can be written as:

$$\hat{F}(\eta,p) = F_0(\eta) + \sum_{m=1}^{\infty} F_m(\eta)p^m \tag{33}$$

$$\hat{\theta}(\eta,p) = \theta_0(\eta) + \sum_{m=1}^{\infty} \theta_m(\eta)p^m \tag{34}$$

$$\hat{C}(\eta,p) = C_0(\eta) + \sum_{m=1}^{\infty} C_m(\eta)p^m \tag{35}$$

$$F_m(\eta) = \frac{1}{m!}\frac{\partial^m \hat{F}(\eta,p)}{\partial p^m}\bigg|_{P=0} \tag{36}$$

$$\theta_m(\eta) = \frac{1}{m!}\frac{\partial^m \hat{\theta}(\eta,p)}{\partial p^m}\bigg|_{P=0} \tag{37}$$

$$C_m(\eta) = \frac{1}{m!}\frac{\partial^m \hat{C}(\eta,p)}{\partial p^m}\bigg|_{P=0} \tag{38}$$

Where the convergence of the series in Eqs. (33) - (35) is dependent on $\hbar$. Assume that $\hbar$ is selected such that the series in Eqs. (33) - (35) are convergent at p = 1, then due to Eqs. (30) - (32) one can write:

$$F(\eta) = F_0(\eta) + \sum_{m=1}^{\infty} F_m(\eta) \tag{39}$$

$$\theta(\eta) = \theta_0(\eta) + \sum_{m=1}^{\infty} \theta_m(\eta) \tag{40}$$

$$C(\eta) = C_0(\eta) + \sum_{m=1}^{\infty} C_m(\eta) \tag{41}$$

Accor ding to initial condition and the rule of solution expressions, it is straight forward that the initial approximation should be in the form: (Eqs.(42)-(44)).

$$RF_m(\eta) = \frac{d^3}{dz^3} F_{m-1}(\eta) + \sum_{j=0}^{m-1} F_j(\eta)\left(\frac{d^2}{d\eta^2} F_{m-1-j}(\eta)\right) - \sum_{j=0}^{m-1} F_j(\eta)\left(\frac{d}{d\eta} F_{m-1-j}(\eta)\right) \quad (42)$$

$$R\theta_m(\eta) = \frac{d^2}{d_z{}^2}\theta_{m-1}(\eta) - \Pr\left(\sum_{j=0}^{m-1}\theta_j(\eta)\left(\frac{d}{d\eta}F_{m-1-j}(\eta)\right)\right) + pr\left(\sum_{j=0}^{m-1} F_j(\eta)\left(\frac{d}{d\eta}\theta_{m-1-j}(\eta)\right)\right) \quad (43)$$

$$RC_m(\eta) = \frac{d^2}{d_z{}^2}C_{m-1}(\eta) - Sc\left(\sum_{j=0}^{m-1}\theta_j(\eta)\left(\frac{d}{d\eta}F_{m-1-j}(\eta)\right)\right) + Sc\left(\sum_{j=0}^{m-1} F_j(\eta)\left(\frac{d}{d\eta}C_{m-1-j}(\eta)\right)\right) \quad (44)$$

Differentiating the zeroth-order deformation equations m times with respect to p, dividing by m! and finally setting p = 0 the following mth-order deformation problems can be defined as:

$$L_1[F_m(\eta) - \chi_m F_m - 1(\eta)] = h R_m F(\eta) \quad (45)$$
$$L_2[\theta_m(\eta) - \chi_m \theta_m - 1(\eta)] = h R_m \theta(\eta) \quad (46)$$
$$L_3[C_m(\eta) - \chi_m C_m - 1(\eta)] = h R_m C(\eta) \quad (47)$$

From above equations the final formulation of each function can be obtained as:

$$\begin{aligned} F_1(\eta) = -\frac{3.333\ \hbar}{\mathrm{Re}^2}&(1.37(\mathrm{Re})^2 e^{-\eta} - 0.15(\mathrm{Re})^2 e^{-2\eta} \\ &+1.07(\mathrm{Re})^2\eta e^{-\eta} - 1.2G_{rT}Ne^{-\eta} - 3.5M(\mathrm{Re})^2\eta e^{-\eta} \\ &-2.3F_w(\mathrm{Re})^2\eta e^{-\eta} - 1.2G_{rT}e^{-\eta} - 3.5M(\mathrm{Re})^2\eta^3 e^{-\eta} \\ &-1.2G_{rT}e^{-\eta} - 2.3F_w(\mathrm{Re})^2 e^{-\eta} + 0.05F_w(\mathrm{Re})^2\eta^3 e^{-\eta} \\ &+0.05M(\mathrm{Re})^2\eta^3 e^{-\eta} + 0.15G_{rT}N\eta^2 e^{-\eta} - 1.2G_{rT}N\eta\ e^{-\eta} \\ &+0.3(\mathrm{Re})^2\eta^2 e^{-\eta} - 0.05(\mathrm{Re})^2\eta^3 e^{-\eta} + 0.15G_{rT}\eta^2 e^{-\eta} \\ &-0.15F_w(\mathrm{Re})^2\eta^2 e^{-\eta} - 1.22(\mathrm{Re})^2 + 2.3F_w(\mathrm{Re})^2 \\ &+3.5M(\mathrm{Re})^2 + 1.2G_{rT}N + 1.2G_{rT}) \end{aligned} \quad (48)$$

$$\begin{aligned} \theta_1(\eta) = &-\hbar\eta e^{-\eta} - 0.00045\hbar e^{-\eta} - 0.5\hbar(\mathrm{Pr})e^{-2\eta} \\ &+\hbar(\mathrm{Pr})F_w\eta e^{-\eta} + 0.00045\hbar(\mathrm{Pr})F_w e^{-\eta} \\ &+0.5\hbar(\mathrm{Pr})e^{-\eta} + 0.00045\hbar - 0.000022\hbar(\mathrm{Pr}) + 0.00045\hbar(\mathrm{Pr})F_w \end{aligned} \quad (49)$$

$$\begin{aligned} C_1(\eta) = &-\hbar\eta e^{-\eta} - 0.00045\hbar e^{-\eta} - 0.5\hbar(Sc)e^{-2\eta} \\ &+\hbar(Sc)F_w\eta e^{-\eta} + 0.00045\hbar(Sc)F_w e^{-\eta} \\ &+0.5\hbar(Sc)e^{-\eta} + 0.00045\hbar - \\ &0.000022\hbar(Sc) + 0.00045\hbar(Sc)F_w \end{aligned} \quad (50)$$

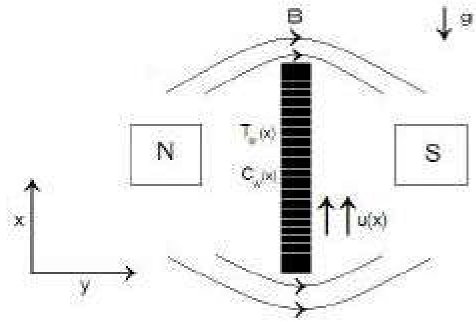


Fig. 1: Physical configuration and coordinate system

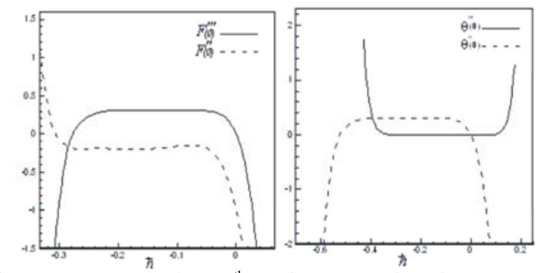

Fig. 2: $\hbar$ -curves for 15th -order approximations

Thus the final solution can be written as:

$$F(\eta) = F_0(\eta) + F_1(\eta) + F_2(\eta) + F_3(\eta) + . \quad (51)$$
$$\theta(\eta) = \theta_0(\eta) + \theta_1(\eta) + \theta_2(\eta) + \theta_3(\eta) + ... \quad (52)$$
$$C(\eta) = C_0(\eta) + C_1(\eta) + C_2(\eta) + C_3(\eta) + ... \quad (53)$$

**Convergence of the HAM Solution:** It is necessary to prove the convergence of the solution series (Eqs. (48-50)).The convergence and rate of approximation for the HAM solution of the series are strongly dependent upon the auxiliary parameter. Therefore, one can choose the proper values of $\hbar$by plotting the $\hbar$ -curves which ensure that the solution series (Eqs. (48-50)) converge, as suggested by Liao [2-4].For this purpose the $\hbar$ -curves are plotted for 15th-order of approximations in Fig (2). These figures observably shows that the range for the acceptable values of $\hbar$ is $-0.3 \le \hbar \le 0.11$ .Obviously the calculations show (Figs. 2-4) that the series (Eqs. (51)-(53)) converge in the whole region of g when.$\hbar = -0.15$

## RESULTS AND DISCUSSIONS

In order to verify the accuracy of our present method, a comparison of wall velocity gradient $F''(0)$ for various values of Hartmann number (M) with those reported by Yih [14] and Abdoulkhalek [18]. The result of this comparison is given in Table 1.The comparison in all the above cases is found to be in admirable harmony between

Table 1: Comparison of non-dimensional wall velocity gradient F"(0) for various values of M

| | M=0 | M=0.5 | M=1 | M=1.5 | M=2 |
|---|---|---|---|---|---|
| Yih [14] | -1 | -1.2247 | -1.4142 | -1.5811 | -1.7321 |
| Abdelkhalek [18] | -1 | -1.2356 | -1.4156 | -1.5821 | -1.7334 |
| Present work | -1 | -1.2316 | -1.4150 | -1.5819 | -1.7331 |

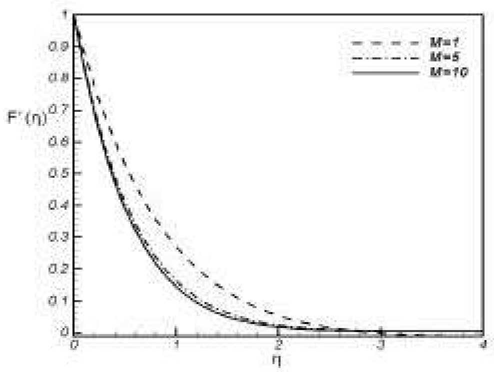


Fig. 3: Effects of M on tangential velocity profiles Pr = 0.72, Re = 50, N = 0, Sc = 0.2,GrT= 5 and Fw = 0

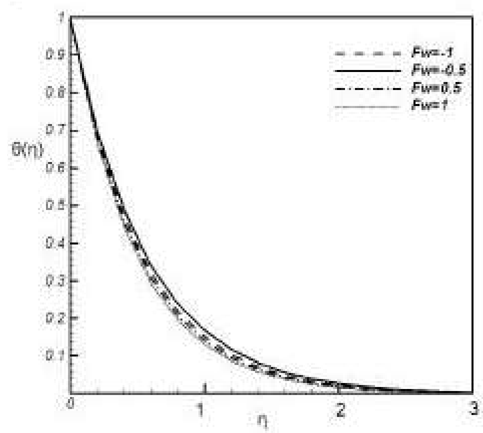


Fig. 4 : Effects of Fw on temperature profiles, Pr = 0.72, Re = 50, N = 0, Sc = 0.2 and GrT = 5.

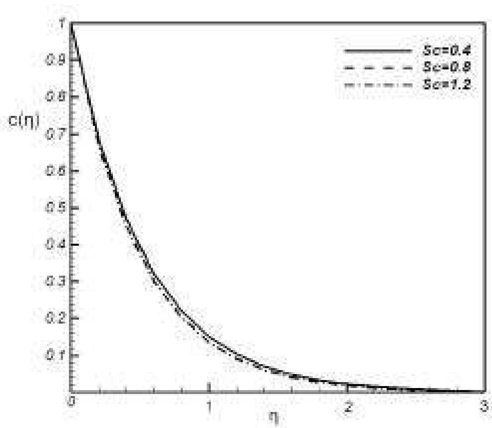


Fig. 7: Effects of Sc on concentration profiles Pr = 0.72, Re = 50, N = 0, M=1

the present results and the previous studies. The general results of the examinations are that the external magnetic field reduces the velocity value and consequently the flow rate and also the wall heat transfer. In addition, considerable influences on the flow and thermal fields can be seen with temperate magnetic field strengths. This situation happen only for liquid metal flows while in this elements the effects of magnetic fields and Joule heating is little. In order to get the physical insight into the current problem HAM are carried out for different values of Hartmann number. Fig. 3 demonstrates the influence of the Hartmann number on the velocity profiles in the boundary layer. Application of magnetic field to an electrically conducting fluid gives climb to a resistive type force called the Lorentz force. This force has the tendency to calm down the movement of the fluid in the boundary layer. Fig. 4 shows the temperature $\theta$ ($\eta$) profiles across the boundary layers at different values of the suction or injection parameter. It is known that the imposition of wall fluid suction reduces both the hydrodynamic and thermal boundary layers which specify reduction in the temperature profiles. However, the opposite behavior is produced by imposition of wall fluid blowing or injection. The influence of Schmidt number (Sc) on the concentration is demonstrated in Fig.5. As Sc number increases the mass transfer rates increases. Hence, the concentration decreases with increasing Sc.

## CONCLUSIONS

The main purpose of the present study is investigation of momentum, free convection heat and mass transfer of MHD flow over a movable permeable plumb surface using HAM. Results and tables are presented to examine the effects of the Hartman number (M), buoyancy ratio (N), Schmidt number (Sc) and blowing or suction parameter ($F_w$)on the velocity and temperature and concentration profiles.

- The velocity $F'$ is detected to reduce as the value of the Hartman number (M) increase.
- The velocity $F'$ increase when buoyancy ratio (N) is increased.
- When the magnitude of suction parameter ($F_w$>0) is increased, as well as blowing parameter ($F_w$<0), the temperature is decreased.
- The concentration, decreased when Schmidt number (Sc) is increased.

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