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MHD stagnation point flow over a stretching or shrinking sheet in a porous medium with velocity slip

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Magnetohydrodynamics (MHD) stagnation point flow in a porous medium with velocity slip is investigated in this study. The governing system of partial differential equations is transformed into a set of non-linear ordinary differential equations by using the similarity transformation. Subsequently, the transformed equations are numerically solved by using the shooting method in MAPLE software. The skin friction coefficient and the local Nusselt number are obtained and presented graphically. The effects of the governing parameters including the velocity slip, magnetic and permeability parameters, are examined. It is found that both the skin friction coefficient and the local Nusselt number increase as magnetic and permeability parameters increase.

Keywords: *MHD stagnation point flow, porous medium, stretching/shrinking sheet, velocity slip.*

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1. Introduction

MHD was first introduced and developed by a physicist named Hannes Alfven, who won the Nobel in Physics in 1970 [1]. The basic idea of MHD is the magnetic field, which generates an electrical flow in the moving conductive fluid and which can change the magnetic field. The MHD equations are the combination of the Navier–Stokes equation and Maxwell electromagnetic equations [1]. It is known that the fluid which has characteristics of MHD possesses the ability to manipulate the flow, which means it can control separation flow. It also helps to optimise the heat transfer from the electrically conductive fluid. Thus, MHD flow is an essential research in engineering such as nuclear reactor cooler and power generator. Many researchers have recently become interested in MHD studies for their various interesting physical properties and their applications in the engineering field.

Pavlov, in 1974 studied viscous flow past a stretching sheet in the presence of a uniform magnetic field, which has practical relevance in polymer processing (Mahapatra et al. [2]). The Pavlovian similarity solutions are then exhibited by Andersson [3] where it shows that solutions are not only for the boundary layer equations but also for the complete Navier–Stokes equations. Next, Andersson's results were further developed by Liu [4] to discover the stretching sheet's temperature distribution. The flow and heat transfer over a stretching sheet in the presence of uniform magnetic field has also been considered by Chakrabarti and Gupta [5], Chiam [6], Mahmoud [7], Prasad et al. [8] and Ishak et al. [9]. On the other hand, the effects of non-uniform magnetic field on the development of boundary layers on a stretching sheet were studied by Helmy [10], Chiam [11] and Ishak et al. [12]. Furthermore, Sharma et al. [13] investigated MHD mixed convection stagnation point flow over a linearly stretching sheet with the presence of heat source/sink. This study showed that the heat transfer rate increases with the increase of the magnetic field.

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Compared to the stretching case, less study has been considered on the MHD flow over the shrinking sheet. Fang and Zhang [14] studied a closed-form exact solutions of MHD viscous flow over a shrinking sheet. Then, Fang et al. [15] analytically solved the MHD flow over a shrinking sheet under the slip conditions and presented multiple solution branches for a certain range of the parameter. Previously mentioned, Ishak et al. [9] studied MHD stagnation point flow towards a stretching sheet while Mahapatra and Gupta [16] and Lok et al. [17] extended Wang's problem to MHD stagnation point flow towards a shrinking sheet where dual solutions exist for small values of the magnetic parameter. In addition, Yian et al. [18] carried out a more extensive study on MHD flow, which includes the suction effect over a shrinking sheet. From this study, a non-unique solution was discovered when the suction strength increased. Motivated from the previous studies, many researchers are interested in further studying the MHD flow by adding physical effects on the boundary layer, such as slip, thermal radiation, suction and heat generation effects (Aman et al. [19]; Chen et al. [20]; Mansur et al. [21]; Khashi'ie et al. [22]; Alias & Hafidzuddin [23]).

In recent years, the study of MHD flow and heat transfer in porous media has received a great deal of research interest due to its importance in engineering and industrial applications. Mohd Noor and Hashim [24] studied the MHD flow and heat transfer past a shrinking sheet in a porous medium. Following this, Zheng et al. [25] further studied by considering velocity slip and temperature jump in their problem. This study found a closed-form solution for the flow field which the porosity, suction, shrinking, and velocity slip parameter has been taken into account. Next, Khalili et al. [26] worked on MHD stagnation point flow towards stretching/shrinking permeable plate in a porous medium filled with a nanofluid while Chaudhary and Choudhary [27] considered heat and mass transfer by MHD flow near the stagnation point flow over a stretching or shrinking sheet in a porous medium. It is found that the surface heat transfer rate decreases with the permeability parameter, but the opposite behaviour is observed for the magnetic parameter. Other researchers have analysed the problem with a porous medium in their research, including (Seth et al. [28]; Mishra et al. [29]; Khashi'ie et al. [30]; Khashi'ie et al. [31]).

In recent times, magnetohydrodynamics (MHD) are well known in the field of fluid dynamics. However, the porous medium was not commonly regarded as a concern in most of the previous study. Therefore, in this current research, our interest is to extend the work done by Aman et al. [19] in studying the MHD stagnation point flow towards a stretching/shrinking sheet with a slip effect. To expand the previous findings, porous media has been examined with the velocity slip considered. This problem will study the effect of the stretching or shrinking parameter c, the magnetic field parameter M and the porosity parameter K on the surfaces' flow and heat transfer behaviour.

2. Mathematical formulation

Consider a two-dimensional steady stagnation point flow towards a shrinking or stretching sheet through a porous medium with velocity slip. The velocity of the external flow is given by $U_\infty = ax$, where $a > 0$ is the strength of the stagnation flow. It is assumed that the velocity of the stretching or shrinking sheet is given by $U_w = bx$, where b is the stretching/shrinking rate, with $b >$ and $b < 0$ are for the stretching and shrinking cases, respectively. It is also assumed that a constant magnetic field B_0 is applied normal to the surface and the induced magnetic field is neglected as it is assumed small. Under the boundary layer approximations, the governing equations for the continuity, momentum and energy can be written as:

- continuity equation

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

- momentum equation

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = U_\infty \frac{dU_\infty}{dx} + \nu \frac{\partial^2 u}{\partial y^2} + \frac{\nu}{K_1}(U_\infty - u) + \frac{\sigma B_0^2}{\rho}(U_\infty - u); \tag{2}$$

• energy equation

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

with the boundary conditions:

$$\begin{gathered} v = 0, \quad u = U_w(x) + L\frac{\partial u}{\partial y}, \quad T = T_w \quad \text{at} \quad y = 0, \\ u \to U_\infty(x), \quad T \to T_\infty \quad \text{as} \quad y \to \infty, \end{gathered} \tag{4}$$

where u and v are assumed to be the velocity components along x and y-direction, respectively, where x-axis is measured along the stretching/shrinking sheet and the y-axis is measured normal to it. q is the fluid density, P is the pressure, K is the permeability of the porous medium and T is the temperature of the fluid.

The governing equations (1)–(3) associated with the boundary conditions (4) are transformed to ODEs by applying the similarity transformations as shown below:

$$\psi = (axU_\infty)^{\frac{1}{2}} f(\eta), \quad \eta = \left(\frac{U_\infty}{ax}\right)^{\frac{1}{2}} y, \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty},$$

$$u = axf'(\eta), \quad v = -(\alpha a)^{\frac{1}{2}} f(\eta),$$

where the variable of similarity is η and function of stream is ψ described as $u = \frac{\partial\psi}{\partial y}$ and $v = -\frac{\partial\psi}{\partial x}$, that comply with Eq. (1) equivalently. After done with the fransformations, Eqs. (2) and (3) and boundary conditions (4) can be written as the system of differential equations in ODEs as follows

$$Pr\, f''' + ff'' + 1 - f'^2 + K(1 - f') + M^2(1 - f') = 0, \tag{5}$$

$$\theta'' + f\theta' = 0 \tag{6}$$

subjected to the conditions below

$$\begin{gathered} f(0) = 0, \quad f'(0) = c + Af''(0), \quad \theta(0) = 1, \\ f'(\eta) \to 1, \quad \theta(\eta) \to 0 \quad \text{as} \quad \eta \to \infty, \end{gathered} \tag{7}$$

where $c = \frac{b}{a}$ in which $c > 0$ for a stretching case, $c < 0$ for a shrinking case and $A = L(a/\alpha)^{\frac{1}{2}}$.

$\mathrm{Pr} = \frac{\nu}{\alpha}$ is the Prandtl number, $K = \frac{\nu}{ak_1}$ is the permeability parameter and $M = (\sigma/a\rho)^{\frac{1}{2}} B_0$ is the magnetic parameter.

The quantities of physical interest are the skin friction or shear stress coefficients C_f and the local Nusselt number Nu_x, which are given as follows

$$C_f = \frac{\tau_w}{\rho U_\infty^2}, \quad \mathrm{Nu}_x = \frac{xq_w}{k(T_w - T_\infty)}, \tag{8}$$

where τ is the shear stress of the stretching or shrinking sheet and q_w is the heat flux from the surface of the stretching or shrinking sheet, which are defined as

$$\tau_w = \mu\left(\frac{\partial u}{\partial y}\right)_{y=0}, \quad q_w = -k\left(\frac{\partial T}{\partial y}\right)_{y=0}. \tag{9}$$

Replace equation (9) into (8), we obtain

$$C_f = \frac{Pr^{1/2} f''(0)}{\mathrm{Re}_x^{1/2}}, \quad \mathrm{Nu}_x = -\mathrm{Pe}_x^{1/2}\theta'(0),$$

where $\nu = \mu/\rho$ is the dynamic viscosity, $\mathrm{Pr} = \nu/\alpha$ is the Prandtl number, $\mathrm{Re}_x = ax^2/\nu$ is the local Reynolds number and $\mathrm{Pe}_x = U_\infty x/\alpha$ is the local Peclet number.

3. Results and discussion

The transformed equations (5) and (6) subjected to the boundary conditions (7) have been solved numerically using the shooting method in Maple software. This study considered certain values of the governing parameters, including the magnetic parameter M, the velocity slip parameter A, the stretching/shrinking parameter c and the permeability parameter K when the Prandtl number Pr remains constant. Just as in the earlier problems, the computation is performed until the solution exists up to the smallest value of c where the results for the skin friction coefficient $f''(0)$ and the local Nusselt number $-\theta'(0)$ are both convergent. The comparison of $f''(0)$ for the shrinking case ($c < 0$) with those obtained by Bhattacharyya et al. [32] for several values of c are shown in Table 1. The comparison shows an excellent agreement.

Table 1. Comparison of the results for skin friction coefficient $f''(0)$ when $\text{Pr} = 1$ and $M = K = A = 0$.

c	Bhattacharya et al. [32]	Present Results
-1.2465	0.55429	0.58429
-1.15	1.08223	1.08224
-1	1.32882	1.32882
-0.75	1.48929	1.48930
-0.5	1.49566	1.49567
-0.25	1.40224	1.40224

The variation of the skin friction coefficient $f''(0)$ and the local Nusselt number $-\theta'(0)$ with stretching/shrinking parameter c for selected values of the velocity slip parameter A are shown in Figures 1 and 2, respectively. It is observed that in the shrinking case where $c < 0$; dual solutions exist, while in the stretching case where $c > 0$, unique solution exist, and when c is equal to the critical value, there is no solution. As with dual solutions, the first solution is assumed to be physically stable and generally exists in nature, while the second solution is not physically accomplished. This can be confirmed by conducting a stability analysis, but this is beyond the reach of the present research. However, this analysis can be found in the paper written by Merkin et al. [33].

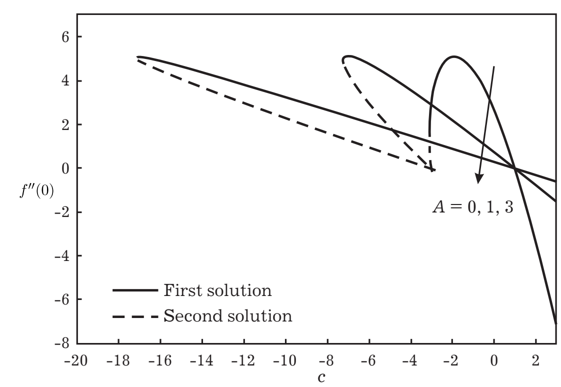

Fig. 1. Variation of $f''(0)$ with c for different values of A when $M = 1$, $K = 1$ and $\text{Pr} = 0.5$.

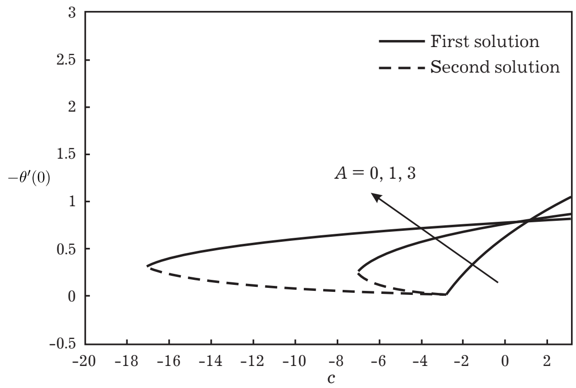

Fig. 2. Variation of $-\theta'(0)$ with c for different values of A when $M = 1$, $K = 1$ and $\text{Pr} = 0.5$.

The value of $f''(0)$ is equal to zero when $c = 1$, as can be seen in Figure 1. This is because the fluid and the solid boundary travel with the same velocity, and therefore there is no friction at the fluid-solid layer. However, as seen in Figure 2, heat transfer occurs at the boundary, even in the absence of friction, because the fluid and solid surface temperatures are different. It is further shown that the skin friction coefficient $f''(0)$ decreases with increasing the slip parameter A, but, the opposite effect has been observed in Figure 2, where the rise in A would lead to a decrease in the local Nusselt number $-\theta'(0)$.

Figures 3 and 4 show the variation of the skin friction coefficient $f''(0)$ and the local Nusselt number $-\theta'(0)$ with stretching/shrinking parameter c, respectively, for $M = 0.2$, $0,5$ and 1. The solution for a specific value of the parameter M is shown to exist up to a critical value of $c = c_c (< 0)$, where the boundary layer separates from the sheet. The critical values of $f''(0)$ for the corresponding values of

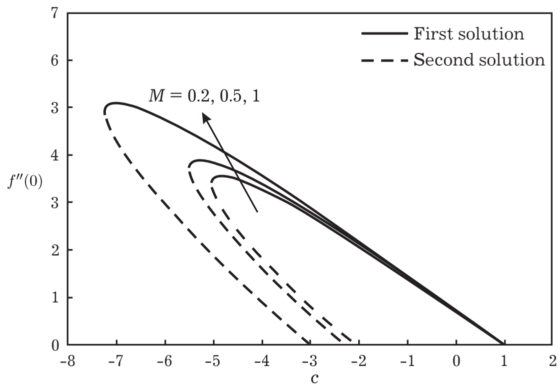

Fig. 3. Variation of $f''(0)$ with c for different values of M when $A = 1$, $K = 1$ and $\Pr = 0.5$.

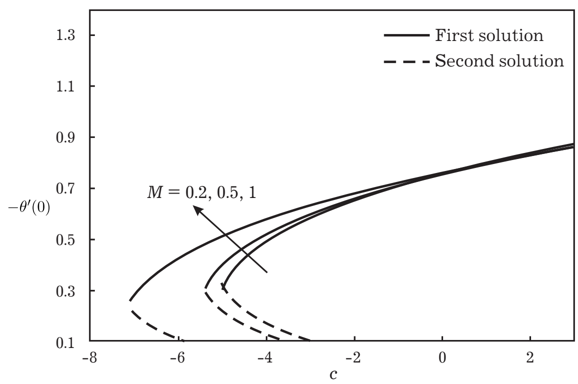

Fig. 4. Variation of $-\theta'(0)$ with c for different values of M when $A = 1$, $K = 1$ and $\Pr = 0.5$.

magnetic parameter M are shown in Table 2. Moreover, it can be inferred from Figures 3 and 4 that as M increases, the values of $f''(0)$ and $-\theta'(0)$, respectively, increases. These values first rise to the maximum value before decrease to zero. If the effect of the magnetic field is strong, the maximum value is higher. This is due to the presence of a magnetic field, which can result in the deceleration of the fluid's momentum and thereby increase the skin friction coeffient $f''(0)$ on the surface.

Table 2. Variation of c_c for different values of magnetic parameter M when $\Pr = 0.5$, $K = 1$ and $A = 1$.

M	0.2	0.5	1.0
Values of c_c	-5.041	-5.506	-7.238

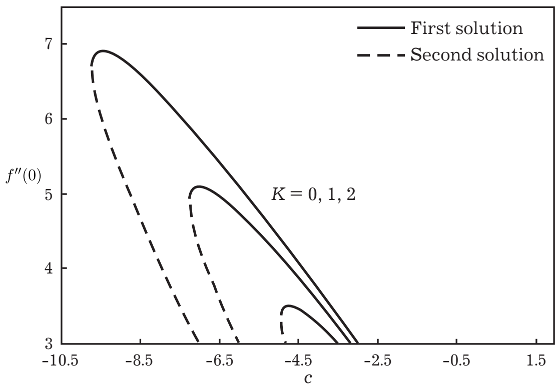

Fig. 5. Variation of $f''(0)$ with c for different values of K when $A = 1$, $M = 1$ and $\Pr = 0.5$.

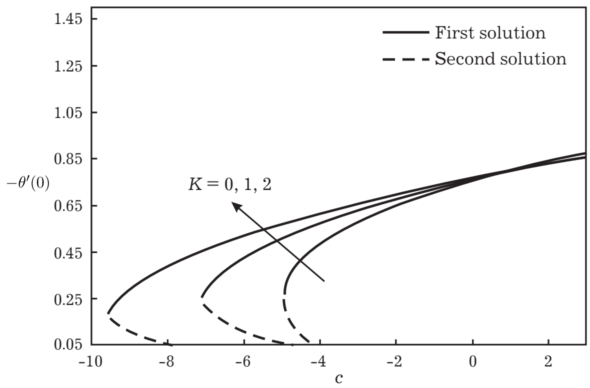

Fig. 6. Variation of $-\theta'(0)$ with c for different values of K when $A = 1$, $M = 1$ and $\Pr = 0.5$.

Figures 5 and 6 illustrate the effect of permeability parameter K on the skin friction coefficient $f''(0)$ and the local Nusselt number $-\theta'(0)$, respectively. These results show that as the value of K increases, so does the value of both $f''(0)$ and $-\theta'(0)$. Besides, it can be deduced that there exists a dual solution for the shrinking case ($c < 0$). It is seen that as the permeability parameter K increases, the critical value c_c increases. Moreover, these figures also demonstrate that as the value of K increases, which signifies a lower porosity of the porous medium, the range of solutions increases. In conclusion, it can be noted from Figures 1 to 6 that the range of c for which the solutions exists for equations (5) and (6) is wider than stated by Lok et al. [17] due to the presence of the magnetic field and permeability parameters in the present study. These parameters could widen a solution domain, which would delay the separation of boundary layers.

Figures 7 and 8 show the impact of permeability parameter K on velocity $f'(\eta)$ and temperature $\theta(\eta)$ profiles using different values of c, assuming that other parameters remain constant. From these figures, it can be shown that the velocity decreases with the increasing values of the permeability parameter K, but the opposite pattern is seen for the temperature profiles. For higher values of the permeability parameter K, the velocity and temperature profiles are almost identical for the first solution in which the boundary layer is bound to a very thin region. These figures support the validity of the numerical findings acquired in this research as the boundary condition (7) was asymptotically satisfied.

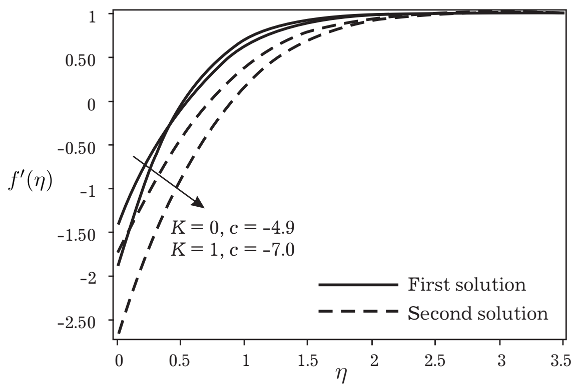

Fig. 7. Velocity profiles for different values of K and c when $A = 1$, $\mathrm{Pr} = 0.5$ and $M = 1$.

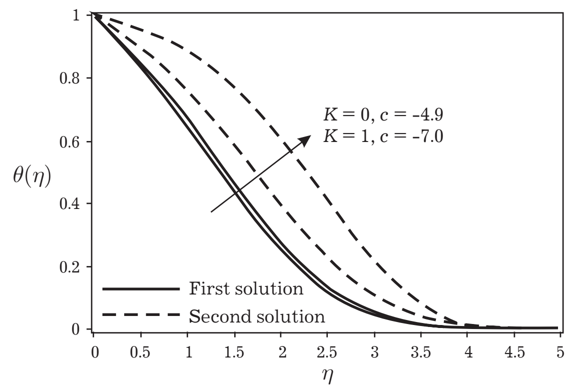

Fig. 8. Temperature profiles for different values of K and c when $A = 1$, $\mathrm{Pr} = 0.5$ and $M = 1$.

4. Conclusion

In the present study, we investigated numerically the problem of MHD stagnation point flow over a stretching or shrinking sheet in a porous medium with velocity slip. The various parameters that affect the flow characteristics, including velocity slip, magnetic and permeability are taken into consideration. Dual solutions have been found for shrinking cases. The presence of magnetic and permeability parameter increases the magnitude of the skin friction coefficients and local Nusselt number. In summation, velocity slip, magnetic, and permeability parameters all increase the critical value and thus increases the range of solutions. The magnetic and permeability parameters have a positive relationship with the skin friction coefficients and the local Nusselt number for the MHD problem.

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МГД потік в точці застою на листі, що розтягується або стискається, у пористому середовищі зі швидкістю ковзання

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У цій роботі досліджується магнітогідродинамічний потік через точку застою у пористому середовищі зі швидкістю ковзання. Визначальна система диференціальних рівнянь в частинних похідних перетворена на систему нелінійних звичайних диференціальних рівнянь методами перетворень подібності. Перетворені рівняння вирішені чисельно з допомогою методу стрільби у програмі MAPLE. Отримані та представлені графічно коефіцієнт поверхневого тертя та локальне число Нуссельта. Досліджено вплив керуючих параметрів, у тому числі швидкості ковзання, магнітного параметра та проникності. Встановлено, що коефіцієнт поверхневого тертя та локальне число Нуссельта збільшуються зі збільшенням магнітного параметра та проникності.

Ключові слова: *МГД потік у точці застою, пористе середовище, розтягнення/стискання листа, швидкісне ковзання.*