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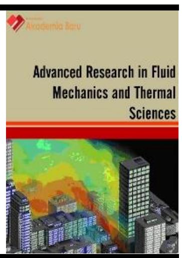

Dual Solutions of MHD Stagnation Slip Flow Past a Permeable Plate

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ABSTRACT

In this paper, dual solution to the problem of steady laminar magnetohydrodynamics boundary layer stagnation slip flow of the electrically conducting fluid over a permeable plate with suction effect is performed. The governing partial differential equations of the boundary layer are transformed into nonlinear ordinary differential equations via similarity transformations, and then numerically solved using the bvp4c method, which is the integrated algorithm of MATLAB. The effect of magnetic, slip and suction parameters on the skin friction coefficients and the velocity profiles $f'(\eta)$, $g(\eta)$ and $h(\eta)$ are presented in graphical form and discussed in detail. Dual solutions have been identified when suction is implied.

1. Introduction

The theory of magnetohydrodynamic (MHD) boundary layers plays a momentous role in the recent development of magnetohydrodynamic [1]. Over the last few years, the study of MHD flow and heat transfer near stagnation point has attracted a great deal of interest from researchers due to the effect of the magnetic field on the boundary layer flow [2–8]. Convective boundary layer flow of electrically conductive fluid in the presence of a magnetic field has been the focus of a significant number of investigations due to its fundamental significance in industrial and technical applications, including crystal growth, reactor cooling and metal surface coating. The Lorentz force, which is synonym with magnetic field, is influential and works with the buoyancy force in controlling the flow and temperature fields. The effect of the Lorentz force is known to suppress the convection and an external magnetic field is applied as a control mechanism in material manufacturing industry [9]. The MHD parameter is one of the important parameters by which the cooling rate can be controlled and the product of the desired quality can be achieved [9]. Zhu *et al.,*

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[10] studied the steady two-dimensional MHD stagnation flow towards a nonlinear stretching surface. The no-slip condition on the solid boundary replaced with partial slip condition. Ellahi *et al.,* [11] investigated the combined effects of magnetohydrodynamic heat transfer flow with the influence of slip over a moving at plate. The effect of entropy generation was also examined. A research done by Nandeppanavar *et al.,* [12] regarding the heat transfer characteristics of the stagnation point flow of MHD flow over a non-linearly moving plate with momentum and thermal slip effects in the presence of non-uniform heat source showed that the non-uniform heat source parameters enhance the temperature distribution.

Stagnation-point flow towards a stretching vertical sheet with slip effects was studied by Zaimi and Ishak [13]. The effects of partial slip on stagnation-point flow and heat transfer due to a stretching vertical sheet were investigated. Zaimi and Ishak [13] found that dual solutions exist in a certain range of buoyancy parameters. Dual solutions for a certain range of shrinking parameter also reported in the study by Bachok *et al.,* [14,15]. Later, Mukhopadhyay [16] described the boundary layer flow and heat transfer towards a porous exponential stretching sheet in the presence of magnetic field. Velocity slip and thermal slip were considered instead of no-slip condition. Khan *et al.,* [17] studied the magnetohydrodynamic boundary layer thermal slip flow by non-linearly stretching cylinder with the effect of suction and radiation. The flow was discussed in the presence of velocity and thermal slip conditions. Lok *et al.,* [18] investigated a steady two-dimensional magnetohydrodynamic stagnation point flow with suction towards a shrinking sheet, and found that strong suction is necessary for the multiple solutions to exist. Ishak *et al.,* [19] studied the effect of suction/injection on the laminar mixed convection boundary layer flow over a vertical wall in an incompressible viscous fluid, and observed that dual solutions exist for assisting flow only. The MHD stagnation point flow of a nanofluid over a permeable stretching/shrinking sheet problem has studied by Mansur *et al.,* [20].

Motivated by the above-mentioned literatures, the interest in this current study is to carry out a comprehensive study which will provide dual solutions to the problem considered by Ali *et al.,* [21], with the effect of suction. Many studies on dual solutions have been done by various researchers such as [22–28]. Moreover, no investigation has yet been conducted into this problem. This study also only limited to the problem of the steady laminar boundary layer flow of electrically conducting viscous fluid on the flat plate. Using similarity variables, a nonlinear ordinary differential equations corresponding to the momentum equations is obtained. These equations are solved numerically using bvp4c method. The effects of the magnetic parameter, the velocity slip parameter and the suction parameter on velocity fields are studied and analyzed by graphical aid.

2. Methodology

Consider the steady two-dimensional boundary layer flow of a viscous, incompressible and electrically conducting fluid in the presence of an applied magnetic field near the stagnation point on a plane surface, as shown in Figure 1, where the $x-$axis is measured along the plane surface, the $y-$axis is measured in the transverse direction and the $z-$axis is measured in the normal direction to the plane $z=0$. Following Wang [29], it is assumed that the flow takes place in the $x-z$ plane in the region $z>0$. Therefore, all variables are independent of the *y* coordinate. Further, it is assumed that the plane moves with velocity U in the $x-$direction and with velocity V in the $y-$direction. The external boundary layer flow (inviscid flow) of velocity $u_e(x)=ax$, where a is a positive constant, impinges on the plane $z=0$. It is also assumed that a uniform magnetic field of strength B_0 is applied normal to the plane $z=0$.

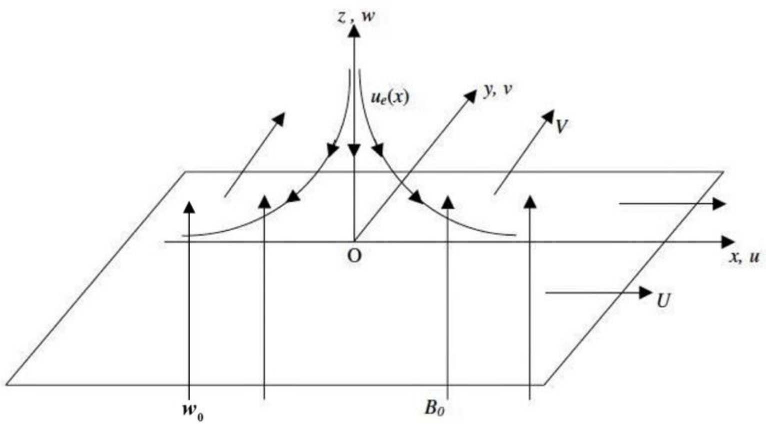

Fig. 1. The physical model with coordinate system of this problem

Under the boundary layer approximations and the assumptions that the viscous dissipation, radiation flux and Joule heating are neglected, the basic equations of the problem under consideration are given by

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0, \tag{1}$$

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

$$u\frac{\partial v}{\partial x}+w\frac{\partial v}{\partial z}=\nu\frac{\partial^2 v}{\partial z^2}-\frac{\sigma B_0{}^2}{\rho}v, \tag{3}$$

$$u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=\nu\frac{\partial^2 w}{\partial z^2}, \tag{4}$$

subject to the boundary conditions

$$\begin{aligned} &w=w_0,\quad u-U=A\rho\nu\frac{\partial u}{\partial z},\quad v-V=A\rho\nu\frac{\partial v}{\partial z}\quad \text{at}\quad z=0,\\ &u=u_e\left(x\right)=ax,\quad v=0\quad \text{as}\quad z\to\infty, \end{aligned} \tag{5}$$

where u, v and w are the velocity components along the $x-$, $y-$ and $z-$axes, respectively, σ is the electrical conductivity, ν is the kinematic viscosity, A is a slip constant, a is a positive constant, u_e is a velocity of the external boundary layer flow, B_0 is a constant of magnetic field of strength and ρ is the fluid density. Velocity U in the $x-$direction and velocity V in the $y-$direction. The following similarity transformations has been introduced

$$u=axf'\left(\eta\right)+Ug\left(\eta\right),\quad v=Vh\left(\eta\right),\quad w=-\sqrt{a\nu}\,f\left(\eta\right),\quad \eta=\sqrt{\frac{a}{\nu}}z \tag{6}$$

where η is the similarity variable and prime denotes differentiation with respect to η. Therefore, Eq. (1) is satisfied. Substituting (6) into Eq. (2)-(4), we obtain the following nonlinear ordinary differential equations

$$f''' + ff'' - (f')^2 + 1 + M(1 - f') = 0, \tag{7}$$

$$g'' + fg' - f'g - Mg = 0, \tag{8}$$

$$h'' + fh' - Mh = 0, \tag{9}$$

and boundary conditions (6) reduced to

$$\begin{aligned} &f(0) = S, \quad f'(0) = \lambda f''(0), \quad g(0) = 1 + \lambda g'(0), \quad h(0) = 1 + \lambda h'(0) \\ &f'(\infty) \to 1, \quad g(\infty) \to 0, \quad h(\infty) \to 0, \end{aligned} \tag{10}$$

where M is the magnetic parameter, S is the constant mass transfer parameter and λ is the slip parameter given by

$$M = \frac{\sigma B_0^{\,2}}{a\rho}, \quad S = \frac{-w_0}{\sqrt{a\nu}}, \quad \lambda = A\rho\sqrt{a\nu}. \tag{11}$$

The physical quantities of practical interest are the skin frictions τ_{wx} and τ_{wy} in the $x-$ and $y-$ directions of the plate, which are defined as

$$\begin{aligned} \tau_{wx} &= \mu\left(\frac{\partial u}{\partial z}\right)_{z=0} = \mu\sqrt{\frac{a}{\nu}}\left[axf''(0) + Ug'(0)\right], \\ \tau_{wy} &= \mu\left(\frac{\partial v}{\partial z}\right)_{z=0} = \mu\sqrt{\frac{a}{\nu}}\left[Vh'(0)\right]. \end{aligned} \tag{12}$$

3. Results Analysis

In this present study, we solved numerically the problem of a magnetohydrodynamics (MHD) stagnation slip flow with suction effect. The MHD nonlinear partial differential equations are reduced to nonlinear ordinary differential equations via similarity transformation. The Eq. (7) - (9) subject to boundary conditions (10) have been solved numerically by applying the bvp4c MATLAB solver. The method used in this research is to obtained the skin friction coefficients and the velocity profiles $f'(\eta)$, $g(\eta)$ and $h(\eta)$ for various values of magnetic parameter M, slip parameter λ and suction parameter S. Table 1 shows the comparison of the numerical results for the skin friction coefficient $f''(0)$ for different values of M with fixed $\lambda = S = 0$ with those study by Ariel [30] and Ali *et al.,* [21], in order to compare the accuracy and validity of the method used. The results display that there is a very good agreement between them.

Figure 2 until 4 show the velocity profiles of $f'(\eta)$, $g(\eta)$ and $h(\eta)$ for different values of magnetic parameter M when $S=5.0$ and $\lambda=5.0$, respectively. From Figure 2, we can observe that the velocity profile $f'(\eta)$, displays an increasing behaviour for the first and second solutions when the magnetic parameter M increases. The boundary layer thickness for the second solution is larger than the first solution. Next, Figure 3 shows decreasing behaviour for both solutions of velocity profile $g(\eta)$ when the magnetic parameter M is applied. The magnetic parameter gives increment in the boundary layer thickness. Figure 4 shows that the decreasing behaviour for the first and second solutions when the magnetic parameter M increases. This is because with the increase in M, Lorentz force increases and it produces more resistance to the flow.

Table 1
Comparison values of the skin friction coefficient $f''(0)$ for several values of M at fixed $\lambda=S=0$.

M	Ariel [30]	Ali *et al.,* [21]	Present
0.05	1.25252550	1.25253678	1.25253674
0.1	1.27216910	1.27218018	1.27218016
0.5	1.41975479	1.41976289	1.41976287
0.1	1.58532985	1.58533070	1.58533068
2.0	1.87355121	1.87352729	1.87352728

Figure 5 until 7 show the velocity profiles $f'(\eta)$, $g(\eta)$ and $h(\eta)$ for various values of slip parameter λ when $S=5.0$ and $M=0.1$, respectively. In Figure 5, velocity profiles are shown for different values of slip parameter λ. The velocity profiles show an increasing behaviour for both solutions when the slip parameter increases. The velocity curves show that the rate of transport decreases with the increasing distance η from the plate. Figure 6 shows the velocity profiles decreasing behaviour for the first solution as the slip parameter increases. Besides, for the second solution, with the increasing value of the slip parameter λ, the velocity profiles found to decrease initially but after a certain distance from the plate, it increases with the slip parameter. The velocity curve for both solutions show that the rate of transport decreases with the increasing distance η of the plate. In Figure 7, the velocity profiles $h(\eta)$ for the first and the second solutions present some sort of decreasing behaviour with the increase of slip parameter λ. The velocity curves show that the rate of transport decreases with the increasing distance η from the plate.

Figure 8 until 10 show the velocity profiles of $f'(\eta)$, $g(\eta)$ and $h(\eta)$ for variation values of suction parameter S when $M=0.1$ and $\lambda=5.0$, respectively. The velocity profiles $f'(\eta)$ for different values of suction parameter S are shown in Figure 8. As we can see from Figure 8, the velocity profiles increase as the suction parameter increases in both solutions. It is observed that suction results in an increase in the skin friction coefficient, which led to a reduction in the momentum of the boundary layer thickness, thus enhancing the flow near the surface of the wall. Figure 9 shows that the velocity profile $g(\eta)$ decreases as the suction parameter increases for the first solution. While for the second solution, there is an increasing in the velocity profiles when the suction parameter increases. Therefore, it is observed that with the increasing of suction parameter, the boundary layer thickness increases for the first solution while it decreases for the second solution. Figure 10 displays the decreasing of velocity profiles $h(\eta)$ as the suction S increases for the first and second solutions. It is also found that the boundary layer thickness decreases as the suction parameter increases.

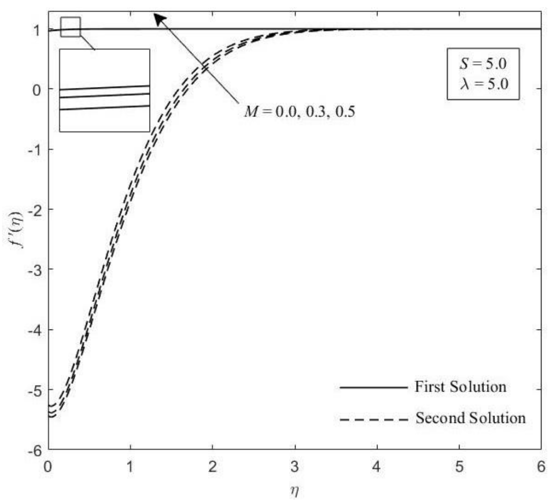

Fig. 2. The velocity profiles $f'(\eta)$ for different values of M

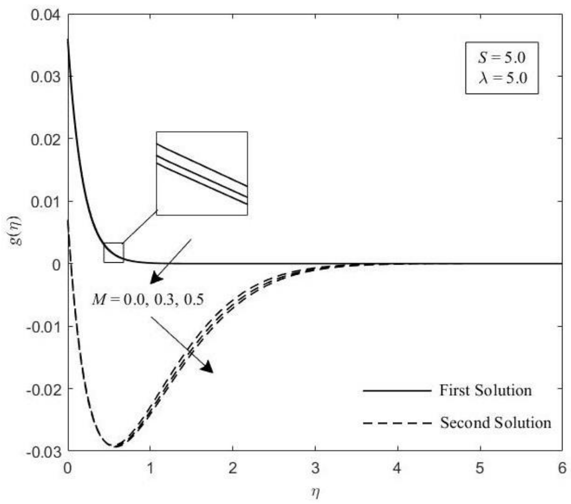

Fig. 3. The velocity profiles $g(\eta)$ for different values of M

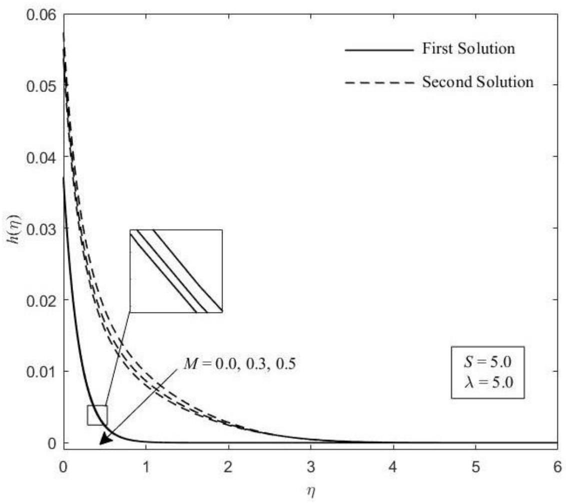

Fig. 4. The velocity profiles $h(\eta)$ for different values of M

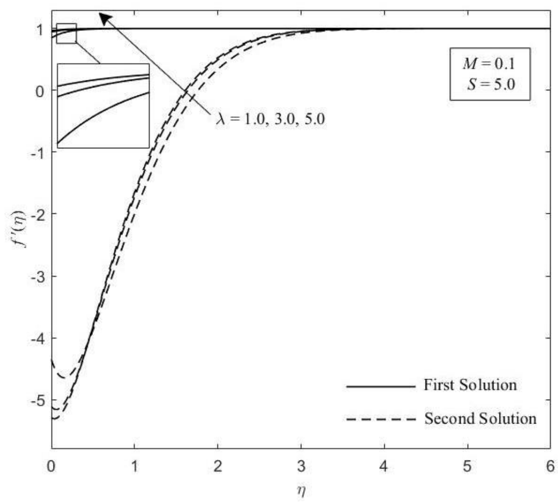

Fig. 5. The velocity profiles $f'(\eta)$ for different values of λ

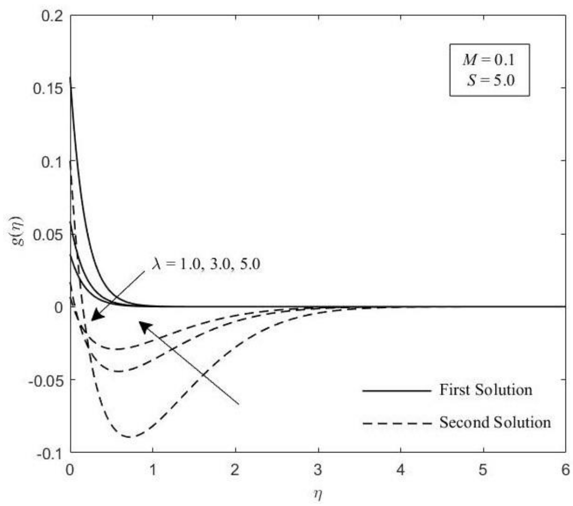

Fig. 6. The velocity profiles $g(\eta)$ for different values of λ

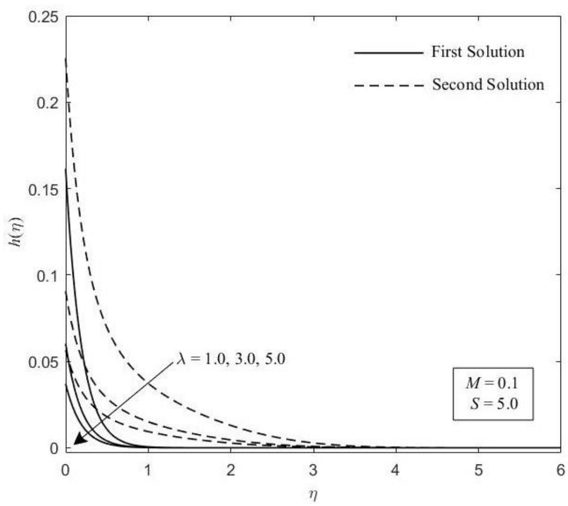

Fig. 7. The velocity profiles $h(\eta)$ for different values of λ

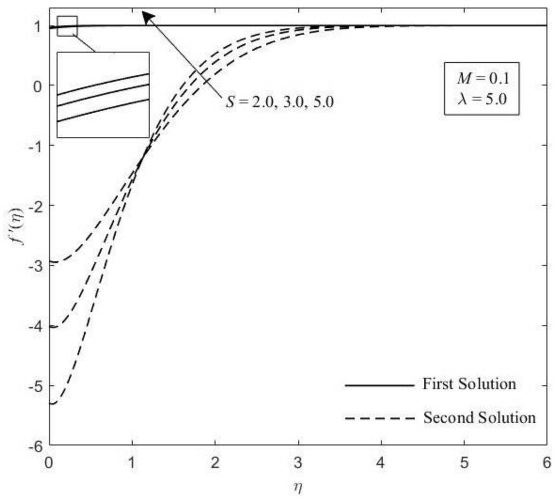

Fig. 8. The velocity profiles $f'(\eta)$ for different values of S

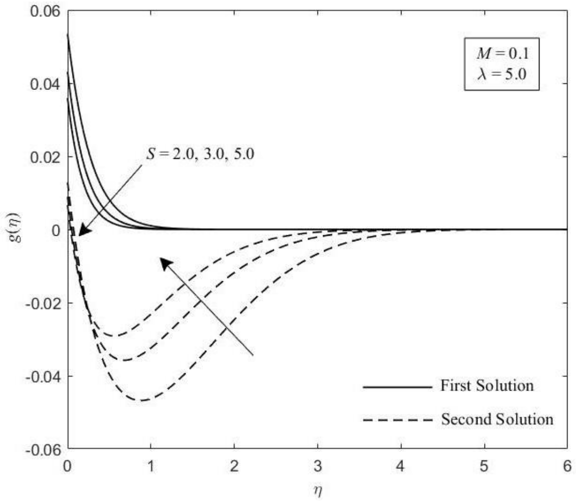

Fig. 9. The velocity profiles $g(\eta)$ for different values of S

As we have seen in Figure 2 until 9, all these profiles met the boundary conditions (10), thereby promoting the validity of the results obtained and the existence of non-unique solution (dual solutions) are clearly demonstrated in this study. Figure 11 until 13 depict the dual solutions for the physical quantities of interest, which are the skin friction coefficient $f''(0)$, $g'(0)$ and $h'(0)$ against S with the influence of M for a fixed $\lambda = 3.0$. From Figure 11, we can observed that, as the value of magnetic parameter M increases, the skin friction coefficient $f''(0)$ also increases as the magnitude of the suction parameter increases. This is because of the presence of a transverse magnetic field is determined by the Lorentz force, which results in a hindering force in the velocity field, as discussed earlier in Figure 2 until 4. However, as we look at Figure 12 and 13, the variations $g'(0)$ and $h'(0)$ decrease as the magnitude of the suction and magnetic parameters increase. It is intriguing to point out that, in this study, dual solutions are found to exist infinitely for any value of the parameters considered. As a result, there is an absence in the critical value and the turning point, as opposed to other studies that have managed to obtain multiple solutions for a certain range of parameters. This scenario has been mentioned by Hafidzuddin *et al.,* [31].

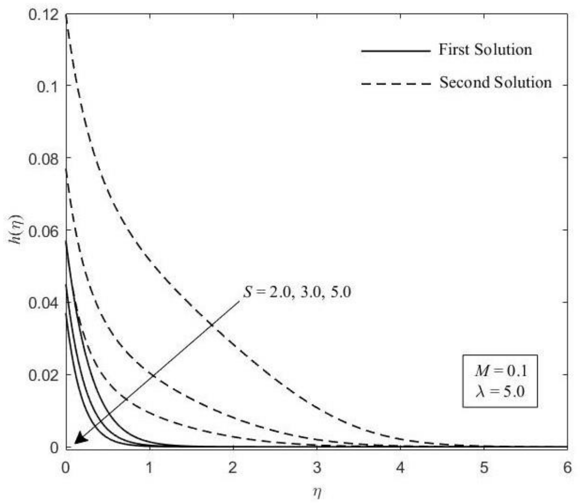

Fig. 10. The velocity profiles $h(\eta)$ for different values of S

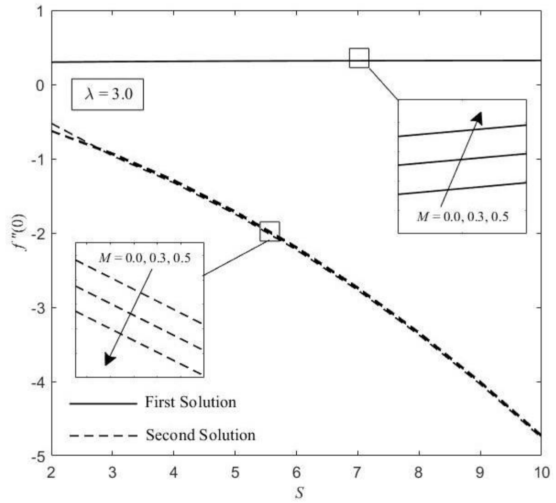

Fig. 11. Variation of the skin friction coefficient $f''(0)$ with S for several values of M

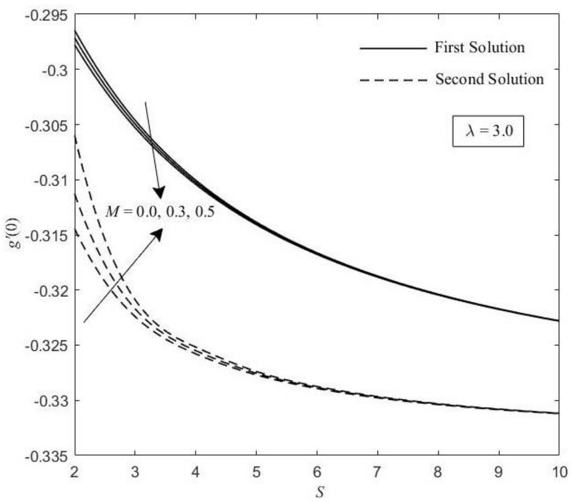

Fig. 12. Variation of the skin friction coefficient $g'(0)$ with S for several values of M

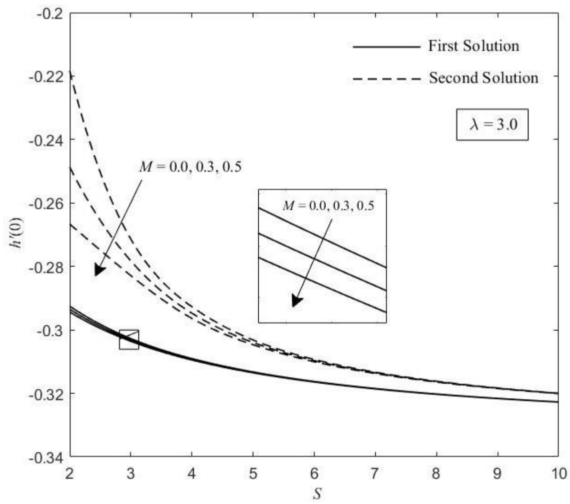

Fig. 13. Variation of the skin friction coefficient $h'(0)$ with S for several values of M

4. Conclusions

The present research deals with the numerical analysis of magnetohydrodynamics (MHD) stagnation slip flow over a permeable plate with suction effect. By using the bvp4c method, the numerical results obtained and compared with the previous published results and a good agreement was found in this study. Based on the results obtained in this study, we can say that the velocity profiles are obtained from the solver with the increasing value of the magnetic, slip and suction parameters. It is found that velocity profile $f'(\eta)$ shows increasing behaviour as magnetic, slip and suction parameters increase. In addition, velocity profiles $g(\eta)$ and $h(\eta)$ show decreasing behaviour with the magnetic, slip and suction parameters. This can be concluded that the increasing of magnetic parameter gives increment in the skin friction coefficient. Next, the increasing of suction parameter affect in an increase the skin friction coefficient, which caused the reduction of momentum boundary layer thickness, enhance the flow near the surface of the wall. The dual solutions are found to exist infinitely when suction is implied.

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