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ORIGINAL ARTICLE

Numerical simulation of Fluid flow over a shrinking porous sheet by Successive linearization method

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Abstract In this article, stagnation point flow of a Maxwell fluid over a shrinking porous sheet is considered. The governing partial differential equations are reduced to ordinary differential equations by using similarity transformations. The solution of the resulting nonlinear boundary value problem is calculated with the help of Successive linearization method (SLM) using computational software Matlab. The present analysis confirmed the existence of dual solution for shrinking sheet, while for stretching case the solution is unique. The effects of suction parameter S on the velocity profiles are shown through graphs and analyzed in detail.

1. Introduction

In fluid mechanics non-Newtonian and Newtonian flow over a shrinking and stretching sheet is very important and plays vital role in polymer industry. Newtonian and non-Newtonian fluid flow due to stretching body originated in contraction and expanding surface in a fluid i.e., elongation of pseudopods, hot rolling, production of glass fiber, production of rubber and plastic sheets, expulsion of sheet material from a die, melt spinning and to cool down the metallic plates. Yacob and Ishak [1] investigated the two dimensional micropolar fluid over a shrinking sheet. He found that the solutions can be obtained if the adequate suction is considered in the permeable sheet. He also analyzed that stronger suction is necessary for the case of non-Newtonian fluid as compared to Newtonian fluid. Suali et al. [2] studied the unsteady stagnation point flow with heat transfer on a stretching and shrinking sheet having surface heat flux. He analyzed that with the increment in unsteadiness parameter, skin friction and local Nusselt number increase. Wang [3] examined the two dimensional axisymmetric stagnation point flow through a shrinking sheet. He found that for large shrinking rates, solution does not exist and also analyzed that with the increment in the thickness of boundary layer, convective heat transfer with shrinking rate decreases. Various experimental and numerical investigations have been done by different authors [4–19].

Stagnation point flows have gained a lot of importance recently because of their numerous applications including

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flows over the tips of rockets, aircrafts, submarines and oil ships. The two dimensional stagnation point flow with a fixed flat plate was first introduced by Hiemenz [20]. Vyas and Srivastava [21] explored the boundary layer flow in porous exponentially shrinking sheet with the help of Runga–Kutta (RK) method and Shooting method. Nadeem and Awais [22] investigated the influence of variable viscosity with thermo-capillarity on Newtonian fluid flow in a thin film through a porous medium. Ali et al. [23] found the dual solution with the help of shooting method for the nonlinear porous shrinking sheet of a Newtonian fluid under the influence of MHD. He analyzed that dual solutions can only be obtained for the positive values of the controlling parameter. Awati and Bujurke [24] examined analytically the Newtonian fluid of Magneto-hydrodynamic (MHD) flow of nonlinear porous shrinking sheet with the help of Dirichlet series and Method of stretching variables. He found that Dirichlet series with Method of stretching variables have faster convergence as compared to the Homotopy analysis method (HAM), Homotopy perturbation method (HPM) and Adomian decomposition method (ADM).

Literature survey reveals that no such attention has been given to the shrinking flow for Maxwell fluids. There are situations such as rising shrinking balloons, and so forth, the standard stretching phenomenon is not useful therefore, where shrinking phenomena are used. The purpose of this article was to analyze the Fluid flow over a shrinking sheet in the Region of a Stagnation Point through a porous medium by using Successive linearization method (SLM) and Chebyshev spectral collocation method [25–31]. With the help of this method the governing nonlinear resulting differential equation and boundary conditions transformed into an iterative scheme. The iterative scheme can be further solved with the help of Chebyshev spectral collocation method. Niu et al. [32] examined the unsteady axisymmetric boundary layer flow of a non-Newtonian fluid through a cylinder under the influence of heat transfer. According to the best of authors' knowledge, Fluid flow over a shrinking porous sheet in the region of a stagnation point by Successive linearization method (SLM) has not been investigated before.

The paper is formulated as follows: Section 2 denotes the basic formulation of the governing flow problem, and Section 3 describes the methodology and solution of the problem. In Section 4 graphical results have been sketched for various physical parameters whereas Section 5 includes the conclusion of the present analysis.

2. Mathematical formulation

Let us consider the steady two-dimensional incompressible, irrotational flow of a Maxwell fluid near a stagnation point over a shrinking porous sheet coinciding with the plane at $z = 0$. The flow being confined to $z > 0$, Cartesian coordinates (x, z) fixed in space are taken in such a way that $x - axis$ is taken along the plate and the $z - axis$ is taken normal to it respectively. We will consider the flow of a Maxwell fluid near the stagnation point on the porous shrinking sheet as shown in Fig. 1.

The governing equations of continuity and momentum equation for the Maxwell fluid flow can be written as [33,34]

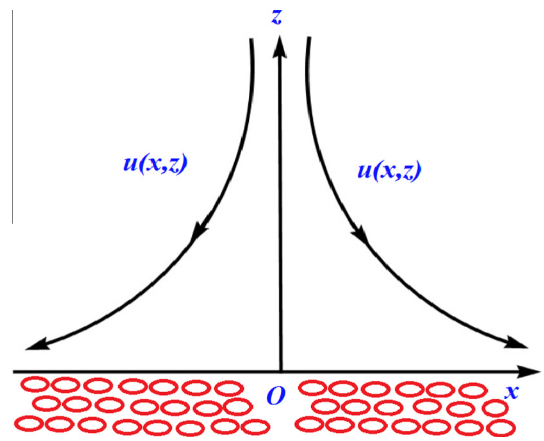

Fig. 1 Geometry of the problem.

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

$$\tilde{u}\frac{\partial \tilde{u}}{\partial x} + \tilde{w}\frac{\partial \tilde{u}}{\partial z} + \lambda\left(\tilde{u}^2\frac{\partial^2 \tilde{u}}{\partial x^2} + 2\tilde{u}\tilde{w}\frac{\partial^2 \tilde{u}}{\partial x \partial z} + \tilde{w}^2\frac{\partial^2 \tilde{u}}{\partial z^2}\right) = U\frac{dU}{dx} + \nu\frac{\partial^2 \tilde{u}}{\partial z^2} + \frac{\nu}{k}(U - \tilde{u}), \tag{2}$$

where $\tilde{u}$ and $\tilde{w}$ are the velocity components along x, and z axis whereas $U = ax$ is the free stream velocity, ν is the kinematic viscosity and λ is the relaxation time. Their respective boundary conditions are given by

$$\tilde{u} = b(x + c), \tilde{w} = 0, \text{ at } z = 0,$$
$$\tilde{u} = ax, \tilde{w} = -az, z \to \infty, \tag{3}$$

where a is the strength of the stagnation flow, b is stretching rate (shrinking occurs when $b < 0$), and c is the location of the stretching origin. The similarity variables are stated as follows [3]

$$\zeta = \sqrt{\frac{a}{\nu}}z, \tilde{u} = axg'(\zeta) + bch(\zeta),$$
$$v = 0, \tilde{w} = -\sqrt{a\nu}g(\zeta). \tag{4}$$

Using these transformations, Eq. (1) is identically satisfied and Eq. (2) gives

$$g'''(\zeta) + g(\zeta)g''(\zeta) - g'^2(\zeta) + 1 - \beta(g^2(\zeta)g'''(\zeta) - 2g(\zeta)g'(\zeta)g''(\zeta)) + K(1 - g'(\zeta)) = 0,$$
$$h''(\zeta) - g'(\zeta)h(\zeta) + g(\zeta)h'(\zeta) - \beta\left(g^2(\zeta)h''(\zeta) - 2g(\zeta)h(\zeta)g''(\zeta)\right) = 0, \tag{5}$$

where prime denotes differentiation with respect to ζ, $\beta(= \lambda a)$, is the dimensionless Deborah number and $K(= \nu/a\tilde{k})$ is the porous parameter. The corresponding boundary conditions take the new form

$$g(0) = -\frac{\tilde{u}_{\tilde{w}}}{\sqrt{a\nu}} = S, g'(0) = \alpha, g'(\infty) = 1,$$
$$h(0) = 1, h(\infty) = 0, \tag{6}$$

where S is the suction/injection parameter, $\alpha = b/a$, and $\alpha > 0$ corresponds to the stretching sheet case, $\alpha < 0$ corresponds to shrinking sheets case and for $\alpha = 0$, planar stagnation flow toward a stationary sheet case occurs, and for $\alpha = 1$, the flow has no boundary layer.

3. Solution of the problem

We apply the Successive linearization method (SLM) to Eq. (5) with their boundary conditions in Eq. (6), by setting

$$g(\zeta) = g_i(\zeta) + \sum_{m=0}^{i-1} g_m(\zeta), \qquad (i = 1, 2, 3, \ldots), \tag{7}$$

where g_i are unknown functions which are obtained by iteratively solving the linearized version of the governing equation and assuming that g_i $(0 \leqslant m \leqslant i-1)$ are known from previous iterations. Our algorithm starts with an initial approximation $g_0(\zeta)$ which satisfy the given boundary conditions in Eq. (6) according to SLM. The suitable initial guess for the governing flow problem is

$$g_0(\zeta) = S + \zeta + (\alpha - 1)\left(1 - e^{-\zeta}\right). \tag{8}$$

We write the equation in general form as

$$\mathbb{L}(g, g', g'', g''') + \mathbb{N}(g, g', g'', g''') = 0, \tag{9}$$

where

$$\mathbb{L}(g, g', g'', g''') = g''', \tag{10}$$

and

$$\mathbb{N}(g, g', g'', g''') = gg'' - g'^2 + 1 - \beta\left(g^2 g''' - 2gg'g''\right) + K(1 - g'), \tag{11}$$

where $\mathbb{L}$ and $\mathbb{N}$ are the linear and nonlinear part of Eq. (5). By substituting Eq. (7) in Eq. (5) and taking the linear term only, we get

$$g_i''' + a_{0,i-1} g_i''' + a_{1,i-1} g_i'' + a_{2,i-1} g_i' + a_{3,i-1} g_i = r_{i-1}, \tag{12}$$

the corresponding boundary conditions become

$$g_i(0) = 0, g_i'(0) = 0, g_i'(\infty) = 0, \tag{13}$$

We solve Eq. (12) numerically by a well known method namely Chebyshev spectral collocation method. For numerical implementation, the physical region $[0, \infty)$ is truncated to $[0, \Theta]$, we can take Θ to be sufficient large. This region is further transformed to the space $[-1, 1]$ using the following transformation

$$\delta = -1 + \frac{2}{\Theta}\zeta. \tag{14}$$

We define the following discretization between the interval $[-1, 1]$ and now we can apply any numerical approximation method. For this purpose we choose the Gause–Lobatto collocation points to define the nodes in $[-1, 1]$ by

$$\delta_j = \cos\left(\frac{\pi j}{N}\right), \qquad (j = 0, 1, \ldots, N), \tag{15}$$

with $(N+1)$ number of collocation points. Chebyshev spectral collocation method is based on the concept of differentiation matrix $\mathbb{D}$. This differentiation matrix maps a vector of the function values $\mathbb{G} = [g(\delta_0), \ldots, g(\delta_N)]^T$, the collocation points to a vector $\mathbb{G}'$ is defined as

$$\mathbb{G}' = \sum_{k=0}^{N} \mathbb{D}_{kj} g(\delta_k) = \mathbb{D}\mathbb{G}, \tag{16}$$

the derivative of p order for the function $g(\delta)$ is generally represented by

$$g^{(p)}(\delta) = \mathbb{D}^p \mathbb{G}. \tag{17}$$

The entries of matrix $\mathbb{D}$ can be computed using different ways and we used the method proposed by Trefethen [26]. Then apply the spectral method, with derivative matrices on linearized equation Eqs. (12) and (13) which leads to the following linearized matrix system.

$$\mathbb{A}_{i-1}\mathbb{G}_i = \mathbb{R}_{i-1}, \tag{18}$$

the boundary conditions take the following form

$$g_i(\delta_N) = 0, \quad \sum_{k=0}^{N} \mathbb{D}_{Nk} g_i(\delta_N) = 0, \quad \sum_{k=0}^{N} \mathbb{D}_{0k} g_i(\delta_N) = 0,$$
$$\sum_{k=0}^{N} \mathbb{D}_{0k}^2 g_i(\delta_N) = 0, \tag{19}$$

where

$$\mathbb{A}_{i-1} = \mathbb{D}^3 + a_{0,i-1}\mathbb{D}^3 + a_{1,i-1}\mathbb{D}^2 + a_{2,i-1}\mathbb{D} + a_{3,i-1}. \tag{20}$$

In the above equation $a_{s,i-1} (s = 0, 1, \ldots, 3)$ are $(N+1) \times (N+1)$ diagonal matrices with $a_{s,i-1}(\delta_j)$ on the main diagonal and

$$\mathbb{G}_i = g_i(\delta_j), \mathbb{R}_i = r_i(\delta_j). \qquad (j = 0, 1, \ldots, N.) \tag{21}$$

After employing Eq. (19) on the linear matrix system in Eq. (18), we obtained the solutions for g_i by iteratively solving the system in Eq. (19). We obtain the solution for $g(\zeta)$ from solving Eq. (19) and now the next Eq. (5) is now linear; therefore, we will apply Chebyshev pseudospectral method directly, which gives

$$\mathbb{B}\mathbb{H} = \mathbf{S}, \tag{22}$$

with their corresponding boundary conditions

$$h(\delta_N) = 1, h(\delta_0) = 0, \tag{23}$$

where

$$\mathbb{B} = \mathbb{D}^2 - \beta g^2 \mathbb{D}^2 + g\mathbb{D} - g' + \beta g g'', \tag{24}$$

where $\mathbb{H} = h(\delta_j)$, $\mathbf{S}$ is a vector of zeros, and all vectors in Eq. (24) are converted to diagonal matrix. We imposed the boundary conditions Eq. (23) on the first and last rows of $\mathbb{B}$ and $\mathbf{S}$ respectively.

4. Numerical results and discussion

In this section the graphical results or various physical parameters of interest are sketched and discussed. For this purpose Figs. 1–11 have been drawn. Fig. 1 shows the geometrical interpretation of the governing flow problem. Figs. 2 and 3 are plotted to see the effects of shrinking parameter (α) on the velocity respectively for two different values of suction/injection parameter (S). The dashed line represents the sheet is rigid and the solid line is for porous shrinking sheet. It is observed that by increasing the shrinking sheet, the velocity of the fluid decreases and boundary layer thickness increases. It is further depicted that for porous shrinking sheet, the velocity profile changes in magnitude but the property of velocity remains the same as for rigid sheet as shown in Fig. 2. In Fig. 3, the variation in velocity profile against shrinking

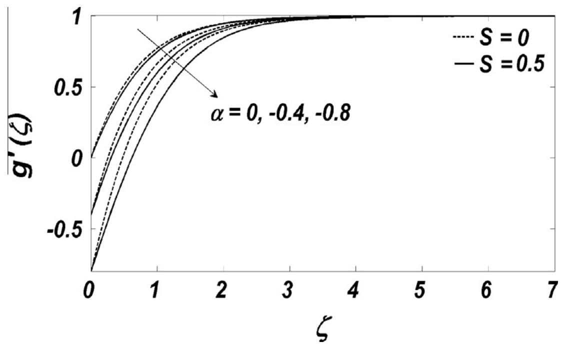

Fig. 2 Effects of the suction parameter S and the shrinking parameter $\alpha(\alpha < 0)$ on $g'(\zeta)$ when $\beta = -0.2$.

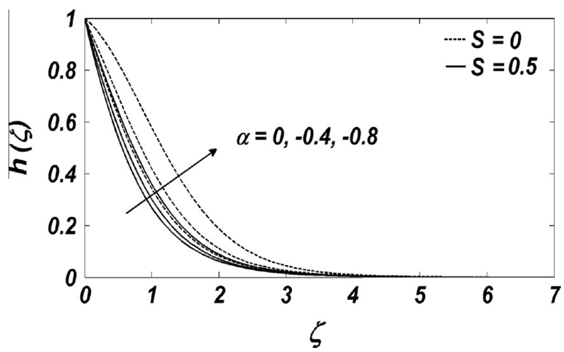

Fig. 3 Effects of the suction parameter S and the shrinking parameter $\alpha(\alpha < 0)$ on $h(\zeta)$ when $\beta = -0.2$.

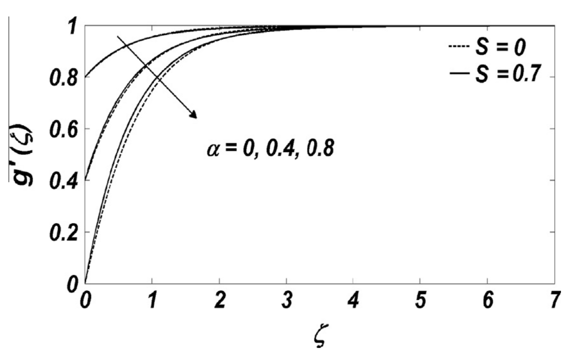

Fig. 4 Effects of the suction parameter S and the stretching parameter $\alpha(\alpha > 0)$ on $g'(\zeta)$ when $\beta = -0.2$.

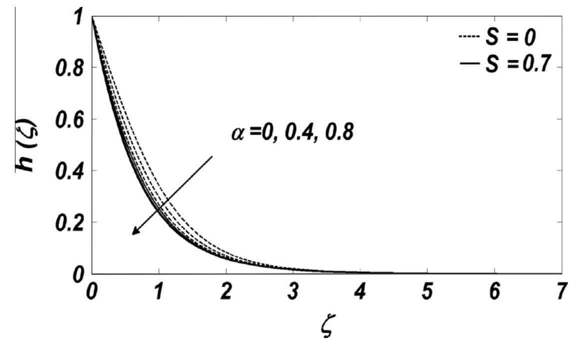

Fig. 5 Effects of the suction parameter S and the stretching parameter $\alpha(\alpha > 0)$ on $h(\zeta)$ when $\beta = -0.2$.

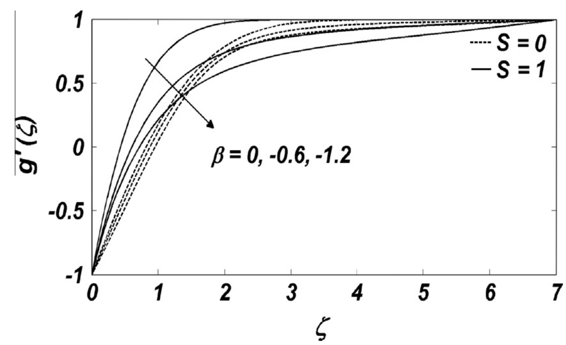

Fig. 6 Effects of the suction parameter S and the parameter β on $g'(\zeta)$ when $\alpha = -1$.

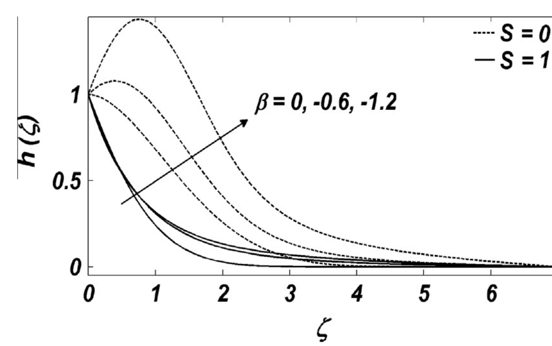

Fig. 7 Effects of the suction parameter S and the parameter β on $h(\zeta)$ when $\alpha = -1$.

parameter (α) for $S = 0$ and $S = 0.5$ is drawn. It is shown that the shrinking of sheet helps to increase the velocity profile for both rigid and porous sheet and the boundary layer thickness is changed in comparatively lesser in magnitude for $S = 0.5$ as compared to $S = 0$ against shrinking parameter (α).

Figs. 4 and 5 are drawn to show the effects of stretching parameter (α) on the velocity profiles for $S = 0$ and $S = 0.7$ and qualitatively and these effects are similar in nature as of shrinking sheet. The effects of Deborah number on velocity profile are shown for $S = 0$ and $S = 1$ in Figs. 6 and 7 respectively when $\alpha = -1$. It is seen that the boundary layer thickness varies in larger magnitude against Deborah number when suction of the shrinking sheet is taken into consideration. An interesting fact is observed in velocity profiles, if we consider the sheet as rigid, and it occurs overshoot near the sheet. This overshoot can be controlled by introducing the pores in the sheet. Similarly, again the effects of Deborah number (β) for $S = 0,\ 1$ against velocity profiles are shown in Figs. 8 and 9 for $\alpha = 0.6$ respectively.

The variation in velocity profiles against suction/injection parameter (S) is shown in Figs. 10 and 11 respectively. The remaining parameters are kept fixed at $\beta = -0.4$ and $\alpha = 0$. It is pertinent to mention that by increasing the suction parameter (S) of the sheet, velocity profile $g(\zeta)$ is decreased and boundary layer thickness increases as shown in Fig. 10. On the other hand by increasing Suction/injection parameter (S) of shrinking sheet, the velocity profile increases and boundary layer thickness increases. It can also be observed from Fig. 12 that when the porous parameter (K) increases then the

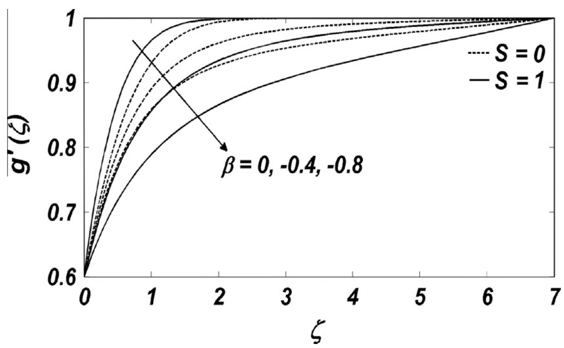

Fig. 8 Effects of the suction parameter S and the parameter β on $g'(\zeta)$ when $\alpha = 0.6$.

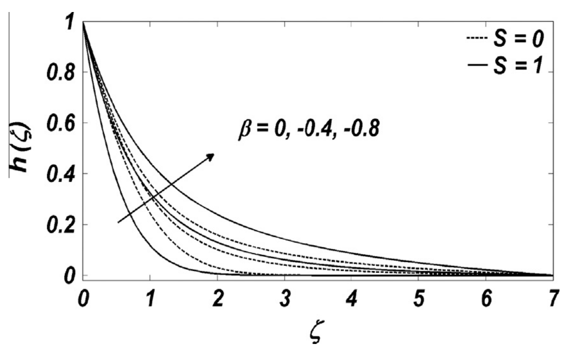

Fig. 9 Effects of the suction parameter S and the parameter β on $h(\zeta)$ when $\alpha = 0.6$.

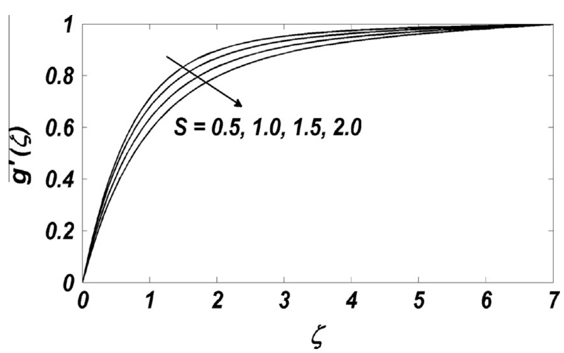

Fig. 10 Effects of the suction parameter S on $g'(\zeta)$ when $\beta = -0.4;\ \alpha = 0$.

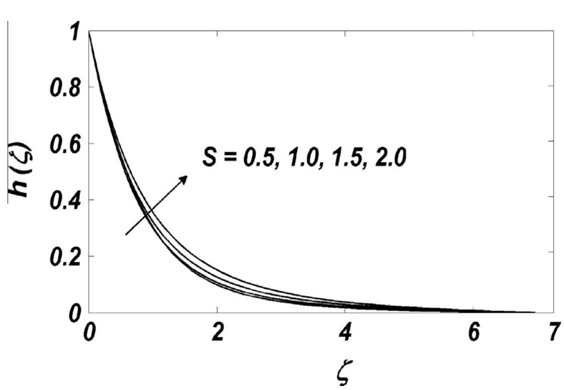

Fig. 11 Effects of the suction parameter S on $h(\zeta)$ when $\beta = -0.4;\ \alpha = 0$.

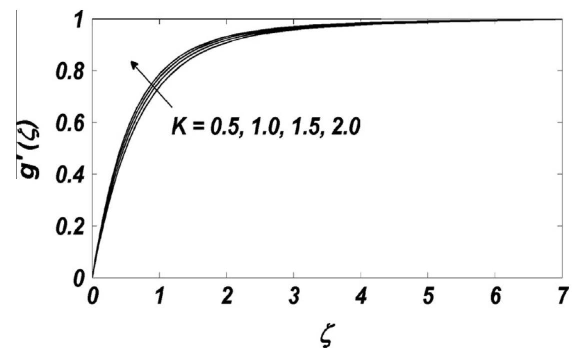

Fig. 12 Effects of the porous parameter K on $g'(\zeta)$ when $\beta = -0.4;\ \alpha = 0$.

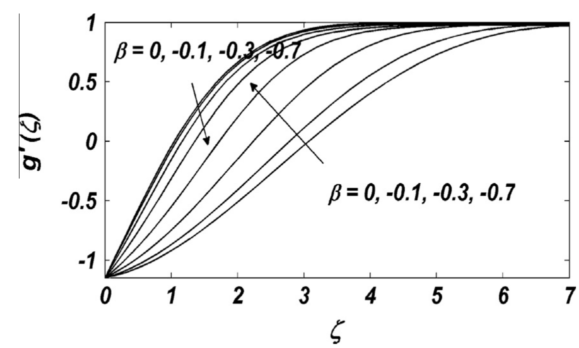

Fig. 13 Existence of dual solution: Effect of β on $g'(\zeta)$ when $\alpha = -1.15$.

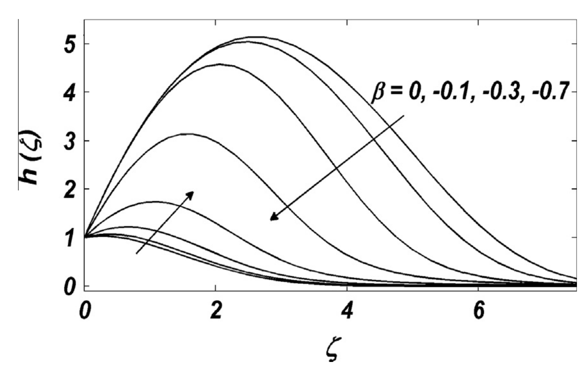

Fig. 14 Existence of dual solution: Effect of β on $h(\zeta)$ when $\alpha = -1.15$.

magnitude of the velocity increases. Figs. 13 and 14 are sketched to show the existence of dual solution for various values of β.

5. conclusion

In this article, the boundary layer flow for Maxwell fluid in the region of stagnation point over a two-dimensional shrinking porous sheet is discussed. The similarity variables are used to transform the partial differential equations to ordinary differential equations. The resulting nonlinear ordinary differential equation are solved with the help of Successive linearization method (SLM). The study also confirmed the existence of a dual solution for shrinking sheet, while for the stretching case the solution is unique. It is also observed that with the increment in the suction/injection parameter of the shrinking sheet, boundary layer thickness and the velocity profile increase.

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