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A STUDY ON EFFECT OF SUCTION OR INJECTION IN LAMINAR BOUNDARY LAYER FLOW AND HEAT VARIATION ON A STRETCHED SURFACE

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Abstract

The similarity solutions for laminar boundary layer equations with suction or injection across a stretched surface are presented. The surface was expected to move with a power law velocity profile, with a velocity parameter of $-0.93416 \leq m \leq 5.0$, and to be controlled by a dimensionless suction or injection parameter of $-1.0 \leq d \leq 4.0$. For higher negative values of m, it was discovered that suction of the boundary layer on the stretched surface delays backflow while injection enhances the strength of the reverse (or velocity overshoot) flow. For various values of m, non-unique solutions of the governing equations according to the boundary conditions have been obtained. The dimensionless shear stress at the stretched surface increases with increasing d until it reaches a maximum, when the shearing force and the injection inertia force are balanced, and then it drops asymptotically to zero for some decelerated flow ($m < 0$). It decreases asymptotically to zero for accelerated flow ($m > 0$).

Nomenclature

A, = Constant = −0.334287;
B, = Constant = 0.406887;
C, = Constant = −0.171006;
E, = Constant = 0.0240451;
d, = Dimensionless blowing (or suction) parameter;
f, = Dimensionless stream function;
m, = Velocity exponent parameter;
Re_x, = Reynolds number [$= U_o x^{(m+1)}/\nu$ or $= U_w x/\nu$]
u, = Velocity component in x-direction;
U_o, = Constant;
v, = Velocity component in y-direction;

x, = Coordinate in direction of surface motion;
y, = Coordinate in direction normal to surface motion.

Greek symbols

δ, = Boundary layer thickness;
η, = Dimensionless similarity variable [$= y\sqrt{(m+1)/2}\sqrt{(U_o x^{m-1}/\nu)}$];
μ, = Absolute viscosity;
ν, = Kinematic viscosity;
τ, = Shear stress.

Subscripts

w, = Condition at the surface;
∞, = Condition at ambient medium.

Superscripts

′, = Differentiation with respect to η

General Introduction

Fluid mechanics is a new and exciting branch of applied mathematics. Almost all sectors of engineering, as well as astrophysics, biology, biomedicine, meteorology, physical chemistry, plasma physics, and geophysics, are interested in it. It contains a big number of tasks that can be used to supplement science and technology mathematics instruction. We live in a world that is predominantly fluid. The behaviour of air, oceans, rivers, and other fluids is primarily described using continuum hypothesis ideas. The constitutive equations are constructed around some assumptions about fluid material behaviour and flow conditions. Its study is crucial for physicists and applied mathematicians who are interested in understanding the physical events involved. Fluid motion is used to modify heat and mass transfer rates in heat exchanges, cooling towers, boilers, chimneys, artificial kidneys, heart and lung machines, semi conductor device manufacturing, and spacecraft protection from intense heating during re-entry into the earth's atmosphere, among other applications. Aeronautics, astronautics, automotive engineering, biomedical engineering, mining and metallurgical engineering, naval architecture, and nuclear engineering all require a solid understanding of fluid mechanics. Fluid dynamical engineers, on the other hand, used empirical formula to solve a variety of actual difficulties. Understanding this subject also aids us in explaining a range of amazing natural occurrences that occur all around us. The rules of fluid mechanics can be used to understand the causes of natural disasters such as tornadoes, hurricanes, and monsoons. The laws of fluid dynamics control the human circulatory system. The flow of air into our lungs and the flow of blood through our arteries and veins, as well as other circulatory systems, are both considered vital. Water flows in channels, rivers, and other Newtonian/non-Newtonian liquid flows in technical systems are also relevant to our day-to-day living conditions. It is vital to grasp the distinction between a solid and a fluid before proceeding with the topic of fluid qualities. There are four states of matter: solid, liquid, gas, and plasma (ionized gases). Fluids are the general term for liquids and gases. Fluid Mechanics is the subject in which we deal with flow problems involving one of these phases, such as liquid, gas, or plasma, or a combination of these phases, primarily the first two or last two. All materials defonnate when they are subjected to external stimuli. When the defonnation in a material grows indefinitely to the point where its constituent particles are freely mobile, the material is referred to as fluid. In contrast to solid substances, a fluid is defined as a cohesive material entity whose pieces are easily transported past one another or, in other words, a substance that offers minimal resistance to changing its shape [Kaufmann (1963)]. Understanding the basic principles followed by various types of fluids is critical for the preservation of our natural living circumstances as well as numerous technological advancements.

Laminar flows and Turbulent

Fluid flows can be classified into two types based on experimental findings: laminar and turbulent. Osborne Reynolds (1894) used dye to conduct an experiment on fluid flows via a conduit at various speeds. He discovered that the flow exhibits a streamline pattern at low velocity, but that at a certain high velocity, the flow begins to mix stream lines. The former is referred to as laminar flow, whereas the latter is referred to as turbulent motion. To separate the aforementioned two states of motion, a non-dimensional number related with viscous fluid flow motion, such as the Reynolds number, is added. The Reynolds number is defined as Re = Udp/ J.L in the case of viscous fluid flowing in a pipe, where U is the typical mean velocity.

Flows in the boundary layer

The theory of boundary layers has offered a framework for studying a variety of characteristics of fluid flow at high Reynolds numbers. In 1904, during the third Congress of Mathematicians in Heidelberg, Germany, Ludwig Prandtl presented his boundary layer theory. The narrow region of flow close to a surface known as a boundary layer is the layer in which the flow is impacted by friction between the solid surface and the fluid.

The theory was founded on a few key observations. In all regions, the viscosity of the fluid in motion cannot be ignored. This results in a serious condition known as no slip. The flow at the body's surface is at a standstill in relation to the body. The viscosity of the flow can be ignored again at a certain distance from the subject. The boundary layer is a very thin layer near to the body in which the effects of viscosity are significant. This is also known as the fluid layer in which the tangential component of the fluid's velocity relative to the body grows from zero at the surface to the free stream value at a certain distance away. The boundary layer theory is the foundation of our understanding of the flow of air and other low-viscosity fluids in a variety of engineering situations. A study of the flow within the boundary layer and its effect on the general flow around the body has therefore cleared many complicated problems in aerodynamics. Even though a comprehensive mathematical study is currently impractical, the boundary layer notion has proven to be quite lucrative and valuable. Navier-Stokes equations are notoriously difficult to solve analytically.

This is especially true when the frictional and internal forces in the entire flow field are of the same order of magnitude, implying that neither can be ignored. Solutions are possible in some circumstances of low Reynolds number flow phenomena, such as creeping motions, when frictional forces may dominate inertial forces. For the case of flow with a large Reynold's number, Prandtl's boundary layer theory is applicable (except in the immediate vicinity of fixed boundary of solid object). Prandtl (1904) conducted a series of experiments and hypothesised that viscous forces are insignificant everywhere except near solid borders, where the no-slip condition exists.

Many industrial uses exist for the laminar boundary layer flow field created by a continuously stretched surface in a quiescent fluid. Continuously extruded polymer sheets and plastic films from a slit, as well as the coating of a moving surface that is isothermal, are examples of such applications (Rezaian and Poulikakos). As a result, the effect of suction or injection of the boundary layer across a stretched surface is investigated in this work. The velocity profiles of the surface are believed to be more broad power law profiles. Sakiadis has published flow field analyses for both continuous flat and cylindrical surfaces. The stretched surface was assumed to move with uniform velocity (m = 0, d = 0) in his study, and similarity solutions for the governing equations were generated to map out the boundary layer thickness, displacement, and momentum thickness, respectively. Banks investigated a class of flow field similarity solutions for extending a surface with a power law velocity distribution, but suction or injection were not allowed: He also stated that there is no evidence for dual solutions of the governing equations subject to boundary conditions for this type of similarity solutions. Many authors have considered the flow field m = 0, which corresponds to a uniformly moving surface. Taylor investigated the boundary layer of air formed by a sheet of water, while Stuart reported on the problem of oscillatory viscous flow.

Crane studied the flow and temperature fields of a stretched surface (d = 0) moving at a linear speed, and Vleggaar studied flat and cylinderical surfaces moving at a uniform or linear speed. Ali has recently investigated a stretching surface moving with a power law velocity and temperature profiles for three different temperature thresholds.

For linear surface velocity with homogeneous temperature, Gupta and Gupta documented the suction or blowing of the boundary layer over a stretched surface. Ackroyd provided a series solution of the boundary layer equations subject to suction or injection for a vapour boundary layer at the condensate surface.

A family of similarity solutions of the boundary layer equations of a stretched surface moving with a more general power law velocity sensitive to suction or injection at the surface is described in this paper.

Section II presents the problem's mathematical analysis, followed by Section Ill's numerical solution approach. Section IV contains the findings and discussion. Section V concludes with a summary and conclusions.

Equations for boundary layers

One of the most significant achievements in fluid dynamics was the derivation of the boundary layer equations. The well-known governing Navier-Stokes equations of viscous fluid flow can be considerably simplified within the boundary layer using an order of magnitude approach. In contrast to the elliptical fonn of the full Navier-Stokes equations, the characteristic of partial differential equations (PDE) becomes parabolic. This makes solving the problems a lot easier.

The following continuity and momentum equations govern the motion of a laminar incompressible boundary layer flow with constant fluid characteristics over a stretching surface with suction or injection.

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \upsilon \frac{\partial^2 u}{\partial y^2} \tag{2}$$

The aforementioned governing equations with zero axial pressure gradient were developed using the standard boundary layer approximation of a thin region (Schlichting). The following boundary condition is assumed for equations (1) and (2):

$$u = U_w = U_0 x^m, \quad v = v_w \neq 0 \quad @\, y = 0 \tag{3}$$

$$u \to 0., \; @\, y \to \infty \tag{4}$$

where m denotes the velocity stretching parameter and U_o denotes the constant velocity. Figure 1 depicts the cartesian (x,y) and boundary layer representations on a stretched surface. The x-axis in this diagram is parallel to the moving surface, while the y-axis is perpendicular to it. u and v are the velocity components in the x and y directions, respectively. Figure 1 shows qualitative vertical velocity patterns for three different values of m, illustrating an injection flow at the surface boundary. The following similarity transformation can be used to simplify Equations (1) and (2) to a single ordinary differential equation.

$$u = U_o \; x^m \; f'(\eta), \; \eta = y \sqrt{\frac{m+1}{2}} \sqrt{\frac{U_o x^m}{\upsilon \; x}} \tag{5}$$

$$v = -\sqrt{\frac{2\upsilon U_0}{m+1}} \; x^{\frac{m-1}{2}} \left[\frac{m+1}{2} f + \frac{m-1}{2} f' \; \eta \right] \tag{6}$$

η is the similarity variable that depends on y and x, and f is the dimensionless stream function that only depends on η With a prime representing differentiation with respect to η. The transformed governing equation is as follows:

$$f''' + f f'' - \frac{2m}{m+1} f'^2 = 0 \tag{7}$$

The following boundary conditions, derived from equations (3), (4), and (5), apply (6)

$$f'(o) = 1, f(0) = -v_w \sqrt{\frac{x^{1-m}}{\upsilon U_0}} \sqrt{\frac{2}{m+1}}, \; f'(\infty) \to 0 \tag{8}$$

The vertical injection or blowing speed V_w must be a function of the distance (for m ≠1) from the leading edge in order to derive the second of the boundary requirements (8). As a result, v_w is defined by the law.

$$v_w = d\,U_w\,Re^{-1/2},\ \text{or}\ d = \frac{v_w}{U_w}\,Re^{1/2} \qquad (9)$$

in order to arrive at a similarity solution in which η is the sole component of the mathematical solution It should be noted that V_w must be on the order of $U_w\ Re^{-1/2}$[13], where $Re = U_w\ x/v$, in order for a flow with suction or blowing at the surface to satisfy the boundary layer theory assumptions. As a result, d, which is used as suction or blowing parameter, must be of order one (Bejan).

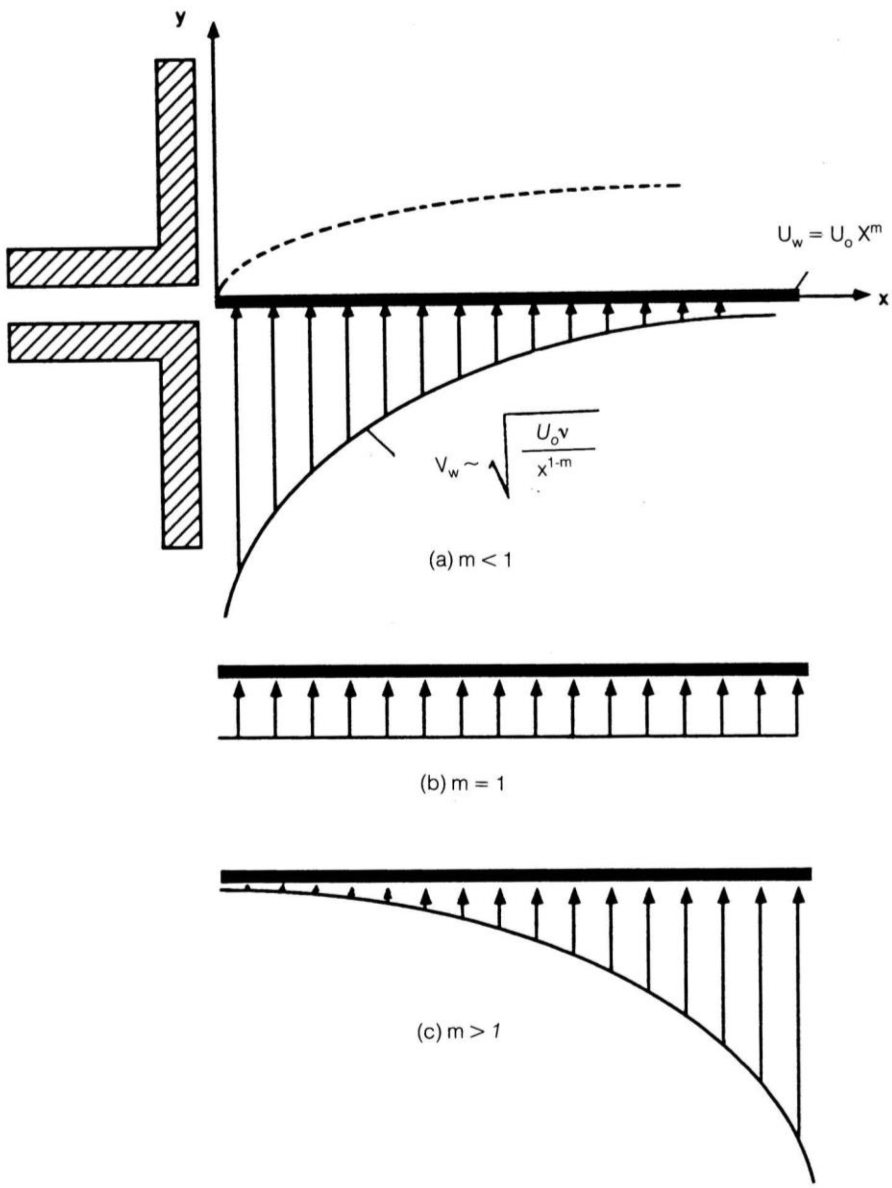

Figure 1. Qualitative representation of boundary layer on a stretched surface with injection velocity V_W for (a) m<1,(b)m=1,(c)m>1

However, if m = 1, v_w is a constant that does not contain x, and the similarity solution can still be determined as Chow describes. Gupta and Gupta simplified Equation (7) and the boundary conditions (8) to Equation (8) and (9) for m = 1. The second boundary condition (number 8) can be stated as

$$f(O) = -d\sqrt{\frac{2}{m+1}} \quad (10)$$

The suction or blowing parameter d is used to determine the strength and direction of the normal flow at the boundary, as shown in Eq. (9). As a result, we obtain a blowing or suction boundary condition for positive and negative d, respectively.

The similarity solution of Eq. (7) and Eq. (5) can be used to derive expressions for shear stress and boundary layer thickness, respectively.

$$\tau = \mu \ U_o x^{m-1} \sqrt{\frac{m+1}{2}} \sqrt{Re_x} \ f'' \ (\eta) \quad (11)$$

$$\delta = \frac{x}{\sqrt{Re_x}} \frac{\eta_{max}}{\sqrt{\frac{m+1}{2}}} \quad (12)$$

In Eq. (11) $f'' \sqrt{((m+1)/2)}$ describes the dimensionless shear stress distribution in the boundary layer and the particular value of $f'' \sqrt{((m+1)/2)}$ at $\eta = 0$ represents the dimensionless shear stress on the stretching surface.

Procedure for solving numerical problems

To intergate equation (7) pursuant to boundary conditions (8) and the modified f(O) given by, the fourth order Runge-Kutta-Merson method was utilised (10). To find f' (0), the half interval approach is employed, and the algorithm has been adjusted in accordance with Chow . The calculations were performed using an IBM compatible 386 personal computer. The solution yields the functions f, f', and f'' that are dependent on η_∞. The value of η_∞ was chosen to be as large as possible without creating numerical oscillations in the solution, ranging from 7 to 20, depending on m and d.

Result and Discussion

Equation (7) has been solved for the velocity parameter $-0.93416 \leq m \leq 5.0$ and various values of the dimensionless speed $-1.0 \leq d \leq 4.0$ under the first and third boundary conditions of (8) and the modified boundary condition (10).

Figure 2 shows some typical velocity profiles for various values of m and injection flow a! the positive value of d = 0.6's boundary. The velocity profiles for m > ϕ in this figure show exponential decay with no inflection points. The slope of the velocity profile is virtually zero at ' η = 0 (f'' (0) =0.005) for m, = -0.147, and it has a separation point. Additionally, as m drops, a backflow develops, and for higher negative values of m, a velocity overshoot is expected, as seen in Fig. 3 for various negative values of m, in which case the surface is stretched with a decreasing velocity, resulting in a decelerated flow. Furthermore, when m lowers, the boundary layer thickness drops, and the velocity profiles shift their slopes to be steeper at the edge of the surface, continuing the velocity overshoot stream. When comparing this situation to decelerated flow over a stationary flat plate (Schlichting), it can be seen that injecting at the decelerated surface's boundary increases the strength of the reverse or overshoot flow and diminishes the boundary layer thickness.

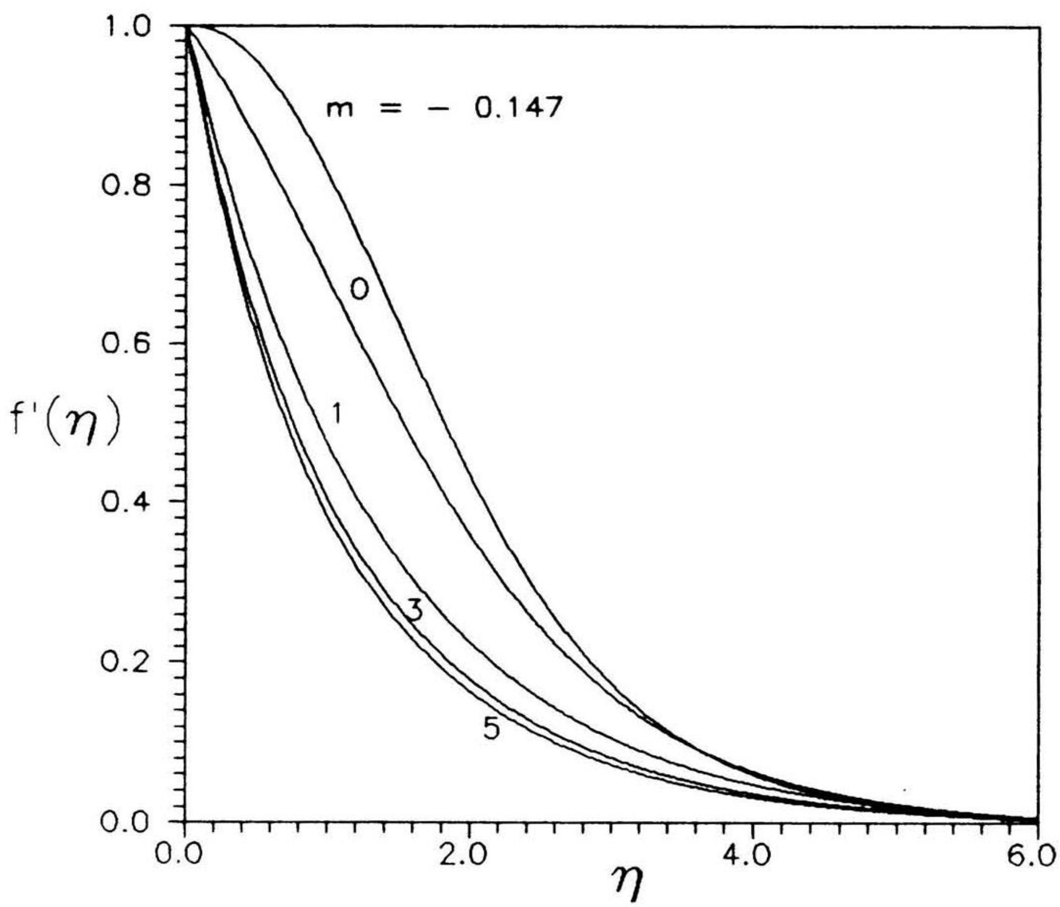

Figure 2. Similarity velocity profile as a function of the similarity variable η for various value of m and for d= 0.6

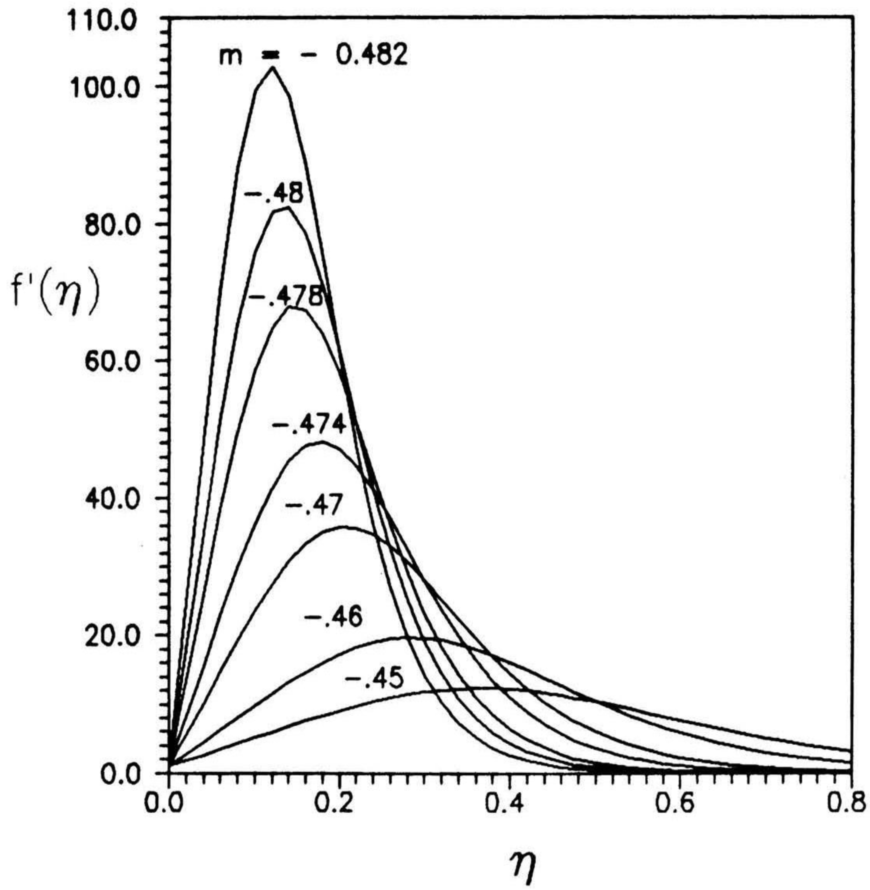

Figure 3. Similarity velocity profiles indicating the velocity overshoot stream for negative value of m and d =0.6.

The existence of an inflection point in the velocity profile indicates flow instability (Lin), and when the mass flow in blowing is increased, it is found that numerical calculations become more complex because the velocity profile kinks. As a result, problems arise when high negative values of m are combined with positive values of d.

Only the solution in which the velocity profiles indicate asymptotic decay to zero was acceptable during the search for similarity solutions of Eq. (7) subject to (8) and (10). As a result, if the velocity profiles contain negative regions, even though they fulfill the governing equation and its boundary conditions, they are unrealistic and should not be considered.

The existence of non-unique solution has been found. Figure 4 presents f' (η) as a function of the similarity variable η for m = 2.0 and 3.5 and for d = 0.6. The non-unique solutions of the velocity profiles are shown in this diagram; one group has one asymptotic decay solution and the other has a negative velocity region for the same value of m. For various values of m, similar curves of velocity profiles for d = 0.4 are shown in Figs. 5 and 6.

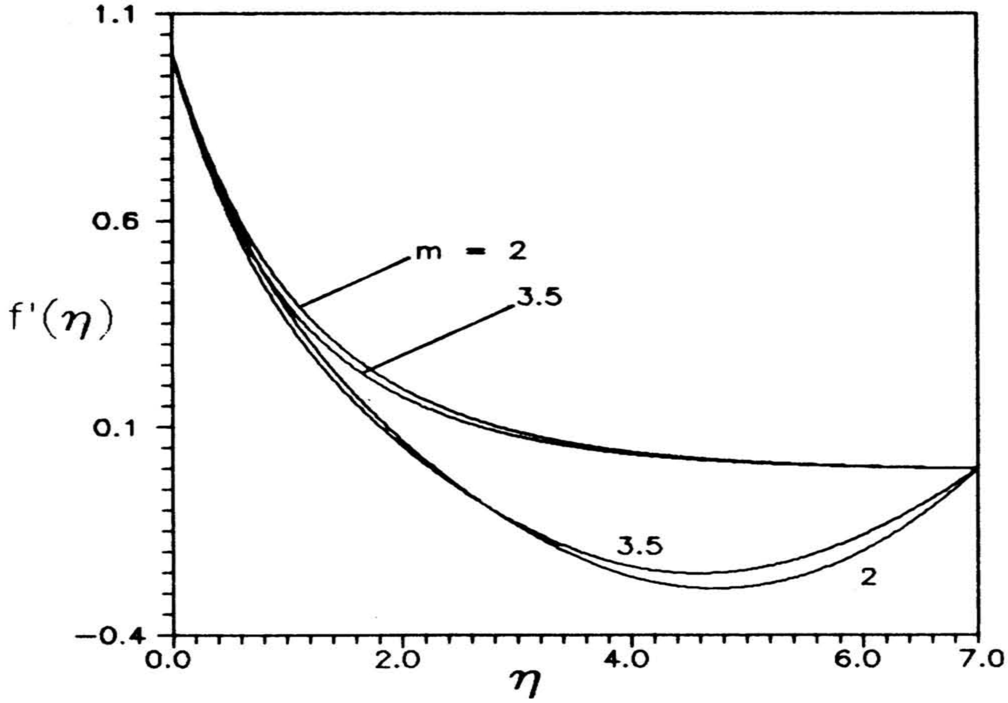

Fig. 4. Similarity velocity distributions showing the existence of non-unique solutions for m = 2 and 3.5 for d = 0.6 .

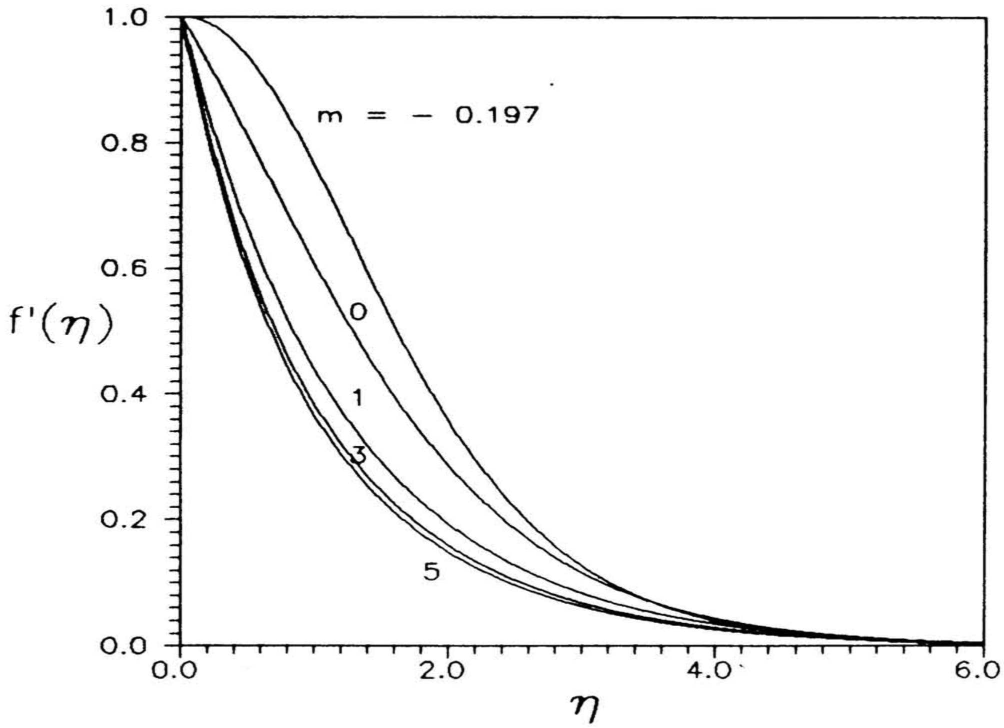

Fig. 5. Similarity velocity profiles as a function of η for different values of m at d = 0.4 .

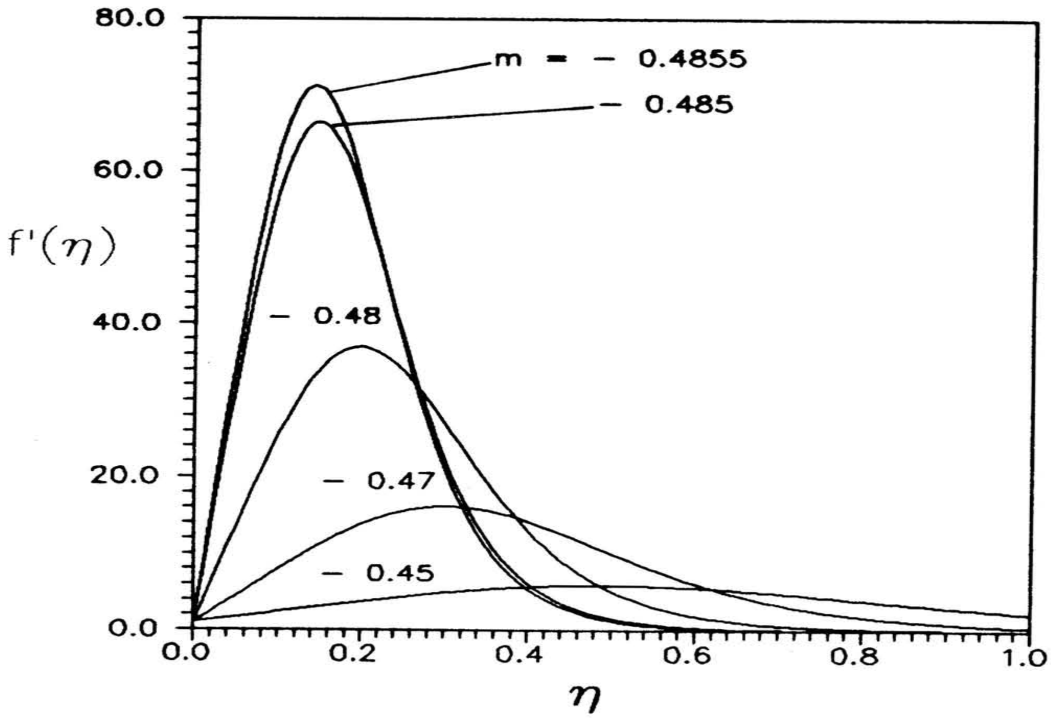

Fig. 6. Similarity velocity profiles showing the velocity overshoot flow for negative values of m and for d = 0.4.

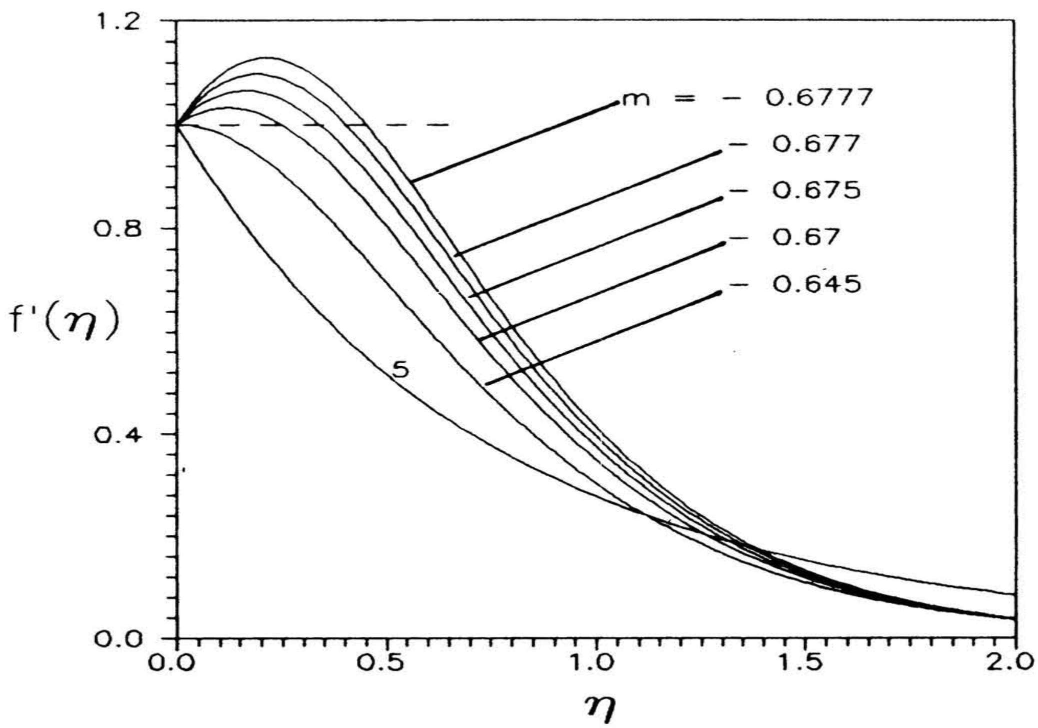

Fig. 7. Similarity velocity profiles for various values of m at d = − 0.6, the dashed line indicating the backflow for f′ (η) > 1.

Figure 7 depicts the boundary layer's suction from the stretched surface for d = -0.6 and various m values. All of the velocity profiles for $-0.645 < m \leq 5.0$ in this diagram show asymptotic decay with no inflection point in the fluid. The fluid has an inflection point at $-0.645 \geq m$, and the reverse flow occurs above the dotted line, and the separation point is extremely near to m = -0.645, where f'' (0) =0.006.

When comparing Figures 3,6, and 7, it is obvious that decreasing the regulating parameter d slows the reverse flow; in other words, m reduces as d lowers, and therefore more aymptotic type solutions with no inflection points can be achieved. The crucial values of m and d for no reverse flow in the fluid are shown in Table 1. Figure 8 shows the relationship between the critical values of m and d reported in Table 1 for zero surface shear stress. To fit the data, the following third order polynomial is employed.

Table 1. The critical values of the velocity parameter m and the injection parameter d for zero surface shear

d	m
2.2000	−0.0100
2.0000	−0.0120
1.8000	−0.0170
1.7000	−0.0190
1.6500	−0.0220
1.6000	−0.0230
1.5500	−0.0250
1.5000	−0.0280
1.4500	−0.0300
1.4000	−0.0320
1.2000	−0.0480
1.0000	−0.0750
0.8000	−0.1070
0.6000	−0.1470
0.4000	−0.1970
0.2000	−0.2600
0.1000	−0.2950
0.0000	−0.333335
−0.1532	−0.4000
−0.2000	−0.4220
−0.3158	−0.4800
−0.4000	−0.5255
−0.6000	−0.6446
−0.8000	−0.7805
−0.9000	−0.85506
−1.0000	−0.93414

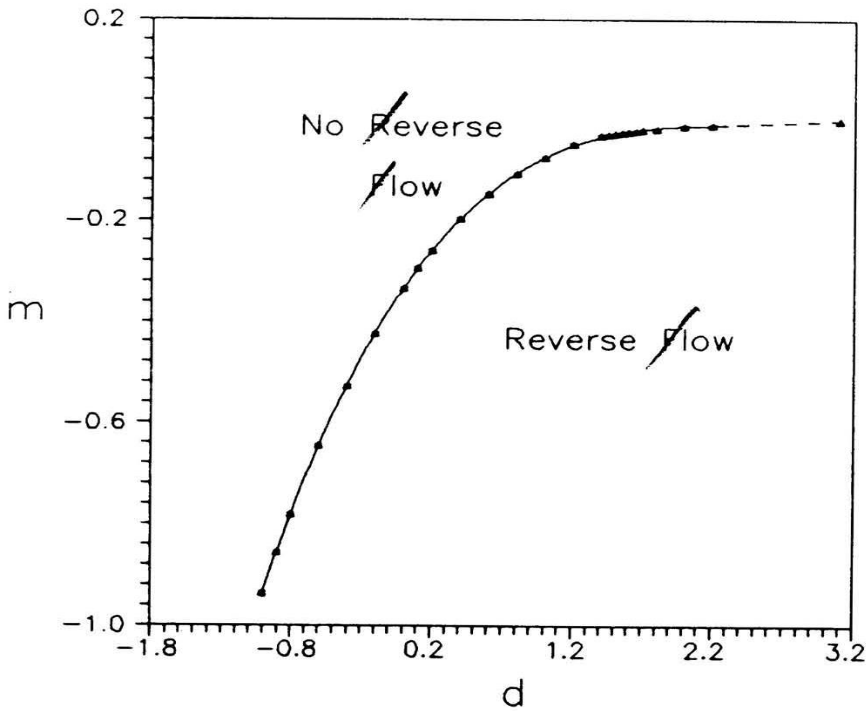

Fig. 8. The critical values of m as a function of the blowing parameter d, the dashed line connecting the computed points to the extrapolated one.

$$m = A + B\,d + C\,d^2 + E\,d^3$$

Where A,B,C, and E are the nomenclature's constants. The extrapolated point in Fig. 8 is d = 3.097 for m = -9.646e-5, where m approaches zero from the negative side since all solutions have no reverse flow for $m \geq 0$. Suction on the stretched surface boundary delays the occurrence of reverse flow, as shown in Figure 8. It should be observed that there is no solution where f(O) blows up for m = -1.

For various values of m as a function of the dimensionless velocity d, the non-dimensional shear stress at the stretched surface presented by $(m+1)/2)^{1/2}$ f'(O) is shown in Fig. 9 for various values of m. The shear stress at the wall grows as d increases, and the velocity profiles that correspond to that change from asymptotic decay before f' (0) reaches zero to profiles with inflection points for all positive values of f' (O) are shown in this figure. Furthermore, for m = - 0.2 and - 0.3, f'(O) reaches a maximum at a certain value of d, where the shearing force and the injection inertia force are balanced, and it declines with increasing the injection parameter d beyond this value.

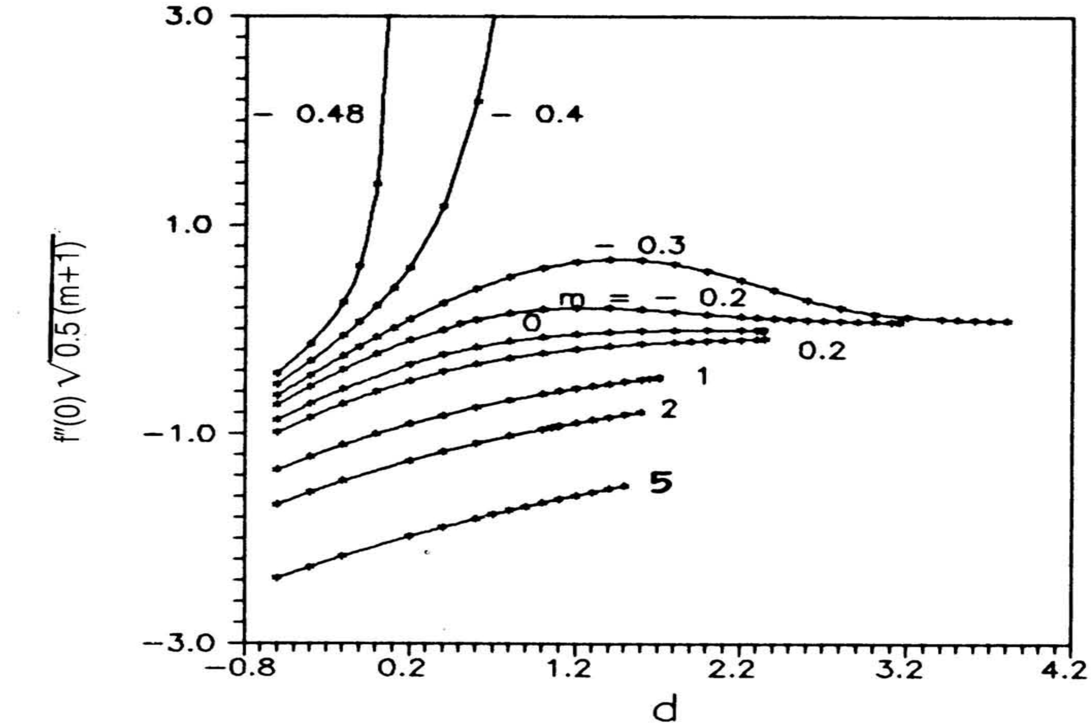

Fig. 9. The dimensionless shear stress distributions at the stretched surface boundary as a function of the blowing parameter d for various values of m .

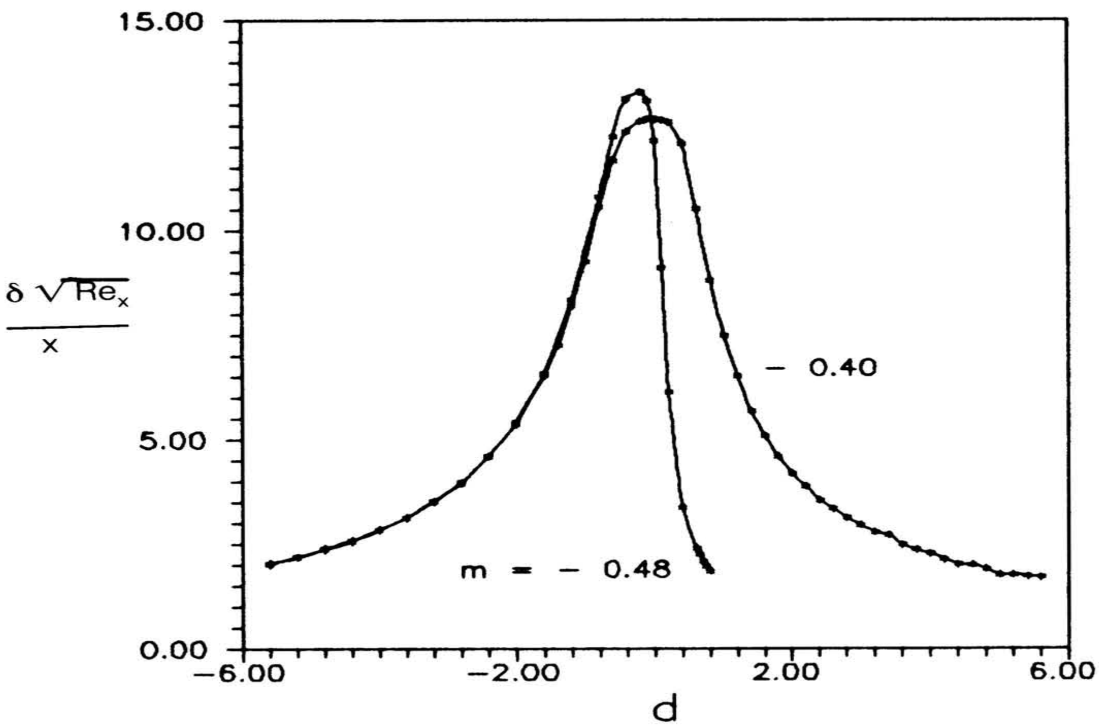

Fig. 10. The nondimensional boundary layer thickness distribution as a function of d for m = − 0.4 and − 0.48 .

For m = - 0.48 and - 0.40, Figure 10 shows the dimensionless boundary layer thickness determined by Equation (12) as a function of d. Suction increases produce increasing weakening of the boundary layer for all m, whereas injection has the opposite effect. . However, caution must be taken for negative m. If blowing is applied or suction degree is reduced ($d > d$ at $f''(0,0) = 0$) beyond the point of separation where $f'(0,0) = 0$, then the strength of backflow is built up. Furthermore, this is corresponding to decrease in (δ) up to a maximum value where a velocity overshoots. Moreover, if suction is allowed to increase 'or degree of blowing decreased ($d < d$ at $f'(0,0) = 0$) then (δ) decreases as in the general scenario mentioned before.

Summary and Conclusion

For various values of m and d, the flow field of the laminar boundary layer over a stretched surface moving with a power law velocity profile with suction or injection at the boundary is described. The similarity solutions display asymptotic behaviour for $m \geq 0$ and all values of d investigated in this study. Backflow (or overshoot) develops for negative values of m, when the stretched surface decelerates in the x-direction, and its strength is dependent on d. . Furthermore, for constant $d > O$, the strength of the reverse (or overshoot) flow increases with decreasing m if blowing is allowed ($d > 0$) at the surface boundary. Furthermore, for the same negative values of m, if suction is allowed ($d<0$) at the boundary, the strength of backflow decreases dramatically compared to the blowing scenario. For the governing equation subject to the boundary conditions, non-unique similarity solutions have been obtained. Despite the fact that these non-unique solutions meet the governing differential equation and boundary conditions, only the one with an asymptotic decline to zero is physically acceptable.

The dimensionless shear stress at the surface grows as d increases for $m \geq 0$, and it asymptotically decays to zero for $m = 0$, and 0.2. Furthermore, as observed for $m = -0.2$ and -0.3, the shear stress continues to build up to a maximum value that depends on d and m ($m <0$) and then drops asymptotically to zero. When suction or injection is used for $m = -0.4$ and -0.48, the thickness of the boundary layer decreases.

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