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Stagnation point flow of a second grade fluid with uniform suction or blowing and heat generation

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SUMMARY

The steady laminar flow of an incompressible non-Newtonian second grade fluid impinging on a permeable flat plate with heat generation is investigated. A uniform suction or blowing is applied normal to the plate which is maintained at a constant temperature. Numerical solution for the governing nonlinear momentum and energy equations is obtained. The effect of the uniform suction or blowing and the characteristics of the non-Newtonian fluid on both the flow and heat transfer is presented and discussed.

Key words: *stagnation point flow, non-Newtonian fluid, suction, steady laminar flow, heat generation.*

1. INTRODUCTION

The two-dimensional flow of a fluid near a stagnation point is a classical problem in fluid mechanics. It was first examined by Hiemenz [1] who demonstrated that the Navier-Stokes equations governing the flow can be reduced to an ordinary differential equation of third order using similarity transformation. Owing to the nonlinearities in the reduced differential equation, no analytical solution is available and the nonlinear equation is usually solved numerically subject to two-point boundary conditions, one of which is prescribed at infinity.

Later the problem of stagnation point flow was extended in numerous ways to include various physical effects. The axisymmetric three-dimensional stagnation point flow was studied by Homann [2]. The results of these studies are of great technical importance, for example in the prediction of skin-friction as well as heat/mass transfer near stagnation regions of bodies in high speed flows and also in the design of thrust bearings and radial diffusers, drag reduction, transpiration cooling and thermal oil recovery. Either in the two or three-dimensional case Navier-Stokes equations governing the flow are reduced to an ordinary differential equation of third order using a similarity transformation. The effect of suction on Hiemenz problem has been considered in the literature. Schlichting and Bussman [3] gave the numerical results first. More detailed solutions were later presented by Preston [4]. An approximate solution to the problem of uniform suction is given by Ariel [5]. The effect of uniform suction on Homann problem where the flat plate is oscillating in its own plane is considered by Weidman and Mahalingam [6]. In hydromagnetics, the problem of Hiemenz flow was chosen by Na [7] to illustrate the solution of a third-order boundary value problem using the technique of finite differences. An approximate solution of the same problem has been provided by Ariel [8]. The effect of an externally applied uniform magnetic field on the two or three-dimensional stagnation point flow was given, respectively, by Attia in Refs. [9] and [10] in the presence of uniform suction or injection.

The study of heat transfer in boundary layer flows is of importance in many engineering applications such as the design of thrust bearings and radial diffusers, transpiration cooling, drag reduction, thermal recovery of oil, etc. Massoudi and Ramezan [11] used a perturbation technique to solve for the stagnation point flow and heat transfer of a non-Newtonian fluid of second grade. Their analysis is valid only for small values of the parameter that determines the behaviour of the non-Newtonian fluid. Later Massoudi and Ramezan [12] extended the problem to nonisothermal surface. Garg [13] improved the solution obtained by Massoudi and Ramezan [12] by computing numerically the flow characteristics for any value of the non-Newtonian parameter using a pseudo-similarity solution.

Non-Newtonian fluids were considered by many researchers. Thus, among the non-Newtonian fluids, the solution of the stagnation point flow, for viscoelastic fluids, has been given by Rajeshwari and Rathna [14], Beard and Walters [15], Teipel [16], Arial [17], and others; for power-law fluid by Djukić [18]; and for micropolar fluids by Nath [19], Kelson et al. [20], Desseaux [21] and Nazar et al. [22]. Stagnation point flow of a non-Newtonian second grade fluid was studied by Teipel [23] and Ariel [24] in the hydrodynamic case. In hydromagnetics, Attia [25] introduced the influence of a magnetic field on the flow of a second grade fluid.

The purpose of the present paper is to study the steady laminar flow of an incompressible non-Newtonian second grade fluid at a two-dimensional stagnation point with heat generation. A uniform suction or blowing directed normal to the plane of the wall is applied. The wall and stream temperatures are assumed to be constants. A numerical solution is obtained for the governing momentum and energy equations using finite difference approximations which takes into account the asymptotic boundary conditions. The numerical solution is used to determine the flow and heat characteristics for the whole range of the non-Newtonian fluid characteristics, the suction or blowing parameter and Prandtl number.

2. FORMULATION OF THE PROBLEM

Consider the two-dimensional stagnation point flow of an incompressible non-Newtonian Rivlin-Ericksen fluid impinging perpendicular on a permeable wall and flows away along the x-axis. This is an example of a plane potential flow that arrives from the y-axis and impinges on a flat wall placed at $y=0$, divides into two streams on the wall and leaves in both directions. The viscous flow must adhere to the wall, whereas the potential flow slides along it. The (u,v) are the components of velocity at any point (x,y) for the viscous flow whereas (U,V) are the velocity components for the potential flow. A uniform suction or blowing is applied at the plate with a transpiration velocity at the boundary of the plate given by $-v_0$, where $v_0>0$ for suction. The velocity distribution in the frictionless flow in the neighborhood of the stagnation point is given by:

$$U(x) = ax, \quad V(y) = -ay$$

where the constant a (>0) is proportional to the free stream velocity far away from the stretching surface. A second grade fluid is defined such that the Cauchy stress tensor is related to the fluid motion in the following manner [23]:

$$T = -pI + \mu A_1 + \alpha_1 A_2 + \alpha_2 A_1^2 \tag{1}$$

where p denotes the hydrostatic pressure, I is the identity tensor, μ is the viscosity of the fluid, α_1 and α_2 are scalar constants named as normal stress moduli, and A_1 and A_2 are the first two Rivlin-Ericksen tensors. For $\alpha_1=\alpha_2=0$, Eq. (1) describes a common Newtonian fluid. Then, A_1 represents the usual deformation tensor. All the stress components have to be introduced into the equations of motion. Here, we consider the case $\alpha_2=0$, i.e. the case of a reduced Rivlin-Ericksen fluid. Then, for the two-dimensional steady-state flows, the continuity and momentum equations, using the usual boundary layer approximations [24] and by introducing the stress components, reduce to:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 , \tag{2}$$

$$\begin{aligned} \rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = U\frac{dU}{dx} + \mu\left(\frac{\partial^2 u}{\partial y^2}\right) + \\ + \alpha_1\left(\frac{\partial u}{\partial y}\frac{\partial^2 u}{\partial y^2} + v\frac{\partial^3 u}{\partial y^3} + \frac{\partial}{\partial x}\left(u\frac{\partial^2 u}{\partial y^2}\right)\right) = 0 \end{aligned} \tag{3}$$

where ρ is the density of the fluid, and $U(x)$ is the potential flow velocity over the body surface.

Using the boundary layer approximations and neglecting the dissipation, the equation of energy for temperature T with heat generation or absorption is given [11,12]:

$$\rho c_p\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial y^2} + Q(T - T_\infty) \tag{4}$$

where c_p is the specific heat capacity at constant pressure of the fluid, k is the thermal conductivity of the fluid, and Q is the volumetric rate of heat generation/absorption. A similarity solution exists if the wall and stream temperatures, T_w and T_∞ are constants – a realistic approximation in typical stagnation point heat transfer problems [11,12].

The boundary conditions are:

$$y = 0 : u = 0, v = -v_o , \tag{5a}$$

$$y \to \infty : u \to ax, \tag{5b}$$

$$y = 0 : T = T_w, \tag{6a}$$

$$y \to \infty : T \to T_\infty \tag{6b}$$

A little inspection shows that boundary-layer Eqs. (2) to (4) admit a similarity solution:

$$u(x,y) = axf'(z), \quad v(x,y) = -\sqrt{a\nu}\, f(z), \quad z = \sqrt{a/\nu}\, y \tag{7}$$

where the prime denotes differentiation with respect to z and $\nu=\mu/\rho$. By introducing the non-dimensional variable:

$$\theta = \frac{T - T_\infty}{T_w - T_\infty}$$

and using Eq. (7), we find that Eq. (2) is identically satisfied and Eqs. (3)-(6) reduce to:

$$K(\, f f^{iv} - 2 f' f''' + f''^2 \,) - f''' - f f'' + f'^2 - 1 = 0 \tag{8}$$

$$\theta'' + Pr\, f\theta' + Pr\, B\theta = 0 \tag{9}$$

$$f(0) = A, \quad f'(0) = 0, \quad f'(\infty) = 1 \tag{10}$$

$$\theta(0) = 1, \quad \theta(\infty) = 0 \tag{11}$$

where A is the suction parameter, $A = v_o / \sqrt{a\nu}$; Pr is the Prandtl number, $Pr = \mu c_p / k$; K is the dimensionless normal stress modulus, $K = \alpha_1 a / \mu$; $B = Q / a\rho c_p$ is the dimensionless heat generation/ absorption coefficient and the prime denotes differentiation with respect to z. The heat transfer from the surface to the fluid is computed by application of Fourier's law:

$$q = -k\left(\frac{\partial T}{\partial y}\right)_{y=0}$$

Introducing the transformed variables, the expression for q becomes:

$$q = -k(T_w - T_\infty)\sqrt{a/\nu}\,\theta'(0) \tag{12}$$

The heat transfer coefficient in terms of the Nusselt number Nu can be expressed as:

$$Nu = \frac{q}{k(T_w - T_\infty)\sqrt{a/\nu}} \tag{13}$$

where $\sqrt{a/\nu}$ plays the role of a characteristic length. Using Eq. (12), Eq. (13) becomes:

$$Nu = -\theta'(0) \tag{14}$$

The equations to be solved are Eqs. (8)-(11). The flow Eqs. (8) and (10) are decoupled from the energy Eqs. (9) and (11), and need to be solved before the latter can be solved. The flow Eq. (8) constitutes a non-linear, non-homogeneous boundary value problem (BVP). In the absence of an analytical solution of a problem, a numerical solution is required. The flow Eqs. (8) and (10) are solved numerically using finite difference approximations. A quasi-linearization technique is first applied to replace the non-linear terms at a linear stage, with the corrections incorporated in subsequent iterative steps until convergence. The quasi-linearized form of Eq. (8) is:

$$K\Big(f_n f_{n+1}^{iv} + f_n^{iv} f_{n+1} - f_n f_n^{iv} -$$
$$-2\big(f_n' f_{n+1}''' + f_n''' f_{n+1}' - f_n''' f' \big)_n + 2 f_n'' f_{n+1}'' - f_n''^2 \Big) -$$
$$- f_{n+1}''' - f_n f_{n+1}'' - f_n'' f_{n+1} + f_n'' f_n + 2 f_n' f_{n+1}' - f_n'^2 - 1 = 0$$

where the subscript n or $n+1$ represents the n^{th} or $(n+1)^{th}$ approximation to the solution. Then, Crank-Nicolson method is used to replace the different terms by their second order central difference approximations. An iterative scheme is used to solve the quasi-linearized system of difference equations. The solution for the Newtonian case is chosen as an initial guess and the iterations are continued till convergence within prescribed accuracy. Finally, the resulting block tri-diagonal system was solved using generalized Thomas' algorithm.

The energy Eq. (9) is a linear second order ordinary differential equation with variable coefficient, $f(z)$, which is known from the solution of the flow Eqs. (8) and (10) and the Prandtl number Pr is assumed constant. Equation (9) is solved numerically under the boundary condition (11) using central differences for the derivatives and Thomas' algorithm for the solution of the set of discritized equations. The resulting system of equations has to be solved in the infinite domain $0<z<\infty$. A finite domain in the z-direction can be used instead with z chosen large enough to ensure that the solutions are not affected by imposing the asymptotic conditions at a finite distance. Grid-independence studies show that the computational domain $0<z<z_\infty$ can be divided into intervals each is of uniform step size which equals 0.02. This reduces the number of points between $0<z<z_\infty$ without sacrificing accuracy. The value $z_\infty=10$ was found to be adequate for all the ranges of parameters studied here. Convergence is assumed when the ratio of every one of f, f', f'' or f''' for the last two approximations differed from unity by less than 10^{-5} at all values of z in $0<z<z_\infty$.

3. RESULTS AND DISCUSSION

Figures 1 and 2 present the profiles of f and f', respectively, for various values of the non-Newtonian parameter K and the suction parameter A. The figures show that increasing the parameter K decreases both f and f', but increasing A increases them. The figures indicate also that the effect of K on f and f' is more pronounced for higher values of A (case of suction). However, the effect of A on f and f' becomes more pronounced for higher values of K. Also, increasing K increases the velocity boundary layer thickness while increasing A decreases it.

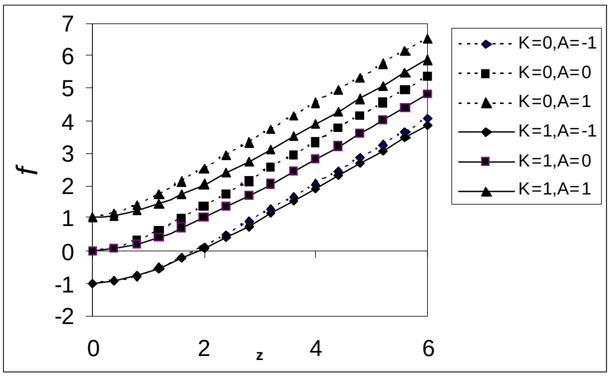

Fig. 1 Profiles of f for different values of the non-Newtonian parameter K and the suction parameter A

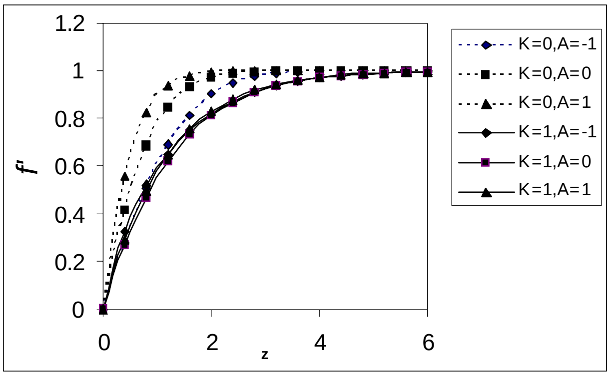

Fig. 2 Profiles of f' for different values of the non-Newtonian parameter K and the suction parameter A

Figure 3 presents the profile of temperature θ for various values of the non-Newtonian parameter *K* and the suction parameter *A* and for *Pr=0.5* and *B=0*. It is clear that increasing *K* increases θ and its effect on θ becomes more apparent for higher values of *A* (suction case). The figure indicates that the thermal boundary layer thickness increases when *K* increases. Increasing *A* decreases θ for all *K* which emphasizes the influence of the injected flow in the cooling process. The action of fluid injection (*A<0*) is to fill the space immediately adjacent to the disk with fluid having nearly the same temperature as that of the wall. As the injection becomes stronger, so that does the blanket extend to greater distances from the surface. As shown in Figure 3, these effects are manifested by the progressive flattening of the temperature profile adjacent to the wall. Thus, the injected flow forms an effective insulating layer, decreasing the heat transfer from the wall. Suction, on the other hand, serves the function of bringing large quantities of ambient fluid into the immediate neighborhood of the surface of the wall. As a consequence of the increased heat-consuming ability of this augment flow, the temperature drops quickly as we proceed away from the wall. The presence of fluid at near-ambient temperature close to the surface increases the heat transfer.

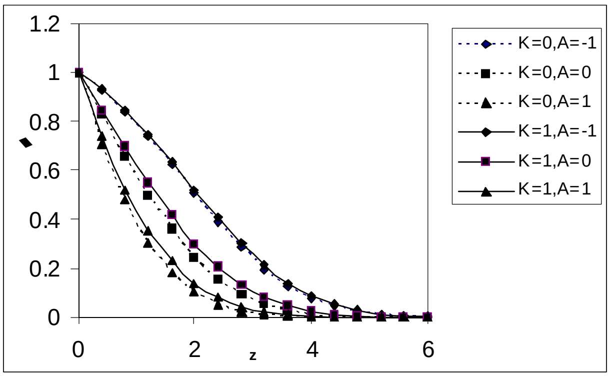

Fig. 3 Profiles of θ for different values of the non-Newtonian parameter K and the suction parameter A (Pr=0.5)

Figures 4 and 5 present the temperature profiles for various values of the parameter *K* and *Pr* and for *A=-0.5* and *0.5*, respectively and for *B=0*. The figures bring out clearly the effect of the Prandtl number on the thermal boundary layer thickness. For the suction case (*A=0.5*), as shown in Figure 5, increasing *Pr* decreases the thermal boundary layer thickness for all *K*. However, for the blowing and Newtonian case (*A=-0.5*, *K=0*), as clear in Figure 4, increasing *Pr* decreases θ. But for the non-Newtonian case (*K=1*), increasing *Pr* increases θ and increasing *Pr* more decreases θ for some distance. The effect of *K* on θ is more pronounced for smaller values of *Pr* for the blowing case (see Figure 4).

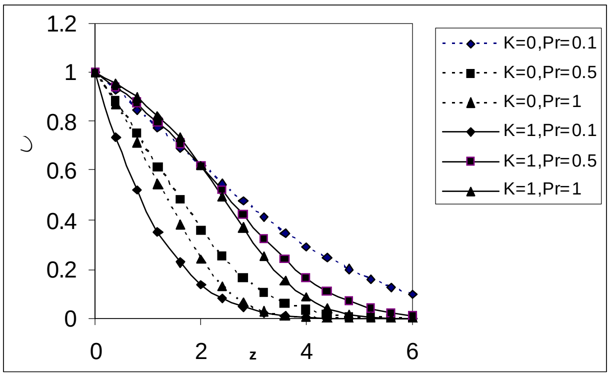

Fig. 4 Profiles of θ for different values of the non-Newtonian parameter K and the Prandtl number Pr (A=-0.5)

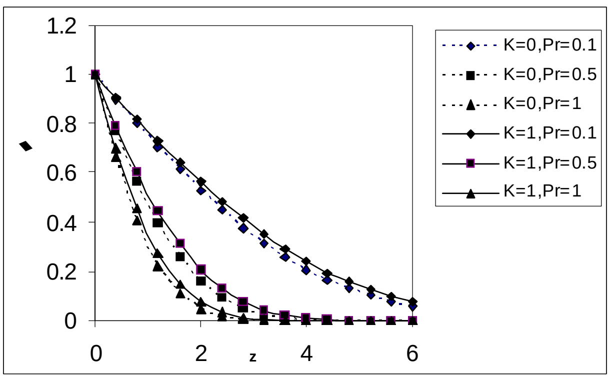

Fig. 5 Profiles of θ for different values of the non-Newtonian parameter K and the Prandtl number Pr (A=0.5)

Tables 1 and 2 present the variation of the wall shear stress $f''(0)$ and the heat transfer rate at the wall $-\theta'(0)$, respectively, for various values of K and A and for $Pr=0.7$ and $B=0$. For $A\geq 0$, increasing K decreases $ff''(0)$. However, for $A<0$, the effect of K on $f''(0)$ depends on the value of K. Also, increasing suction velocity ($A>0$) increases $f''(0)$ for all K. However, the variation of $f''(0)$ with blowing velocity depends on K. Table 2 shows that for suction, increasing K decreases $-\theta'(0)$ the effect of K on $-\theta'(0)$ in the blowing case depends on K. Increasing A increases $-\theta'(0)$ for all K.

Table 3 presents the effect of the parameters A and B on $-\theta'(0)$ for various values of Pr and for $K=1$ and $Pr=0.7$. Increasing A decreases $-\theta'(0)$ for all B but increasing B decreases $-\theta'(0)$ for all A. This is expected since increasing temperature as a result of heat generation decreases the heat transfer rate. Table 4 shows the variation of $-\theta'(0)$ for various values of Pr and B and for $K=1$ and $A=0$. Increasing Pr increases $-\theta'(0)$ for all B.

Table 1 Variation of the wall shear stress f''(0) with K and A (Pr=0.7, B=0)

A	K=0	K=0.5	K=1	K=1.5	K=2
-2	0.4758	5.6708	3.3592	3.1893	2.9899
-1	0.7566	10.7083	5.9994	5.9150	5.5018
0	1.2326	0.9025	0.7528	0.6733	0.5967
1	1.8892	1.0805	0.8469	0.7219	0.6405
2	2.6699	1.1658	0.8857	0.7453	0.6566

Table 2 Variation of the wall heat transfer −θ'(0) with K and A (Pr=0.7, B=0)

A	K=0	K=0.5	K=1	K=1.5	K=2
-2	0.0167	0.1033	0.0749	0.0761	0.0743
-1	0.1456	0.3418	0.2862	0.2931	0.2887
0	0.4959	0.4584	0.4374	0.4270	0.4114
1	1.0162	0.9587	0.9346	0.9193	0.9080
2	1.6217	1.5550	1.5343	1.5219	1.5132

Table 3 Variation of the wall heat transfer rate −θ'(0) with A and B (K=1, Pr=0.7)

B	A=-2	A=-1	A=0	A=1	A=2
-0.1	0.1206	0.3352	0.4969	0.9823	1.5709
0	0.0749	0.2862	0.4374	0.9346	1.5343
0.1	0.0261	0.2341	0.3729	0.8844	1.4965

Table 4 Variation of the wall heat transfer rate −θ'(0) with Pr and B (K=1, A=0)

B	Pr=0.05	Pr=0.1	Pr=0.5	Pr=1	Pr=2
-0.1	0.1688	0.2217	0.4333	0.5742	0.7593
0	0.1567	0.2027	0.3846	0.5004	0.6465
0.1	0.1440	0.1825	0.3321	0.4199	0.5217

4. CONCLUSIONS

The two-dimensional stagnation point flow of a viscous incompressible non-Newtonian second grade fluid with heat transfer is studied in the presence of uniform suction or blowing. A numerical solution for the governing equations is obtained which allows the computation of the flow and heat transfer characteristics for various values of the non-Newtonian parameter K, the suction parameter A, the heat generation/absorption parameter B, and the Prandtl number Pr. The results indicate that increasing the parameter K increases both the velocity and thermal boundary layer thickness while increasing A decreases the thickness of both layers. The effect of the parameter K on the velocity and temperature is more apparent for suction than blowing. The effect of the blowing velocity on the shear stress at the wall depends on the value of the non-Newtonian parameter K.

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TOČKA STAGNACIJE PROTOKA DRUGO-STUPANJSKE TEKUĆINE S JEDNOLIKIM USISAVANJEM ILI PUHANJEM I GENERIRANJEM TOPLINE

SAŽETAK

U ovome se radu istražuje laminarno strujanje nestlačive ne-Newtonove drugo-stupanjske tekućine nanešene na propusnu ravnu ploču s toplinskim zagrijavanjem. Primijenjeno je jednoliko usisavanje ili puhanje okomito na ploču koja se drži na konstantnoj temperaturi. Dobiveno je numeričko rješenje za vodeći nelinearni impuls i jednadžbe energije. Predstavljen je i raspravljen učinak jednolikog usisivanja ili puhanja i obilježja ne-Newtonove tekućine, kako na strujanje, tako i na prijenos topline.

Ključne riječi: *točka stagnacije, ne-Newton-ova tekućina, usisavanje, jednoliko laminarno tečenje, generiranje topline.*