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Unsteady Boundary Layer Stagnation Point Flow and Heat Transfer over a Stretching Sheet in a Porous Medium with Slip Effects

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ABSTRACT

Boundary layer flow and heat transfer over a stretching sheet in a porous medium has many applications in industrial processes. The effect of porosity plays a significant role in determining the behaviour of the fluid flow. Based on that, we analyzed the unsteady boundary layer stagnation point flow and heat transfer towards a stretching sheet by considering the porosity. The velocity and thermal slip effects are taken into consideration in the present analysis. The governing non-linear partial differential equations were transformed into a system of nonlinear ordinary differential equations using similarity transformation. The resulting ordinary differential equations were solved numerically using the shooting method in Maple software. Numerical results for the dimensionless velocity profile, temperature profile, skin friction coefficients and the local Nusselt number are presented for various parameters. The effect of dimensionless material parameter, thermal slip effect and velocity slip effect on the flow field is also discussed. It is found that the skin friction coefficients decrease whereas the local Nusselt number increases with the increase in permeability parameter.

Keywords:
Heat transfer; Unsteady flow; Porous medium; Stretching sheet; Thermal slip effect; Velocity slip effect

1. Introduction

The study of the fluid flow and heat transfer in a porous medium has many practical applications in engineering such as water movements in geothermal reservoirs, underground spreading of chemical waste, nuclear waste repository, food processing, drying process and many more. This subject has received a considerable attention and becomes a popular area of research. Many important contributions in this area can be found in monographs by Pop and Ingham [1], Nield and Bejan [2], Vafai [3] and others.

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Wooding [4] among the first who studied the natural convection in a saturated porous medium and gave the similarity solution for the flow produced by a point or line heat source. Cheng and Minkowycz [5] analysed the steady free convection of a vertical flat plate embedded in a saturated porous medium at high Rayleigh numbers. They obtained similarity solutions for the free convection flow in a porous medium adjacent to a vertical plate with wall temperature being a power function of distance from the leading edge. The steady natural convection heat transfer from an impermeable vertical surface embedded in a saturated porous medium subject to a prescribed non-uniform wall temperature or to a prescribed non-uniform wall heat flux have been studied by Na and Pop [6]. Rees and Pop [7] analysed the steady free convection boundary-layer flow near the stagnation point of a two-dimensional body which is embedded in a porous medium by adopting a two-temperature model of microscopic heat transfer. The unsteady mixed convection boundary-layer flow towards a stagnation point on a heated vertical surface embedded in a porous medium has been considered by Rosali *et al.,* [8]. They found that the critical values of mixed convection parameter increase with the unsteadiness parameter and depend on whether the flow is planar or axisymmetric.

Stagnation point flow and heat transfer over a stretching/shrinking sheet is very important in the industries and has attracted great interest of many researchers. Ishak *et al.,* [9] studied the steady two-dimensional MHD stagnation point flow towards a stretching sheet with variable surface temperature. The steady stagnation point flow and heat transfer over a stretching/shrinking sheet in a porous medium has been studied by Rosali *et al.,* [10]. They found that decreasing the porosity of the porous medium is to widen the range of parameter stretching/shrinking for which the solution exists. Bhattacharyya *et al.,* [11] investigated the unsteady boundary layer stagnation-point flow and heat transfer towards a stretching sheet. Wong *et al.,* [12] considered the steady two-dimensional stagnation-point flow of an incompressible viscous fluid towards a stretching vertical sheet with prescribed surface heat flux. Japili *et al.,* [13] investigated the steady stagnation point flow and heat transfer in a porous medium caused by an exponentially stretching/shrinking sheet. They concluded that the skin friction coefficient and local Nusselt number increases with an increase in suction parameter.

Fauzi *et al.,* [14] analysed the effects of the slip parameter on the steady stagnation-point flow and heat transfer due to a shrinking sheet in a viscous and incompressible fluid and concluded that the velocity slip will delay the boundary layer separation whereas the temperature slip does not affect the boundary layer separation. The effects of partial slip on stagnation-point flow and heat transfer due to a stretching vertical sheet has been discussed by Zaimi and Ishak [15]. They found that the skin friction coefficient decreases while the Nusselt number increases as the slip parameter increases. Prasannakumara *et al.,* [16] investigated the boundary flow and heat transfer of fluid particle suspension with nanoparticles over a nonlinear stretching sheet embedded in a porous medium. They discovered that the Nusselt number increases for nonlinear stretching case when compared to linear stretching case. The stagnation point flow and heat transfer over an exponentially stretching/shrinking sheet in hybrid nanofluid with slip velocity effect has been discussed by Anuar *et al.,* [17]. They found that the skin friction coefficient decreases with an increase of slip parameter for the case of stretching sheet. Ashwini and Katagi [18] analysed the influence of slip velocity on micropolar fluid through a porous channel. They concluded that the presence of micro-rotating elements with slip conditions at the porous boundary influences characteristics features of the flow.

The study of fluid flow and heat transfer in a porous medium has become significantly important in many areas of science and technology. This flow appears in a wide variety of industrial applications, as well as in many natural circumstances such as geothermal extraction, storage of nuclear waste material, ground water flows, oil recovery processes and many more. Due to the importance of this study in all these applications generates the need in understanding the concept of transport processes through porous media. However, we notice that the study of the unsteady boundary layer flow towards a stretching sheet in a porous medium with slip effects has not received much consideration. Therefore, the aim of the present study is to extend the work of Bhattacharyya *et al.,* [11] by including the porosity effects. The effect of velocity and thermal slip on the skin friction coefficient, heat transfer coefficient, velocity and temperature profiles were also discussed.

2. Methodology

We consider the unsteady boundary layer stagnation point flow of a viscous incompressible fluid embedded in a porous medium as shown in Figure 1. It is assumed that the surface is stretched in the x-direction with the velocity, $U_w(x,t)$ varies linearly along it. The surface temperature distribution $T_w(x,t)$ varies with time and also with the distance x along the sheet. Under the assumptions and Boussinesq approximation, the basic unsteady boundary layer equations of the problem under consideration are

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0, \quad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{\partial U_e}{\partial t}+U_e\frac{\partial U_e}{\partial x}+v\frac{\partial^2 u}{\partial y^2}+\frac{v}{K_1}(U_e-u), \quad (2)$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\kappa}{\rho c_p}\frac{\partial^2 T}{\partial y^2}, \quad (3)$$

where u and v are the velocity components along the x and y axes, T is the fluid temperature, K_1 is the permeability of the porous medium, $\nu(=\mu/\rho)$ is the kinematic viscosity, ρ is the fluid density , μ is the coefficient of fluid viscosity, κ is the thermal conductivity of fluid, t is the time and c_p is the specific heat. The boundary conditions are given by

$$u=U_w(x,t)+N_1\nu(\partial u/\partial y)\ , \quad v=0, \quad T=T_w+D_1(\partial T/\partial y) \quad \text{at} \quad y=0$$

$$u\to U_e(x,t), \quad T\to T_\infty \quad \text{as} \quad y\to\infty, \quad (4)$$

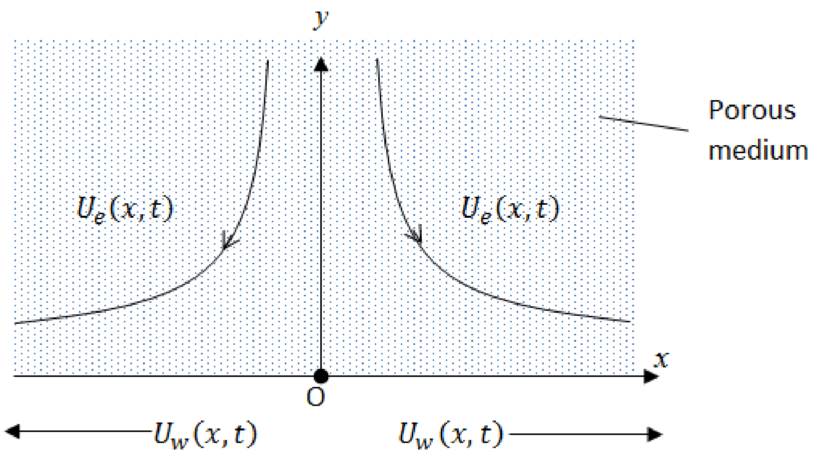

Fig. 1. Physical model and coordinate system

The stagnation flow velocity, U_e is defined as

$$U_e(x,t) = \frac{ax}{(1-\alpha t)}, \quad (5)$$

and the stretching velocity is

$$U_w(x,t) = \frac{cx}{(1-\alpha t)}, \quad (6)$$

where $a(>0)$ is the straining parameter, $c(>0)$ is the stretching parameter and α is a constant.

The velocity and thermal slip factors are varies with time and defined as follows:

$$N_1 = N(1-\alpha t)^{1/2}, \qquad D_1 = D(1-\alpha t)^{1/2} \quad (7)$$

The slip factors N_1 and D_1 have dimensions of (velocity)$^{-1}$ and length. N and D are the initial values of velocity and thermal slip factors. The surface temperature $T_w(x,t)$ is given by

$$T_w = T_\infty + T_o\left[\frac{cx^2}{2\upsilon}\right](1-\alpha t)^{-3/2} \quad (8)$$

where the free stream temperature T_∞ and T_o measures the rate of temperature increment along the sheet and assumed to be constant.

We now introduce the similarity variables

$$\psi = \sqrt{\frac{c\upsilon}{(1-\alpha t)}}\,xf(\eta), \qquad T = T_\infty + (T_w - T_\infty)\theta(\eta), \qquad \eta = y\sqrt{c/\upsilon(1-\alpha t)} \quad (9)$$

The stream function ψ is defined as $u = \frac{\partial\psi}{\partial y}$ and $v = -\frac{\partial\psi}{\partial x}$, which identically satisfies Eq. (1), whereas η is the similarity variable.

Substituting variables from Eq. (9) into Eq. (2) and Eq. (3) gives

$$f''' + ff'' - f'^2 - A\left(f' + \frac{\eta}{2}f'' - b\right) + b^2 + K(b - f') = 0 \quad (10)$$

$$\frac{1}{Pr}\theta'' + f\theta' - 2f'\theta - A(3\theta + \eta\theta')/2 = 0 \quad (11)$$

where $b = \frac{a}{c}$ is the velocity ratio parameter, $A = \frac{\alpha}{c}$ is the unsteadiness parameter and $Pr = \mu c_p/\kappa$ is the Prandtl number.

The boundary conditions in Eq. (4) become

$$f(0) = 0, \quad f'(0) = 1 + \lambda f''(0) \quad \theta(0) = 1 + \delta\theta'(0)$$

$$f'(\eta) \to b, \quad \theta(\eta) \to 0, \quad \text{as} \quad \eta \to \infty \quad (12)$$

where primes denote differentiation with respect to η. The velocity slip parameter λ and the thermal slip parameter δ are given by

$\lambda = N(cv)^{1/2}$ and $\delta = D(c/\nu)^{1/2}$ respectively.

The physical quantity of interest is the skin friction coefficients and the local Nusselt number which can be defined as

$$C_f = \frac{\tau_w}{\rho U_e^2} \quad , \quad Nu_x = \frac{x q_w}{\kappa (T_w - T_\infty)} \tag{13}$$

where the shear stress τ_w and the surface heat flux q_w are given by

$$\tau_w = \mu \left(\frac{\partial u}{\partial y}\right)_{y=0} , \quad q_w = -\kappa \left(\frac{\partial T}{\partial y}\right)_{y=0} \tag{14}$$

Using the similarity variables given by Eq. (9), we obtain

$$b^{\frac{3}{2}} C_f Re_x^{\frac{1}{2}} = f''(0) \tag{15}$$

$$\sqrt{b}\, Pr^{1/2} Nu_x = -\theta'(0) Pe_x^{\frac{1}{2}} \tag{16}$$

where $Re_x = \frac{U_e x}{\nu}$ is the local Reynolds number, $Pe_x = \frac{U_e x}{\alpha_m}$ is the local Pećlet number and α_m is the thermal diffusivity.

3. Result and Discussion

The transformed ordinary differential Eqs. (10) and (11), satisfying the boundary conditions in Eq. (12) are solved numerically using the shooting method for several values of the governing parameters. The effects of these parameters examined on the velocity profile, temperature profile, skin friction coefficients and Nusselt number. By using a shooting technique, the system of ordinary differential equations is converted into an equivalent initial value problem (IVP). Then, we choose a suitable finite value of η_∞ (where η_∞ corresponds to $\eta \to \infty$), which depends on the values of the parameters used. Hence, we set the first-order system of Eqs. (10) and (11).

$$f' = p, \quad p' = q, \qquad q' + fq - p^2 - A\left(p + \frac{\eta}{2} q - b\right) + b^2 + K(b - p) = 0 \tag{17}$$

$$\theta' = r, \qquad \frac{1}{Pr} r' + fr - 2p\theta - A(3\theta + \eta r)/2 = 0 \tag{18}$$

with the boundary conditions

$$f(0) = 0, \quad p(0) = 1 + \lambda p(0) \qquad \theta(0) = 1 + \delta r(0) \tag{19}$$

$$p(\eta_\infty) = b, \quad \theta(\eta_\infty) = 0, \tag{20}$$

In order to solve Eqs. (17) and (18), subject to the boundary condition in Eq. (19), we require the values for $p(0)$ and $r(0)$, i.e. the values of $f''(0)$ and $\theta'(0)$. Since these values are not given, the suitable guess values are chosen for $f''(0)$ and $\theta'(0)$ by adopting a Runge-Kutta-Fehlberg method. Hence, we compare the calculated values for $f'(\eta)$ and $\theta(\eta)$ at η_∞ with the boundary conditions

$f'(\eta_\infty) = b$ and $\theta(\eta_\infty) = 0$, respectively. We can obtain a better approximation for the solution by adjusting the estimated values of $f''(0)$ and $\theta'(0)$. The process is repeated by guessing different values of $f''(0)$ and $\theta'(0)$ until we obtain the values that satisfy the boundary conditions. This computation is done with the aid of shootlib file in Maple software. All velocity and temperature profiles plotted for this problem approaches the infinity boundary conditions asymptotically.

Further, in order to verify the accuracy of the present method, we have compared the present results obtained for the skin friction coefficients $f''(0)$ with those reported by Nazar *et al.,* [19] for $K = 0, A = 0$ (steady) and no-slip condition ($\lambda = 0$ and $\delta = 0$). The comparison is given in Table 1 and it can be seen that the results are in excellent agreement and so give confidence in our numerical approach.

Table 1
Values of $f''(0)$ for different values of $b = \frac{a}{c}$ when $A = 0, K = 0,\ \lambda = 0$ and $\delta = 0$

$b = \frac{a}{c}$	$f''(0)$	
	Nazar *et al.,* [19]	Present Result
0.01	-0.9980	-0.998065
0.02	-0.9958	-0.995811
0.05	-0.9876	-0.987588
0.1	-0.9694	-0.969457
0.2	-0.9181	-0.918118
0.5	-0.6673	-0.667264
2	2.0176	2.017503
3	4.7296	4.729282

Figures 2 and 3 show the velocity and temperature profiles for different values of permeability parameter, K when $A = 1, b = 0.5$ and $\lambda = 1$ with no-thermal slip condition. Boundary layer thickness is arbitrarily defined as the distance from the boundary to the point where the velocity reaches 99% of the free stream velocity. From Figures 2 and 3, we observed that the thickness of boundary layer decreases while the thermal boundary layer thickness is slightly increase with the increase in permeability parameter, K. In Figure 2, it is obvious that the presence of porous medium causes higher restriction to the fluid flow which in turn slows its motion. Therefore, the resistance to the fluid flow is increase with the increasing in permeability parameter K and hence the thickness of the velocity boundary layer decreases. It can be seen in Figure 3 that the temperature profile decreases monotonically with η, and approaches zero as the thickness of the boundary layer far away from the surface, which satisfies the boundary conditions in Eq. (12).

Figure 4 gives the variation of the skin friction coefficients $f''(0)$ with velocity slip parameter, λ, for different values of permeability parameter, K when $A = 1$, $b = 0.5$ and $\delta = 1$ (with thermal slip parameter). From the figure, it shows that the skin friction coefficients $f''(0)$ decrease as permeability parameter K increases. The values of the skin friction coefficients $f''(0)$ approaches certain values with the increase in the value of velocity slip parameter λ for different values of permeability parameter, K. We observed that the effect of permeability parameter K is small for large values of velocity slip parameter, λ.

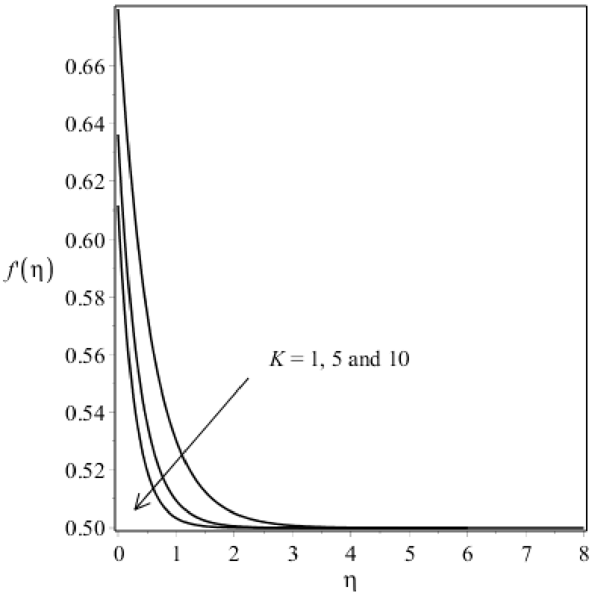

Fig. 2. Velocity profiles for different values of K when $A = 1, b = 0.5$ and $\lambda = 1$

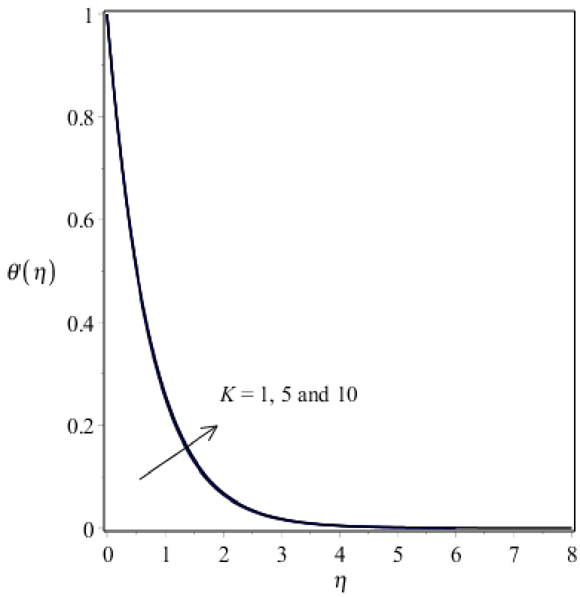

Fig. 3. Temperature profiles for different values of K when $A = 1, b = 0.5$ and $\lambda = 1$

Figure 5 displays the variations of local Nusselt number $-\theta'(0)$ with λ for different values of permeability parameter, K when $A = 1$, $b = 0.5$ and $\delta = 1$ (with thermal slip parameter). It can be observed that the local Nusselt number increases with the increase in permeability parameter K. This shows that high permeability enhanced the heat transfer rate.

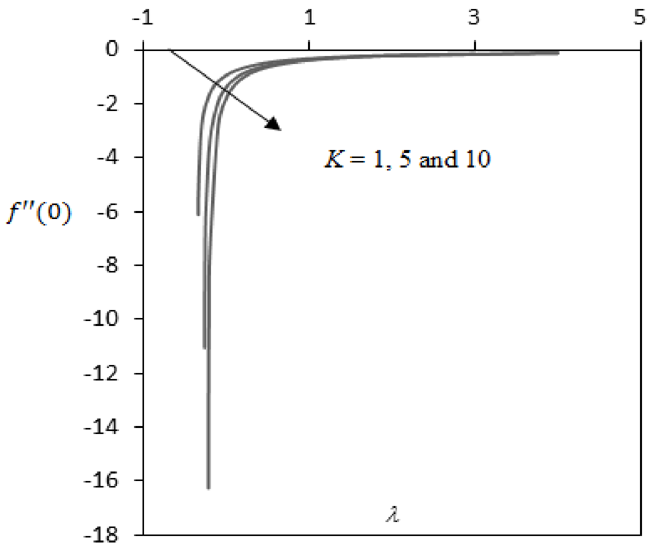

Fig. 4. Variation of skin friction coefficient $f''(0)$ with λ for different values of K when $A = 1,\ b = 0.5$ and $\delta = 1$

Figures 6 and 7 illustrate the velocity and temperature profiles for various values of thermal slip parameter δ with η when $A = 1, b = 0.5$, $K = 1$ and $\lambda = 1$. In Figure 6, it can be seen that the effect of thermal slip parameter δ on velocity profile does not influence the flow. From Figure 7, it shows that the temperature profile decreases with the increase in thermal slip parameter δ, but after a certain distance η from the sheet the temperature profile approaches zero and satisfies the boundary conditions (12). The increase of thermal slip parameter δ, which means less heat is transferred to the fluid from the surface and therefore the temperature is found to decrease.

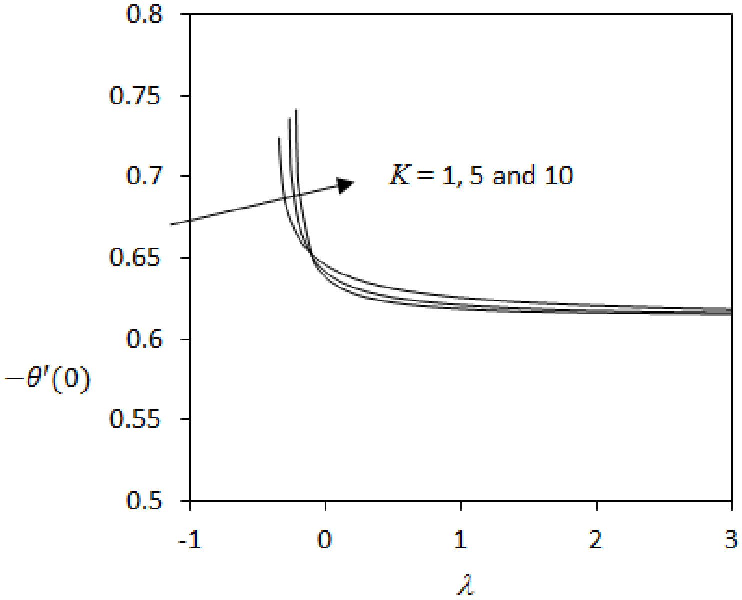

Fig. 5. Variation of local Nusselt number $-\theta'(0)$ with λ for different values of K when $A = 1$ $b = 0.5$ and $\delta = 1$

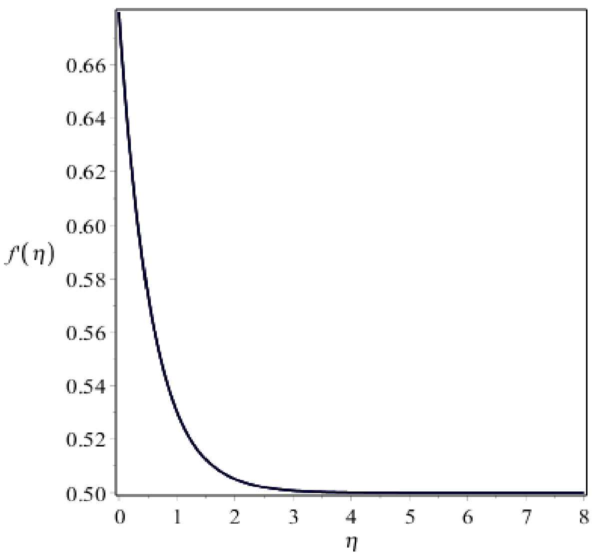

Fig. 6. Velocity profiles for $\delta = 1, 3$ and 5 when $A = 1, b = 0.5$, $K = 1$ and $\lambda = 1$

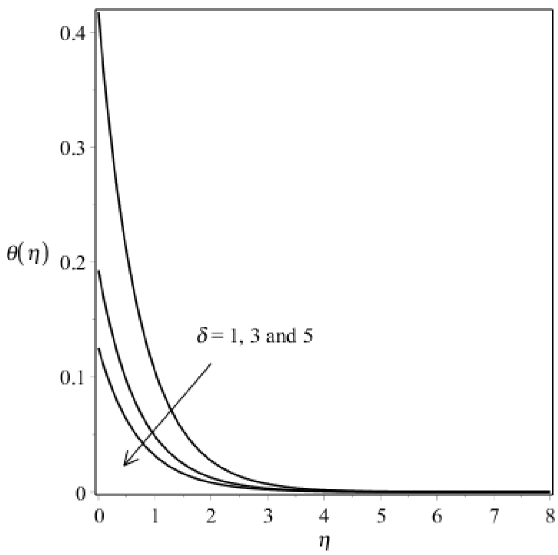

Fig. 7. Temperature profiles for different values of δ when $A = 1, b = 0.5$, $K = 1$ and $\lambda = 1$

Figures 8 and 9 show the velocity and temperature profiles for various values of the velocity slip parameter λ when $A = 1, b = 0.5$, $K = 1$ and $\delta = 1$. From Figure 8, it is observed that fluid velocity decreases as the velocity slip parameter λ increases. This is due to the velocity of the fluid flow near the surface is no longer equal to the velocity stretching surface when the velocity slip occurs. It can be observed in Figure 9 that the velocity slip parameter λ gives a very small effect to the temperature profile.

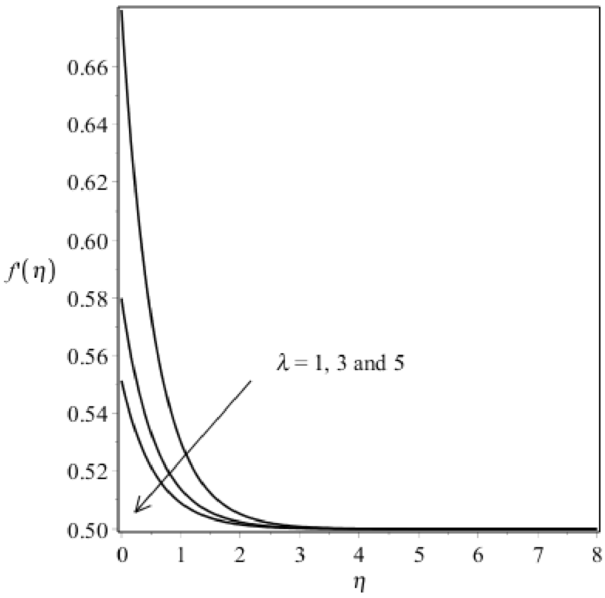

Fig. 8. Velocity profiles for different values of λ when $A = 1, b = 0.5, K = 1$ and $\delta = 1$

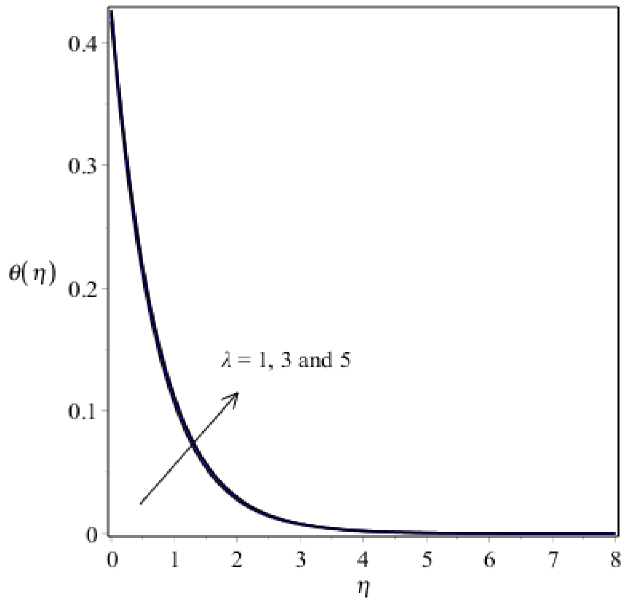

Fig. 9. Temperature profiles for different values of λ when $A = 1, b = 0.5, K = 1$ and $\delta = 1$

4. Conclusion

We have considered the unsteady boundary layer stagnation point flow and heat transfer over a stretching sheet in a porous medium with slip effects. The governing partial differential equations are transformed into a system of ordinary differential equations by using similarity transformation and hence they are solved numerically by the shooting method in Maple software. Numerical results were obtained and present in graphs for certain governing parameters. It is found that

I. The fluid velocity decreases as the velocity slip parameter λ increases.
II. The temperature profile decreases with the increase in thermal slip parameter δ.
III. The skin friction coefficients $f''(0)$ decrease as permeability parameter K increases with velocity slip parameter λ.
IV. The local Nusselt number increases with the increase in permeability parameter K.

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