EFFECTS OF HEAT GENERATION/ABSORPTION ON A STAGNATION POINT FLOW OVER A STRETCHING SURFACE IN POROUS MEDIUM WITH CONVECTIVE BOUNDARY CONDITIONS

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Abstract : In this study, the mathematical modeling for heat generation/absorption effects on a stagnation point flow over a stretching surface in porous medium, with convective boundary conditions is considered. The non linear partial differential equations are transformed to the ordinary differential equations by similarity transformation before being solved numerically using the Runge-Kutta Fehlberg method. Numerical solutions are obtained for the surface temperature, heat transfer coefficient, local Nusselt number and skin friction coefficient as well as the velocity and temperature profiles. The features of the flow and heat transfer characteristics for various values of the permeability parameter, heat source/sink parameter, Prandtl number, stretching parameter and conjugate parameter are analyzed and discussed.

Keywords: Convective boundary conditions, heat generation/absorption, porous medium, stagnation point flow, stretching surface.

1. Introduction

Flow of a viscous fluid past a stretching sheet is a classical problem in fluid dynamics. Crane [1] was the first to study the convection boundary layer flow over a stretching sheet. The heat and mass transfer on a stretching sheet with suction or blowing was investigated by Gupta and Gupta [2]. They considered an isothermal moving plate and obtained the temperature and concentration distributions. Chen and Char [3] studied the laminar boundary layer flow and heat transfer from a linearly stretching, continuous sheet subjected to suction or blowing with prescribed wall temperature and heat flux.

Stagnation flow towards a shrinking sheet was then investigated by Wang [4] who considered the prescribed wall temperature case. Forced convection boundary layer flow at a forward stagnation point with Newtonian heating has been investigated by Salleh et al. [5]. Ishak et al. [6] studied the MHD stagnation point flow towards a stretching sheet. Recently, Mohamed et al. [7] extended the works by Ishak et al. [6] with introduce the thermal radiation effects in Newtonian heating case.

In considering the heat generation/absorption effects, Chamkha and Issa [8] investigated these field with considered thermophoresis on hydromagnetic flow. Layek et al. [9] studied the heat and mass transfer analysis for boundary layer stagnation-point flow towards a heated porous stretching sheet with heat absorption/generation and suction/blowing before being extended by Hamad and Ferdows [10] in nanofluid and Mahmoud and Waheed [11] in micropolar fluid. Also, Ibrahim and Shanker [12] and Mukhopadhyay and Layek [13] investigated the heat effects with MHD and variable fluid viscosity effects, respectively.

Since the early paper by Luikov et al. [14], many contributions to the topic of conjugate heat transfer have been made. The conjugate/convective boundary condition, has been used only quite recently by Aziz [15] who studied the laminar thermal boundary layer over a flat plate. This Blasius flow with the conjugate boundary condition then has been revisited by Rashidi and Erfani [16] and Magyari [17]. Merkin and Pop [18], Yao et al. [19], Yacob et al. [20] and Yacob and Ishak [21] investigated the boundary layer flow past a shrinking/stretching sheet with convective boundary conditions in a viscous fluid, nanofluid or micropolar fluid, respectively. Recently, Mohamed et al. [22] solved the stagnation point flow over a stretching sheet with convective boundary conditions.

According to Layek et al. [9], fluid flow and heat transfer towards a porous stretching sheet have an important bearing on several technological processes. Some metallurgical processes involve the cooling of continuous strips or filaments by drawing them through a quiescent fluid. The rate of cooling can be controlled and final product of desired characteristics can be achieved if strips are drawn through porous media. With this motivation, the aim of this study is to solve the problem of heat generation/absorption effects on a stagnation point flow over a stretching surface in porous medium with convective boundary conditions. Since this problem has not been considered before hence, the reported results are considered new

2. Mathematical Formualation

A steady two-dimensional steady flow on a stagnation-point past a stretching plate immersed in an incompressible porous viscous fluid of ambient temperature, T_∞ are considered. It is assumed that the stretching velocity $u_w(x)$ and the external velocity $u_e(x)$ are of the forms $u_w(x) = ax$ and $u_e(x) = bx$ where a and b are constants. The physical model and coordinate system of this problem is shown in Figure 1. It is further assumed that the plate is subjected to the convective boundary conditions. The boundary layer equations are

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = u_e\frac{du_e}{dx} + \nu\frac{\partial^2 u}{\partial y^2} + \frac{\nu}{k_1}\left(u_e(x) - u\right) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial y^2} + \frac{Q_o}{\rho C_p}\left(T - T_\infty\right) \tag{3}$$

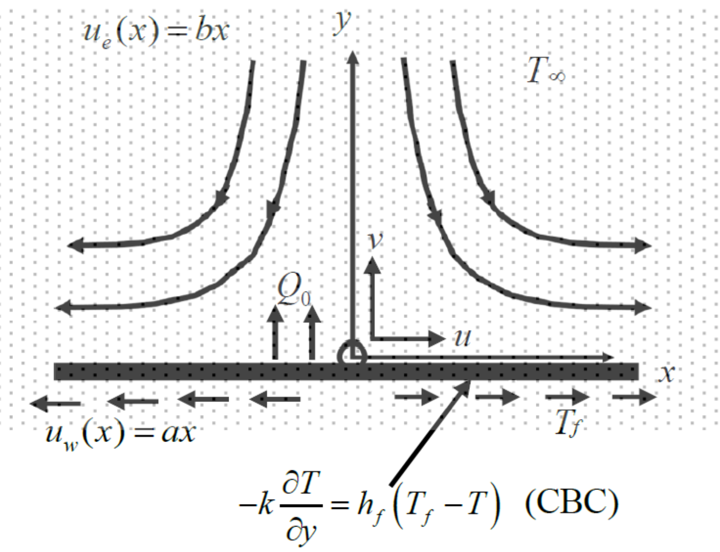

Figure 1. Physical model and the coordinate system

subject to the boundary conditions (see Aziz [15])

$$u = u_w(x), \quad v = 0, \; -k\frac{\partial T}{\partial y} = h_f(T_f - T) \text{ (CBC) at } y = 0$$
$$u = u_e(x), \quad T \to T_\infty \quad \text{as} \quad y \to \infty \tag{4}$$

where u and v are the velocity components along the x and y directions, respectively. Further, T is temperature, T_f is the temperature of the hot fluid under the flat plate, k_1 is the permeability of the porous medium, ν is the kinematic viscosity, Q_o is the dimensional heat generation or absorption coefficient, ρ is fluid density, C_p is the specific heat, k is the thermal conductivity, α is the thermal diffusivity and h_f is the heat transfer coefficient.

It is introduce the following similarity variables (see Salleh et al. [23] and Aziz [15])**:**

$$\eta = \left(\frac{u_e}{\nu x}\right)^{1/2} y, \quad \psi = \left(\nu x u_e\right)^{1/2} f(\eta), \quad \theta(\eta) = \frac{T - T_\infty}{T_f - T_\infty} \text{(CBC)}, \tag{5}$$

where ψ is the stream function defined as $u = \frac{\partial \psi}{\partial y}$ and $v = -\frac{\partial \psi}{\partial x}$, which identically satisfies Equation (1). Thus,

$$u = bxf'(\eta), \qquad v = -(b\nu)^{1/2} f(\eta), \tag{6}$$

where prime denotes differentiation with respect to η. Substituting (5) and (6) into Equations (2) and (3), the following nonlinear ordinary differential equations are obtained:

$$f''' + ff'' - f'^2 - K(f' - 1) + 1 = 0 \tag{7}$$
$$\frac{1}{\Pr}\theta'' + f\theta' + \lambda\theta = 0 \tag{8}$$

where $\Pr = \frac{\nu}{\alpha}$ is the Prandtl number, $K = \frac{\nu}{k_1 b}$ is the permeability parameter for the porous medium and $\lambda = \frac{Qo}{b\rho C_p}$ is the heat source $(\lambda > 0)$ or sink $(\lambda < 0)$ parameter. The boundary conditions (4) become

$$f(0) = 0, \quad f'(0) = \varepsilon, \quad \theta'(0) = -\gamma(1 - \theta(0)) \text{ (CBC)}$$
$$f'(\eta) \to 1, \quad \theta(\eta) \to 0 \quad \text{as} \quad \eta \to \infty \tag{9}$$

where $\varepsilon = \frac{a}{b}$ is the stretching parameter. Further, $\gamma = h_f\left(\frac{\nu}{a}\right)^{1/2} k^{-1}$ is the conjugate parameter for the convective boundary conditions. It is noticed that $\gamma = 0$ is for the insulated plate and $\gamma \to \infty$ is when the surface temperature is constant (CWT).

The physical quantities of interest are the skin friction coefficient C_f and the local Nusselt number Nu_x which are given by

$$C_f = \frac{\tau_w}{\rho u_e^2}, \quad Nu_x = \frac{x q_w}{k(T - T_\infty)}. \tag{10}$$

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

$$\tau_w = \mu \left(\frac{\partial u}{\partial y} \right)_{y=0}, \qquad q_w = -k \left(\frac{\partial T}{\partial y} \right)_{y=0}, \tag{11}$$

with $\mu = \rho \nu$ is dynamic viscosity. Using the similarity variables in (5) give

$$C_f \, \mathrm{Re}_x^{1/2} = f''(0), \qquad \frac{Nu_x}{\mathrm{Re}_x^{1/2}} = -\frac{\theta'(0)}{\theta(0)} = \frac{1}{\theta(0)} - 1 \text{(CBC)} \tag{12}$$

where $\mathrm{Re}_x = \dfrac{u_e x}{\nu}$ is the local Reynolds number.

3. Results and Discussion

The Equations (7) and (8) subject to the boundary conditions (9) were solved numerically using the Runge-Kutta Fehlberg method with five parameters considered, namely the permeability parameter K, heat source/sink parameter λ, Prandtl number Pr, stretching parameter ε and conjugate parameter γ. From the numerical solution, it is known that the wide boundary layer thicknesses η_∞ from 1 to 12 is suitable to provide accurate numerical results. In order to validate the efficiency method used, the comparison has been made. Table 1 and 2 show the comparison between the present results for $f''(0)$ and $-\theta'(0)$ for the case constant wall temperature (CWT) with previously published results. It has been found that they are in good agreement. We can conclude that this method works efficiently for the present problem, and we are also confident that the results presented here are accurate.

Table 1. Comparison for the values of $f''(0)$ with previous results

ε	$f''(0)$			
	Wang [4]	Yacob and Ishak [21]	Mohamed et al. [22]	Present
2	-1.88731	-1.887307	-1.8873066	-1.8873069
1	0	0	0	0
0.5	0.71330	0.713295	0.7132949	0.7132947
0	1.232588	1.232588	1.2325877	1.2325877

Table 2. Comparison for the values of $-\theta'(0)$ (CWT) with previous results when $\varepsilon = 0$, $K = 0$, $\lambda = 0$ and $\gamma \to \infty$.

Pr	$-\theta'(0)$		
	Eckert [24]	Salleh et al. [5]	Present
0.7	0.496	0.4959	0.4958
0.8	0.523	0.5228	0.5227
1	0.570	0.5705	0.5704
5	1.043	1.0436	1.0433
7	-	1.1786	1.1782
10	1.344	1.3391	1.3386

Tables 3 and 4 present the values of $\theta(0),\ -\theta'(0),\ \dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ and $C_f\ \mathrm{Re}_x^{1/2}$ for various values of K when $\Pr = 0.72,\ \gamma = 1,\ \varepsilon = 0$ and $\lambda = -0.5,\ 0,\ 0.5.$ It is observed that, for fixed value of λ, an increase of K results to the decrease of $\theta(0)$ while $-\theta'(0),\ \dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ and $C_f\ \mathrm{Re}_x^{1/2}$ increase. Meanwhile, when K is fixed, the presents of heat generation (heat source) $\lambda > 0,$ have influence to the increase of $\theta(0)$ while $-\theta'(0)$ and $\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ decrease. This is realistic where the increase amount of heat (heat source) enhanced the temperature on plate surface. Furthermore, since $\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ is decreasing, this situation indicates that the presents of heat generation have reduced the fluid capibilities in convective heat transfer hence attend the fluid to pure conduction.. On the other side, the presents of heat absorption (heat sink) $\lambda < 0,$ have results oppositely. Also, from Table 4, it is found that the presents of heat generation/absorption give no effects on reduced skin friction coefficient, $C_f\ \mathrm{Re}_x^{1/2}$.

Table 3. Values of $\theta(0)$ and $-\theta'(0)$ for various values of K when $\Pr = 0.72,\ \gamma = 1,\ \varepsilon = 0$ and $\lambda = -0.5,\ 0,\ 0.5.$

K	$\lambda = -0.5$		$\lambda = 0$		$\lambda = 0.5$	
	$\theta(0)$	$-\theta'(0)$	$\theta(0)$	$-\theta'(0)$	$\theta(0)$	$-\theta'(0)$
0	0.5728	0.4272	0.6660	0.3340	0.8647	0.1353
0.01	0.5727	0.4273	0.6659	0.3341	0.8643	0.1357
0.1	0.5722	0.4278	0.6649	0.3351	0.8614	0.1386
1	0.5681	0.4319	0.6572	0.3428	0.8398	0.1602
10	0.5543	0.4457	0.6331	0.3669	0.7810	0.2190

Table 4. Values of $\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ and $C_f\ \mathrm{Re}_x^{1/2}$ for various values of K when $\Pr = 0.72,\ \gamma = 1,\ \varepsilon = 0$ and $\lambda = -0.5,\ 0,\ 0.5.$

K	$\lambda = -0.5$		$\lambda = 0$		$\lambda = 0.5$	
	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$
0	0.7458	1.2326	0.5015	1.2326	0.1565	1.2326
0.01	0.7461	1.2366	0.5017	1.2366	0.1570	1.2366
0.1	0.7476	1.2722	0.5040	1.2722	0.1609	1.2722
1	0.7603	1.5853	0.5216	1.5853	0.1908	1.5853
10	0.8041	3.3917	0.5795	3.3917	0.2804	3.3917

Tables 5 and 6 present the values of $\theta(0),\ -\theta'(0),\ \dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ and $C_f\ \mathrm{Re}_x^{1/2}$ for various values of ε when $\Pr = 0.72,\ \gamma = 1,\ K = 1$ and $\lambda = -0.5,\ 0,\ 0.5.$ It is suggested that, for fixed value of λ, an increase of stretching parameter ε results to the decrease of $\theta(0)$ and $C_f\ \mathrm{Re}_x^{1/2}$ while $-\theta'(0)$ and $\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ increase. Physically, as ε increases, the ratio of stretching over external velocity increases and thus enhance the fluid move away from the stagnation region rapidly. This situation reduced the plae surface temperature. Next, as table goes horizontally, as ε is fixed, the heat generation/absorption, λ influence are similar as in Table 3.

Table 5. Values of $\theta(0)$ and $-\theta'(0)$ for various values of ε when $\Pr = 0.72,\ \gamma = 1,\ K = 1$ and $\lambda = -0.5,\ 0,\ 0.5.$

ε	$\lambda = -0.5$		$\lambda = 0$		$\lambda = 0.5$	
	$\theta(0)$	$-\theta'(0)$	$\theta(0)$	$-\theta'(0)$	$\theta(0)$	$-\theta'(0)$
0	0.5681	0.4319	0.6572	0.3428	0.8397	0.1603
1	0.5298	0.4702	0.5963	0.4037	0.7114	0.2886
2	0.5002	0.4998	0.5529	0.4471	0.6353	0.3647
3	0.4761	0.5239	0.5195	0.4805	0.5830	0.4170
5	0.4388	0.5612	0.4705	0.5295	0.5141	0.4859
7	0.4106	0.5894	0.4353	0.5647	0.4667	0.5333
10	0.3783	0.6217	0.3966	0.6034	0.4188	0.5812
100	0.1758	0.8242	0.1771	0.8229	0.1786	0.8214

Table 6. Values of $\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$ and $C_f\ \mathrm{Re}_x^{1/2}$ for various values of ε when $\Pr = 0.72,\ \gamma = 1,\ K = 1$ and $\lambda = -0.5,\ 0,\ 0.5.$

ε	$\lambda = -0.5$		$\lambda = 0$		$\lambda = 0.5$	
	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$	$\dfrac{Nu_x}{\mathrm{Re}_x^{1/2}}$	$C_f\ \mathrm{Re}_x^{1/2}$
0	0.7603	1.5853	0.5216	1.5853	0.1909	1.5853
1	0.8875	0	0.6770	0	0.4057	0
2	0.9992	-2.1327	0.8086	-2.1327	0.5741	-2.1327
3	1.1004	-4.7153	0.9249	-4.7153	0.7153	-4.7153
5	1.2789	-11.0073	1.1254	-11.0073	0.9451	-11.0073
7	1.4355	-18.5727	1.2973	-18.5727	1.1427	-18.5727
10	1.6434	-31.9356	1.5214	-31.9356	1.3878	-31.9356
100	4.6883	-1002.9126	4.6465	-1002.9126	4.5991	-1002.9126

Figure 2 shows the temperature profiles $\theta(\eta)$ for various values of λ when $\Pr = 0.72,\ \gamma = 1,\ K = 1$ and $\varepsilon = 1.$ From figure, it is concluded that the presence of heat generation $(\lambda > 0)$ assist to the increase of temperature profiles. This is due to the fact that heat source add more heat to the plate which increases its temperature profiles. This results to the increase of thermal boundary layer thickness. Meanwhile, the presence of heat absorption $(\lambda < 0)$ affects to the decrease of the temperature profiles as well as boundary layer thickness since the heat is removed from the plate.

Figures 3-5 show the temperature profiles $\theta(\eta)$ for various values of $K,\ \varepsilon$ and Pr, respectively. For all Figures 3-5, as $K,\ \varepsilon$ or Pr increases, the temperature and thermal boundary layer thickness decrease. This is due to the fact that when Pr increases, the thermal diffusivity decreases and these phenomena lead to the decreasing of energy ability that reduces the thermal boundary layer. Also, an increase of K which implies to the increase of porous elements represents a resistant to the convection ability that reduces the temperature profiles.

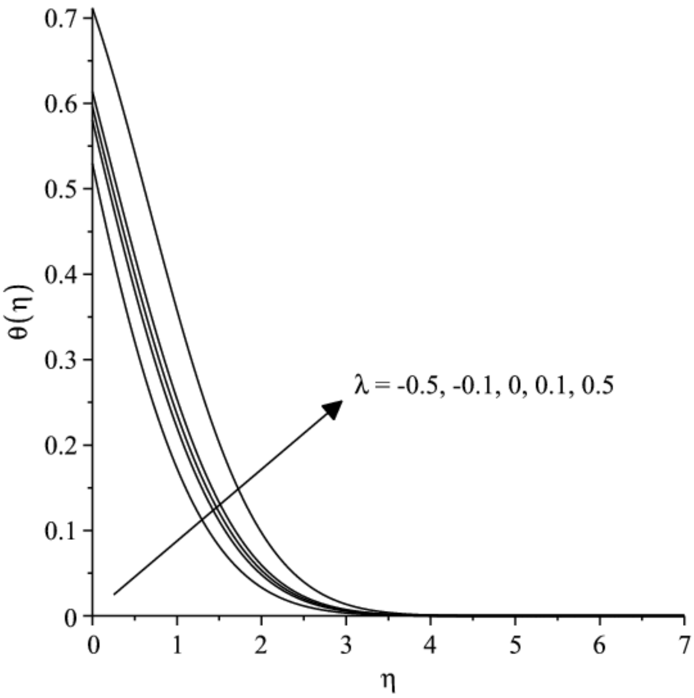

Figure 2. Temperature profiles $\theta(\eta)$ **for various values of** λ **when** $\Pr = 0.72,\ \gamma = 1,\ K = 1$ **and** $\varepsilon = 1.$

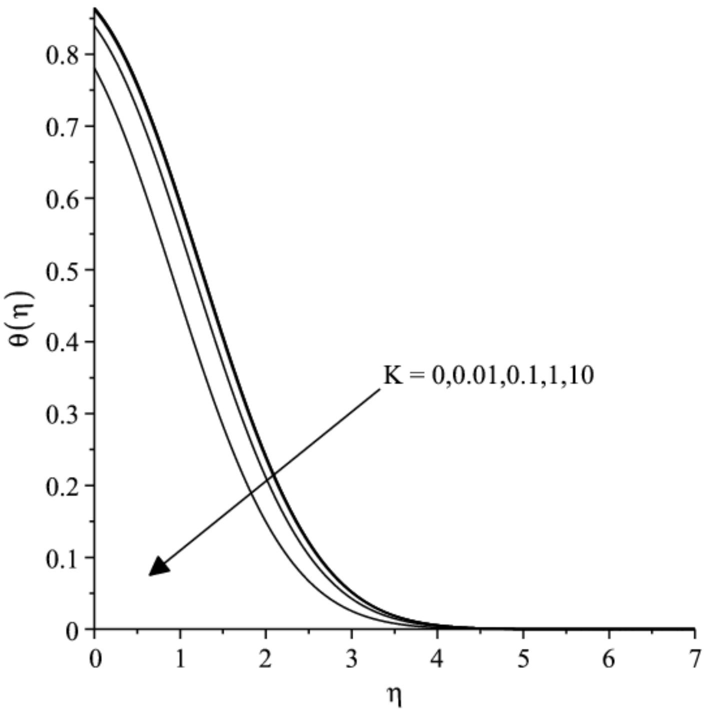

Figure 3. Temperature profiles $\theta(\eta)$ **for various values of** K **when** $\Pr = 0.72,\ \gamma = 1,\ \varepsilon = 0$ **and** $\lambda = 0.5.$

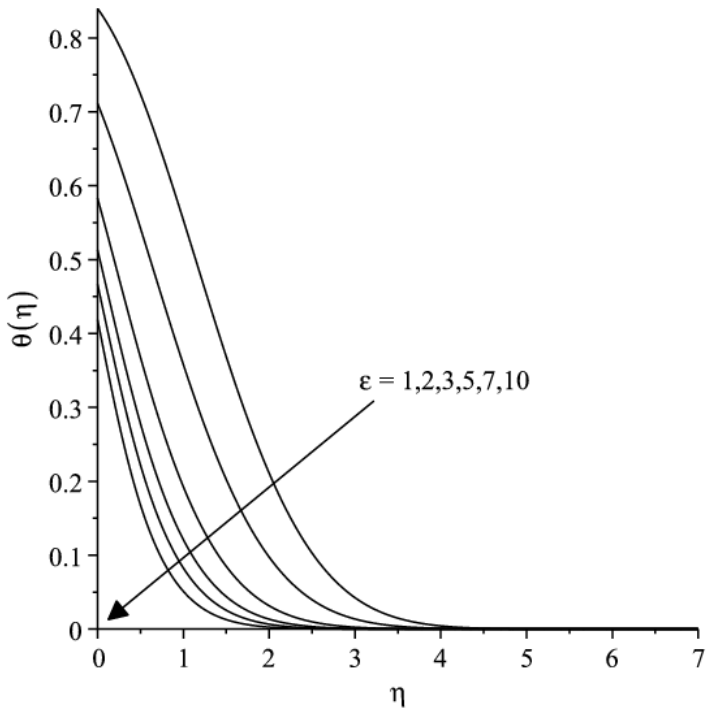

Figure 4. Temperature profiles $\theta(\eta)$ for various values of ε when $\Pr = 0.72,\ \gamma = 1,\ K = 1$ **and** $\lambda = 0.5.$

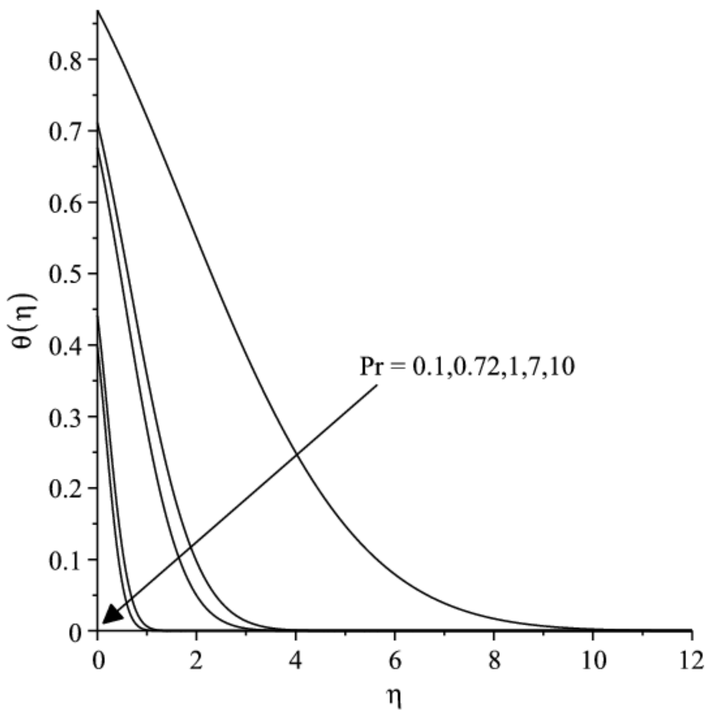

Figure 5. Temperature profiles $\theta(\eta)$ for various values of $\Pr$ **when** $\varepsilon = 1,\ \gamma = 1,\ K = 1$ **and** $\lambda = 0.5.$

Figure 6 shows the temperature profiles $\theta(\eta)$ for various values of γ. Figure 6 consumes the contra trends compared to the temperature profiles in Figures 3-5. It is found that the increase of γ results to the increase of temperature profiles as well as the thermal boundary layer thickness.

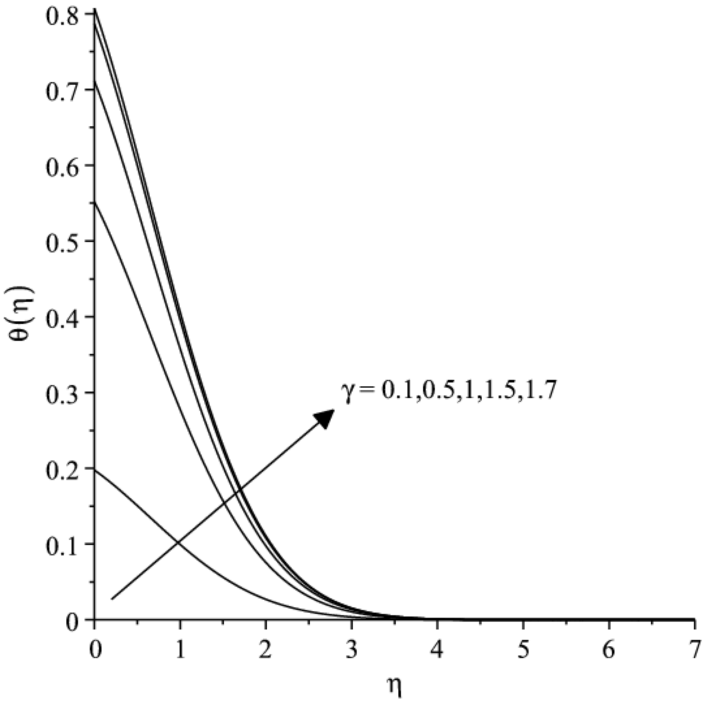

Figure 6. Temperature profiles $\theta(\eta)$ for various values of γ when $\Pr = 0.72,\ \varepsilon = 1,\ K = 1$ and $\lambda = 0.5$.

Next, Figures 7 and 8 present the velocity profiles $f'(\eta)$ for various values of K and ε, respectively. In this study, only parameter K and ε will affect the fluid velocity and skin friction coefficient. Pr, γ and λ will not influence the fluid flow. From Figure 7, it is suggested that, when the stretching velocity is smaller than the external velocity $(\varepsilon < 1)$, the flow has a boundary layer structure. Furthermore, it can be seen that when K increases, the thickness of the boundary layer decreases which implies increasing manner of the magnitude of the velocity gradient at the surface which implies an increase of the skin friction coefficient $f''(0)$.

The velocity profiles for different values of ε which produce $f'(0) = \varepsilon$ and $f'(\eta) = 1$ as $\eta \to \infty$ is plotted in Figure 8. When $\varepsilon > 1$, the flow has an inverted boundary layer structure and the thickness of the boundary layer decreases with ε. On the other hand, when $\varepsilon < 1$, the flow has a boundary layer structure, which results from the fact that when $a/b < 1$, the external velocity of the surface bx exceeds the velocity of the stretching sheet ax. For this case, the thickness of the boundary layer increases with the increase of ε.

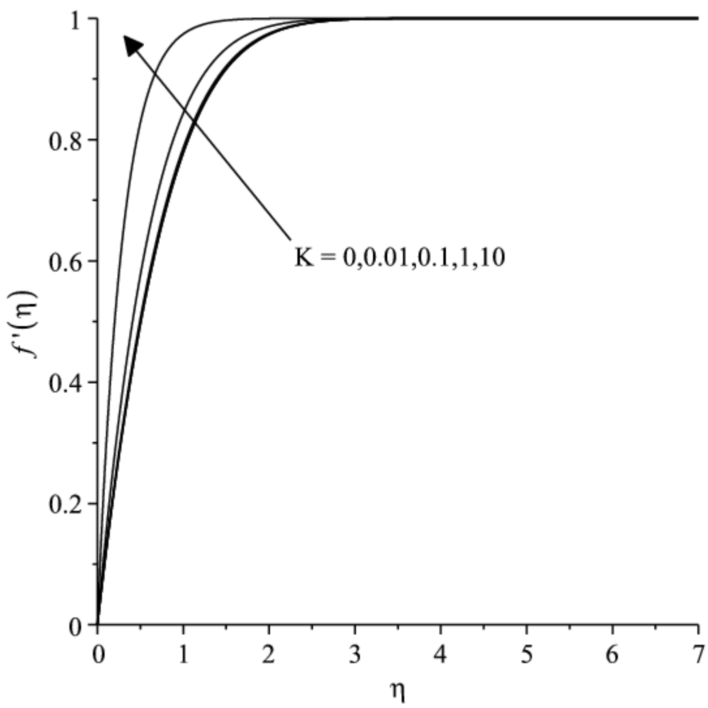

Figure 7. Velocity profiles $f'(\eta)$ **for various values of** K **when** $\Pr = 0.72,\ \gamma = 1,\ \varepsilon = 0$ **and** $\lambda = 0.5.$

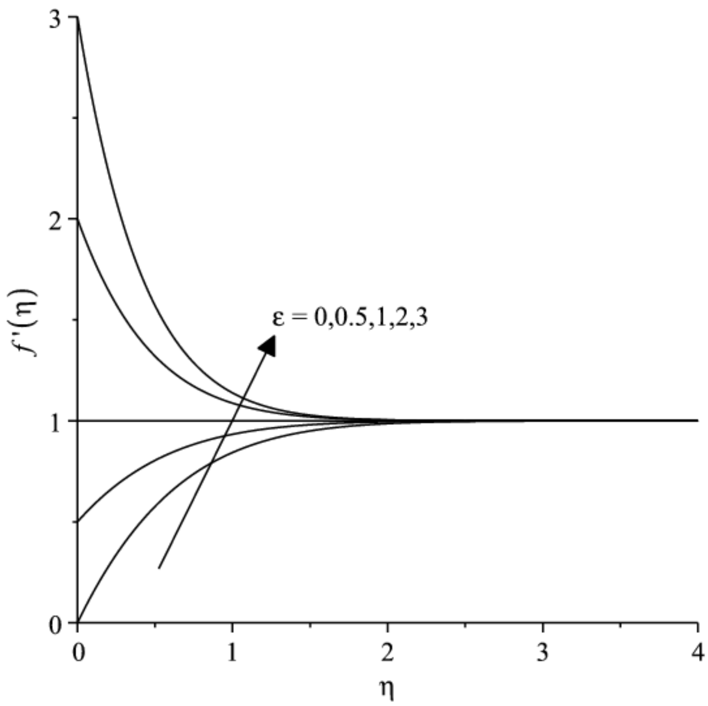

Figure 8. Velocity profiles $f'(\eta)$ **for various values of** ε **when** $\Pr = 0.72,\ \gamma = 1,\ K = 1$ **and** $\lambda = 1.$

4. Conclusion

In this paper we have numerically studied the problem of heat generation/absorption effects on stagnation point flow past a stretching surface with convective boundary conditions. It is shown how the permeability parameter K, heat source or sink parameter λ, stretching parameter ε, prandtl number $\Pr$ and conjugate parameter γ affects the values of the surface temperature, heat transfer coefficient, local nusselt number, skin friction coefficient as well as temperature and velocity profiles.

As a conclusion, the thermal boundary layer thickness depends strongly on these parameters. It is found that the presence of heat generation $(\lambda > 0)$ assist to the increase of fluid temperature and thermal boundary layer thickness while the presence of heat absorption $(\lambda < 0)$ results oppositely. Next, the increase of K, ε and $\Pr$ results to the decrease of temperature and thermal boundary layer thickness. The reason is that smaller values of Pr are equivalent to increasing thermal conductivity, and, therefore, heat is capable of diffusing away from the heated wall more rapidly than at higher values of Pr. However, the increase of conjugate parameter γ leads to an increase the temperature.

Furthermore, it is suggested that only K and ε affects the fluid flow velocity and skin friction coefficient. Pr, γ and λ are not affected the flow. This is clear from the ordinary differential equations 7 and 8.

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