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Effect of Volumetric Heat Generation/ Absorbtion on Mixed Convection Stagnation Point Flow on an Iso-thermal Vertical Plate in Porous Media

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Abstract

Aim of the paper is to investigate convective heat and mass transfer in the presence of the volumetric rate of heat generation/ absorption, which depends on local specie concentration. The main objective is to put forth the concept under rational and critical discussion by the scientific community. To study such a boundary layer flow, heat and mass transfer mixed convection stagnation point flow through porous media is taken. The result observed satisfies the general physical laws of boundary layer flow in the presence of the volumetric heat generation/ absorption.

Keywords : Boundary layer flow; heat transfer; mass transfer; volumetric rate of heat generation/ absorption.

Nomenclature

g	:	Acceleration due to gravity of the Earth
G_T	:	buoyancy parameter$\{= \frac{Gr}{Re^2}\}$
x, y	:	Cartesian coordinates
C_w	:	concentration at the plate surface
C	:	concentration in the fluid
C_∞	:	concentration in fluid far away from plate
D	:	diffusion coefficient
f	:	dimensionless stream function

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Gr	: Grashof number$\left\{= \frac{g\beta(T_w - T_\infty)x^3}{\nu^2}\right\}$
G_C	: modified buoyancy parameter $\left\{= \frac{Gr_M}{Re^2}\right\}$
Gr_M	: modified Grashof number $\left\{= \frac{g\beta C_w x^3}{\nu^2}\right\}$
Nu	: Nusselt number
$\tilde{K}$	: permeability of porous media
K	: permeability parameter$\left\{= \frac{\nu}{\tilde{K}c}\right\}$
Pr	: Prandtl number$\left\{= \frac{\mu C_p}{\kappa}\right\}$
S	: rate of heat generation/ absorption parameter$\{= -1, 0, 1\}$
Re	: Reynolds number $\left\{= \frac{U_\infty x}{\nu}\right\}$
Sc	: Schmidt number$\left\{= \frac{\nu}{D}\right\}$
Sh	: Sherwood number
C_f	: skin-friction coefficient
C_p	: specific heat at constant pressure
T	: temperature of the fluid
T_∞	: temperature of fluid far away from plate
T_w	: temperature of the plate
u, v	: velocity components along x- and y-directions, respectively
Q	: volumetric rate heat generation/absorption
Greek Letters	
β^*	: coefficient of expansion with concentration
β	: coefficient of thermal expansion
μ	: coefficient of viscosity
κ	: coefficient thermal conductivity
ρ	: density of fluid
ϕ	: dimensionless concentration $\left\{= \frac{C - C_\infty}{C_w - C_\infty}\right\}$
θ	: dimensionless temperature $\left\{= \frac{T - T_\infty}{T_w - T_\infty}\right\}$
η	: dimensionless variable
ν	: kinematic viscosity $\left\{= \frac{\nu}{\rho}\right\}$
ψ	: stream function

1 Introduction

A large number of physical phenomena involve free/forced convection (Jaluria [7]), which are enhanced and driven by internal heat generation. In such flows the buoyancy force is incremented due to heat generation resulting in modification of heat/mass transfer characteristic. Convection in the presence of internal heat generation/absorption has numerous applications in fields of geophysical science, fire and safety engineering, nuclear science, chemical engineering etc. The volumetric rate of heat generation $Q[Watt/m3]$ in the boundary layer flows generally has been presented in the literatures (Postelnicu et al. [12]) and studied taking the following form

$$Q = Q\,(T - T_\infty) \tag{1.1}$$

$$Q = Q\,(x, y, z) \tag{1.2}$$

The equation (1.1) represents volumetric rate of heat generation/ absorption (Vajravelu and Hadjinicolaou [15], Vajravelu and Nayfeh [16]), which depends on local fluid temperature distribution and is considered for exothermic/endothermic chemical/biochemical reactions. The temperature distribution is not known a priori. The equation (1.2) represents volumetric rate of heat generation (Crepeau and Clarksean [5], Chamkha and Khaled [3], Magyari and Rees [9], Magyari et al. [10]), which has prior known space distribution and is not controlled by flow pattern and local temperature distribution directly. To this class belongs the heat source whose intensity decays exponentially with the distance. In quest to find the solution for boundary layer flow, the governing equations are made dimensionless and the volumetric rate of heat generation/ absorption discussed above would take the form $S\theta$ or $Se^{-\eta}$ where S is heat source/sink parameter. Thus in general the form can be represented as

$$Sf(\eta) \tag{1.3}$$

where $f(\eta)$ is the shape function e.g. θ or $e^{-\eta}$.

The class of problems where chemical reacting specie is involved, the local concentration of the specie should also be a major factor affecting the volumetric rate of heat generation/ absorption, which is not known priori. Hence, a volumetric rate of heat generation/absorption of kind

$$Q = Q(C - C_\infty) \tag{1.4}$$

is proposed in front of scientific community. In the dimensionless form, it would take the form $S\phi$ where now ϕ is the shape function i.e. the local concentration distribution.

Eldabe [6] examined the flow structure at a rear stagnation point of an incompressible viscous porous medium fluid in the presence of a uniform magnetic field. Raptis and Takhar [14] studied the flow of a viscous fluid through porous media on plate in the presence of free stream. Yih [18, 19] studied MHD forced and free convective stagnation point flow through porous media along an isothermal /non-isothermal permeable surface. Wu et al. [17] analyzed the stagnation point flow in porous media and presented non-linear exact and asymptotic solutions. Kumaran et al. [8] employed a new implicit perturbation scheme to obtain approximate solution to stagnation point flow in porous media. Makinde [15] analysed the mass transfer in porous medium for constant heat flux in the presence of transverse magnetic field. Abdallah [1] studied mass transfer in the presence chemical reactive specie, internal heat generation, Dufour-Soret effect and Hall Effect on a permeable stretching sheet. Rashad and El-Kabeir [13] observed transient mixed convection on a stretching sheet in the porous medium in the presence of chemical reactive specie.

The aim of the paper is to consider the local specie concentration as a factor of the volumetric rate of heat generation. To study this model, a stagnation point flow is chosen, which had been studied earlier to understand flow pattern which varies from clear fluid flow to highly porous flow.

2 Formulation of the Problem

Consider steady laminar stagnation point flow of a viscous incompressible fluid through porous media along a vertical isothermal plate in the presence of volumetric rate of heat generation of the type discussed in equation (1.4). The x-axis is taken along the plate and y-axis is normal to the plate and the flow is confined in half plane $y > 0$ as shown through figure-1.

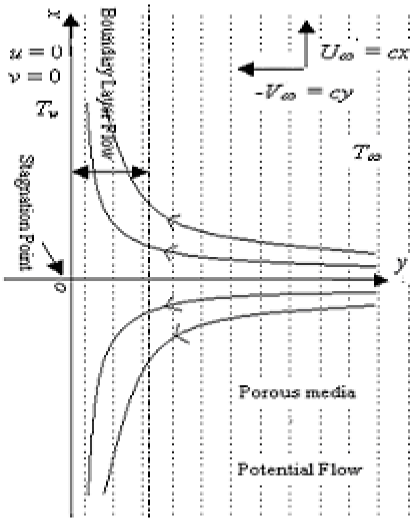

Fig. 1. Schematic diagram for flow in the vicinity of stagnation point

The potential flow arrives from the y-axis and impinges on plate, which divides at stagnation point into two streams and the viscous flow adheres to the plate. The velocity distribution in the potential flow is given by $U_\infty = cx$ and $V_\infty = cy$, where c is a positive constant. Following Yih [19] and Wu et al. [17] the linear Darcy term representing distributed body force due to porous media is retained while the non-linear Forchheimer term is neglected, thus the governing equations of continuity, momentum, energy and specie are given by

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{2.5}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial v}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + g\beta\left(T - T_\infty\right) + g\beta^*\left(C - C_\infty\right) + U_\infty\frac{dU_\infty}{dx} - \frac{\nu}{\tilde{K}}\left(u - U_\infty\right), \tag{2.6}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T}{\partial y^2} + Q, \tag{2.7}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D\frac{\partial^2 C}{\partial y^2}. \tag{2.8}$$

The boundary conditions are

$$\begin{gathered} y = 0 : u = 0, v = 0, T = T_w, C = C_w, \\ y \to \infty, u \to U_\infty = cx, T \to T_\infty, C \to C_\infty. \end{gathered} \tag{2.9}$$

3 Method of Solution

Introducing the stream function $\psi\left(x, y\right)$ such that

$$u = \frac{\partial \psi}{\partial y} \; and \; v = -\frac{\partial \psi}{\partial x}, \tag{3.10}$$

where

$$\psi\left(x, y\right) = \sqrt{c\nu}\, x f\left(\eta\right) \; and \; \eta = y\sqrt{\frac{c}{\nu}}\,, \tag{3.11}$$

and after inspiration of work carried out by Crepeau and Clarksean [5], Chamkha and Khaled [6], Ali [18] etc., Q is taken the form of

$$Q = S\frac{\kappa c\left(T_w - T_\infty\right)}{\nu}\,\phi, \tag{3.12}$$

so that we have the form $S\phi$ [equation (1.3)] where S is heat source/sink parameter and has value 0, -1or1 for absence, absorption or generation of volumetric heat, respectively. It is observed that the equation (2.5) is identically satisfied by equation (3.10). Substituting equations (3.11) and (3.12) into the equations (2.6), (2.7) and (2.8), the resulting non-linear ordinary differential equations are

$$f''' + ff'' - f'^{\,2} + G_T\theta + G_C\phi - K\left(f' - 1\right) + 1 = 0, \tag{3.13}$$

$$\theta'' + Prf\theta' + S\phi = 0, \tag{3.14}$$

$$\phi'' + Scf\phi' = 0,. \tag{3.15}$$

The boundary conditions are reduced to

$$f\left(0\right) = 0, f'\left(0\right) = 0, f'\left(\infty\right) = 1, \theta\left(0\right) = 1, \theta\left(\infty\right) = 0, \phi\left(0\right) = 1, \phi\left(\infty\right) = 0. \tag{3.16}$$

The system of equations (3.13) to (3.15) together with boundary conditions (3.16) are solved using Runge-Kutta fourth order method along with shooting technique (Conte and Boor [4]).

4 Numerical Scheme

The system of equations (3.13), (3.14) and (3.15) is first decomposed into system of linear equations as given below

$$\frac{df}{d\eta} = f_1\left(\eta, f, \tilde{u}, \tilde{v}\right) = \tilde{u},\ f\left(0\right) = 0 \tag{4.17}$$

$$\frac{d\tilde{u}}{d\eta} = f_2\left(\eta, f, \tilde{u}, \tilde{v}\right) = \tilde{v},\ \tilde{u}\left(0\right) = 0 \tag{4.18}$$

$$\frac{d\tilde{v}}{d\eta} = f_3\left(\eta, f, \tilde{u}, \tilde{v}\right) = \tilde{u}^2 - f\tilde{v} - G_T\,\theta\left(\eta\right) - G_C\,\phi\left(\eta\right) + K\left(\tilde{u} - 1\right) - 1,\ \tilde{v}\left(0\right) = ? \tag{4.19}$$

$$\frac{d\theta}{d\eta} = f_4\left(\eta, \theta, w\right) = w,\ \theta\left(0\right) = 1 \tag{4.20}$$

$$\frac{dw}{d\eta} = f_5\left(\eta, \theta, w\right) = -Prf\left(\eta\right)w - S\phi\left(\eta\right),\ w\left(0\right) = ? \tag{4.21}$$

$$\frac{d\phi}{d\eta} = f_6\left(\eta, \theta, e\right) = e,\ \phi\left(0\right) = 1 \tag{4.22}$$

$$\frac{de}{d\eta} = f_7\left(\eta, \theta, e\right) = -Scf\left(\eta\right)e,\ e\left(0\right) = ? \tag{4.23}$$

It is desired to solve the linear system of equation (4.17) to (4.23) using Runge-Kutta method as an initial value problem. Since the values of $\tilde{v}\left(0\right)$,$w\left(0\right)$ and $e\left(0\right)$ are not known, hence shooting method (Conte and Boor [19]) is employed to determine the values. The process says, keep an initial guess for unknown i.e. $\tilde{v}(0) = \alpha^{(0)}$,$w(0) = \beta^{(0)}$ and $e(0) = \gamma^{(0)}$ keeping η small. Apply shooting technique to correct the initial guess which would take the value say $\tilde{v}(0) = \alpha^{(1)}$,$w(0) = \beta^{(1)}$ and $e(0) = \gamma^{(1)}$. Now, increment the value of η and keep $\tilde{v}(0) = \alpha^{(1)}$,$w(0) = \beta^{(1)}$ and $e(0) = \gamma^{(1)}$ as initial guess for the new incremented η. Apply shooting technique once again to correct the initial guess. This process is iterated on each incremented η again and again, and carried up to the point where $\| \alpha^{(k+1)} - \alpha^{(k)} \| < 10^{-6}$, $\| \beta^{(k+1)} - \beta^{(k)} \| < 10^{-6}$ and $\| \gamma^{(k+1)} - \gamma^{(k)} \| < 10^{-6}$ which are taken as conditions of convergence.

5 Particular Case

Yih [19] solved the system of equations (3.13) and (3.14) along with boundary conditions (3.16) using implicit finite difference scheme in the absence of species equation and for non-isothermal sheet surface i.e. where surface temperature varies linearly with x co-ordinate. It is seen from Table 1 that the results obtained for $\theta'(0)$ by present scheme are in good agreement with those obtained by Yih [19], which also vindicates the use of present scheme.

Table 1
Comparison of numerical values of $-\theta'(0)$ for Pr =1.0,K=1.0 and $S = 0.0$ for different values of G_T with those obtained by Yih [12].

	$Yih[12]$	$Present paper$
	$-\theta'(0)$	$-\theta'(0)$
$G_T = 0$	0.853324	0.8533237
1.0	0.898224	0.8982240
10.0	1.147454	1.1474536
-1.0	0.799651	0.7996509

6 Skin-friction Coefficient

Skin-friction coefficient at the plate surface is given by

$$C_f = 2\,(Re)^{-0.5}\, f''(0)\,. \tag{6.24}$$

7 Nusselt Number

The rate of heat transfer in terms of the Nusselt number at the plate surface is given by

$$Nu = -\,(Re)^{-0.5}\,\theta'(0)\,. \tag{7.25}$$

8 Sherwood Number

The rate of mass transfer in terms of the Sherwood number at the plate surface is given by

$$Sh = -\,(Re)^{-0.5}\,\phi'(0)\,. \tag{8.26}$$

9 Results and Discussion

Table 2
Numerical values of $f''(0)$, $-\theta'(0)$, $-\phi'(0)$ for different values of S and K when $G_T = 1.0, G_C = 0.5, Pr = 1, Sc = 0.5$.

-	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
		$K = 0.0$			$K = 0.0$			$K = 0.0$	
S = -1.0	1.8444	1.3908	0.4631	2.9500	1.4059	0.4910	3.7183	1.4154	0.5024
S = 0.0	1.9995	0.6392	0.4789	3.0145	0.6713	0.4971	3.7599	0.6877	0.5098
S = 1.0	2.1342	-0.0730	0.4917	3.0763	-0.0464	0.5028	3.8005	-0.0293	0.5085

Table 3
Numerical values of $f''(0)$, $-\theta'(0)$, $-\phi'(0)$ for different values of Pr and Sc when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$.

-	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$	-	$f''(0)$	$-\theta'(0)$	$-\phi'(0)$
		$Sc = 0.5$				$Pr = 1.0$	
Pr=0.1	3.0760	0.2427	0.5064	Sc = 0.1	3.0335	0.6750	0.2398
Pr=1.0	3.0145	0.6713	0.4971	Sc = 0.5	3.0145	0.6713	0.4971
Pr=10	2.9197	1.6594	0.4896	Sc = 5.0	2.9705	0.6652	1.2816

It is observed from figure 2 and 5 that with the increase in parameter S, the fluid velocity increases. This should happen because increase in volumetric rate of generation means increase in buoyancy force thereby increasing fluid velocity. In addition, the boundary thickness also reduces with the increase in permeability parameter. Thus the flow of the clear fluid experiences more effect of increase in S. It is seen from figures 3 and 6 that fluid temperature increases with the increase in volumetric rate of generation, which is in accord with the physical phenomena. Also the effect of parameter S is pronounced even for increasing values of permeability parameter K. Figures 4 and 7 show that concentration of specie decreases with the increase in the parameter S. This happens because as the value of S increases the fluid velocity increases thereby increasing the diffusion and hence reduces the concentration. From figures 8, 9 and 10 it is seen that as the Prandtl number increases, the fluid velocity and temperature decrease while the concentration of the specie increases. The interplay can be explained, high Prandtl number for the fluid implies low thermal conductivity and therefore the fluid with high Prandtl number attains lower temperature and so temperature gradient is higher at the plate surface. Further, the fluid at lower temperature experiences lesser buoyancy force thus high Prandtl fluid has low velocity, which in turn also implies that at lower fluid velocity the specie diffusion is comparatively lower and hence higher specie concentration is observed at high Prandtl number. Figures 11, 12 and 13 reflect that with the increase in Schmidt number the fluid velocity and concentration decrease while fluid temperature increases slightly. Schmidt number holds the same for specie concentration as the Prandtl number for fluid temperature and hence from same token, as discussed for Prandtl number, the effect of Schmidt number is understood. It is seen from Table 2 that with the increase in the heat parameter S for different values of K, the value of $f''(0)$, which is a metric of the drag increases. This is understood from the fact that as volumetric rate of heat generation increases the fluid velocity increase, thus the plate surface experiences more drag. Also, the rate of heat transfer decreases because due to volumetric heat generation the fluid temperature increases and thus temperature gradient at the plate surface decreases, thereby reducing the heat transfer at the surface. For S =1.0 the rate of heat transfer is negative implying that the heat transfer is from fluid to surface, while for other values of S the value is positive indicating that the heat transfer is from surface to fluid. In addition, the rate of mass transfer increases with the increase in parameter S. This happens because, the increase in fluid velocity results in faster mass distribution of specie in fluid and hence the concentration gradient at the plate surface increases. It is observed from Table 2 that the same characteristics as discussed above prevail, even if the permeability parameter increases i.e. when the model shift from clear fluid flow to porous fluid flow. Table 3 shows that with the increase in Prandtl number the skin-friction and the rate of mass flux at the plate surface decrease, while the rate of heat transfer increases. Also with the increase in the Schmidt number, the skin-friction and rate of heat transfer at the plate surface decrease while the rate of mass flux increases.

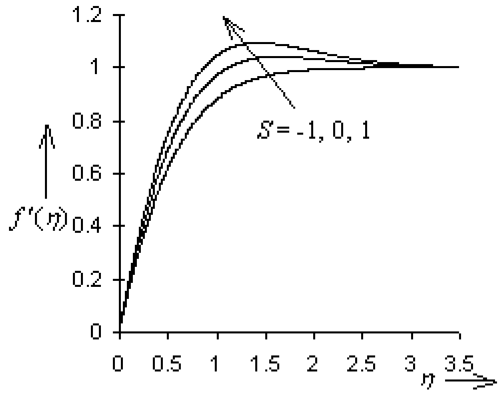

Fig. 2. Velocity distribution versus η when $G_T = 1.0, G_C = 0.5, K = 0.0, Pr = 1$ and $Sc = 0.5$.

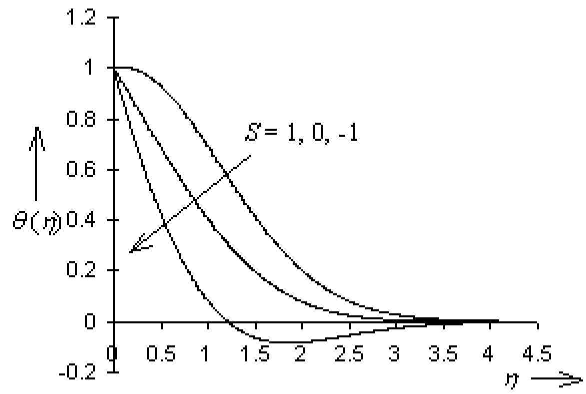

Fig. 3. Temperature distribution versus η when $G_T = 1.0, G_C = 0.5, K = 0.0, Pr = 1$ and Sc=0.5.

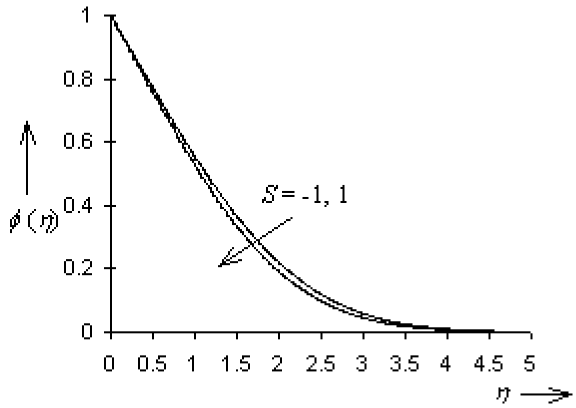

Fig. 4. Concentration distribution versus η when $G_T = 1.0, G_C = 0.5, K = 0.0, Pr = 1$ and Sc=0.5.

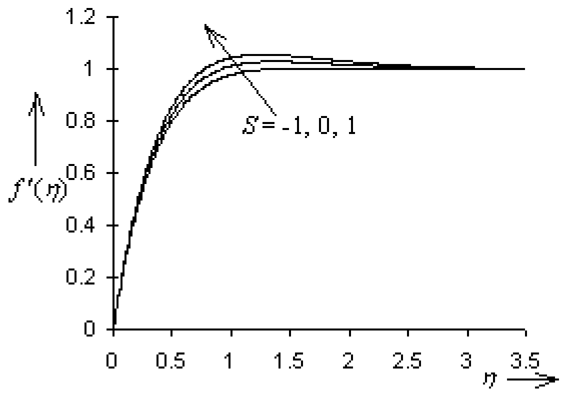

Fig. 5. Velocity distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, Pr = 1$ and $Sc = 0.5$.

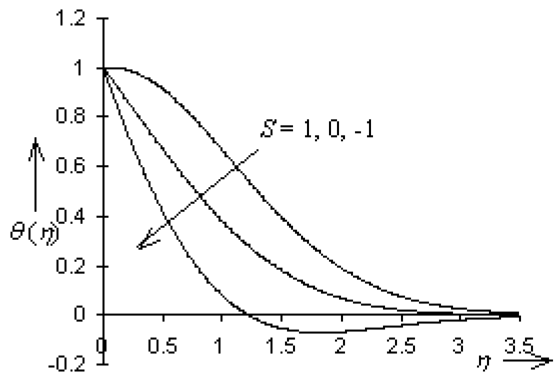

Fig. 6. Temperature distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, Pr = 1$ and $Sc =$ 0.5.

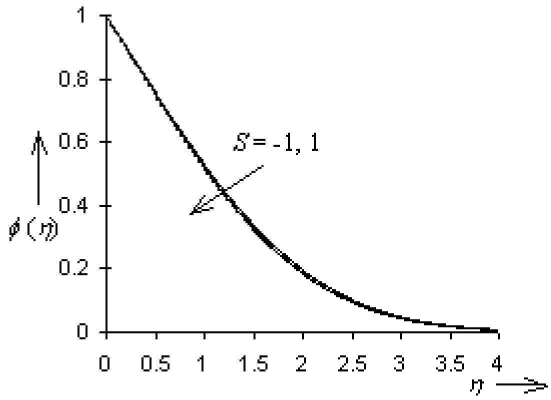

Fig. 7. Concentration distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, Pr = 1$ and $Sc = 0.5$.

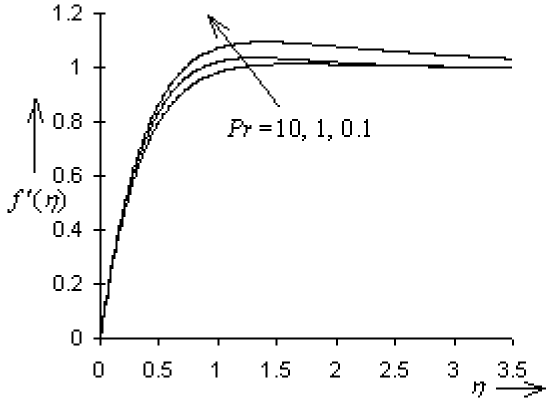

Fig. 8. Velocity distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$ and $Sc = 0.5$.

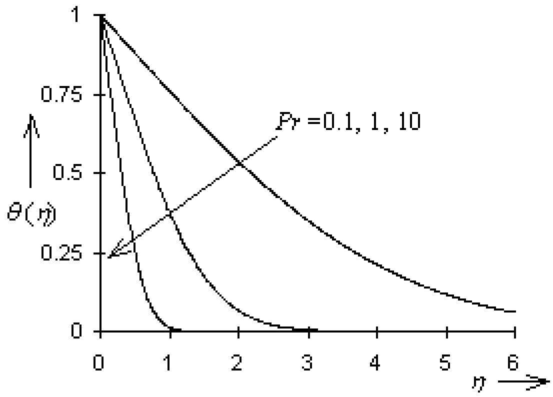

Fig. 9. Temperature distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S= 0.0$ and $Sc = 0.5$.

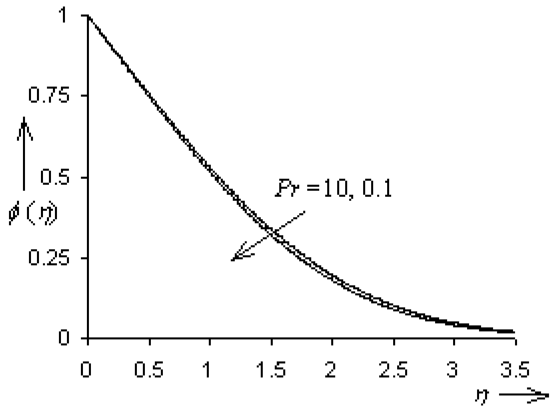

Fig. 10. Concentration distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$ and $Sc = 0.5$.

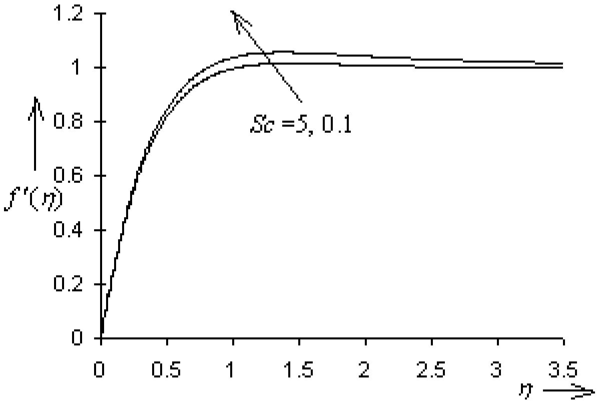

Fig. 11. Velocity distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$ and $Pr = 1.0$.

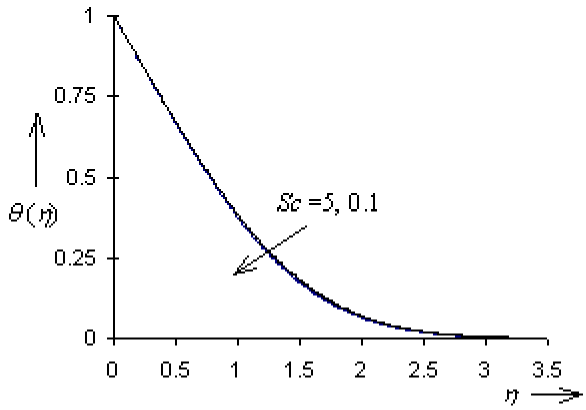

Fig. 12. Temperature distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$ and $Pr = 1.0$.

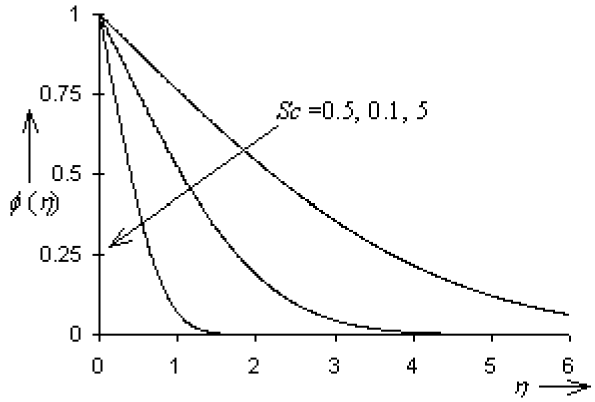

Fig. 13. Concentration distribution versus η when $G_T = 1.0, G_C = 0.5, K = 5.0, S = 0.0$ and $Pr = 1.0$.

10 Conclusions

In view of the figures and tables, the following conclusions are made:

1. The skin-friction and the rate of mass transfer increase, while the rate of heat transfer decreases with the increase in the rate of heat generation/absorption parameter S. The characteristics are the same, as are seen for temperature dependent or exponentially decaying heat source/sink.

2. The fluid velocity and temperature increase, while the concentration of specie decreases with the increase in the rate of heat generation/absorption parameter S. Again, the characteristics are the same, as are seen for temperature dependent or exponentially decaying heat source/sink.

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