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THERMOPHORETIC EFFECT ON MHD FLOW OF MAXWELL FLUID TOWARDS A PERMEABLE SURFACE

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ABSTRACT

Analysis has been carried out to study the stagnation point flow of Maxwell fluid towards a permeable stretching sheet. Using suitable transformations, the governing partial differential equations are first converted to ordinary one and then solved numerically by fourth–fifth order Runge–Kutta method with shooting technique by using MATLAB software. The flow and heat transfer characteristics are analyzed and discussed for different values of the parameters. Present work reveals that the velocity increases whereas the temperature and concentration decrease with the increase of Maxwell parameter. The thermal and concentration boundary layer thickness decreases with velocity ratio, Lewis number, Prandtl number, Brownian motion and thermophoresis parameters. Comparison with known results for Newtonian fluid flow is found to have an excellent agreement.

KEYWORDS: *MHD; Maxwell fluid; Permeable surface; Numerical solution*

INTRODUCTION

There is no doubt that human society development greatly depends upon energy. However the rapid development of human society during the past few years leads to the shortage of global energy and the serious environmental protection. Sustainable energy generation in recent time is thus a challenging issue globally. Solar energy in which circumstances has been regarded one of the best sources of renewable energy via least environmental impact. Solar power in fact is a natural way of obtaining water, heat and electricity. Power tower solar collectors could benefit from the potential efficiency improvements that arise from using a nanofluid as a working fluid. Particle size of nanomaterial is similar or smaller than the wavelength of de Broglie and coherent waves. It is now recognized that solar thermal system with nanofluids becomes the new study hotspot. On the other hand several industrial fluids are non-Newtonian in their flow characteristics. In a Newtonian fluid, the shear stress is directly proportional to the rate of shear strain, whereas in a non-Newtonian fluid, the relationship between the shear stress and the rate of shear strain is nonlinear. Most of the particulate slurries such as china clay and coal in water, multiphase mixtures such as oil–water emulsions, paints, synthetic lubricants

Nomenclature

A	velocity ratio
b, c	constant
C	concentration of the fluid
C_f	Skin friction
c_p	specific heat at constant pressure
C_w	concentration at wall
C_∞	ambient concentration
D_B	Brownian diffusion coefficient
D_T	thermophoretic diffusion coefficient
f	dimensionless velocity
k_0	relaxation time
N_b	Brownian motion parameter
N_t	thermophoresis parameter
Nu_x	local Nusselt number
L_e	Lewis number
$\mathrm{P_r}$	Prandtl number
Re_x	local Reynolds number
Sh_x	local Sherwood number
T	temperature of the fluid
T_w	temperature of the fluid at wall
T_∞	ambient temperature
u, v	velocity components in x, y direction
U_W	stretching velocity of the sheet
U	ambient fluid velocity
x, y	horizontal and vertical coordinate

Greek symbols

υ	kinematic viscosity
ψ	stream function
ρ	density of the base fluid
λ	suction parameter
β	Maxwell parameter
θ	dimensionless temperature
ϕ	dimensionless concentration
η	similarity variable
α	thermal diffusivity
τ	relative heat capacity
τ_W	skin friction

and biological fluids including blood at low shear rate, synovial fluid, and saliva and foodstuffs such as jams, jellies, soups, and marmalades are examples of non-Newtonian fluids. Because of the large variety of the non-Newtonian fluids, many models of non-Newtonian fluids exist. Maxwell model is one subclass of rate type fluids. This fluid model predicts the relaxation time effects. Such effects cannot be predicted by differential-type fluids. This fluid model is especially useful for polymers of low molecular weight. A review of non-Newtonian fluid flow problems may be found in [1–3]. Initially, Sakiadis [4] introduced the concept of boundary layer flow over a moving surface. Crane [5] modified the idea introduced by Sakiadis and extended this concept linear stretching sheet.

Flow in the neighborhood of stagnation point in a plane was first studied by Hiemenz [6]. Mahapatra and Gupta [7–9] investigated the magnetohydrodynamic stagnation point flow towards a stretching sheet. They show that the velocity at a point decreases/increases with increase in the magnetic field when the free stream velocity is less/greater than the stretching velocity. Also they have studied the temperature distribution when the surface has constant temperature and constant heat flux. Further they have extended their work on power law fluid and discussed the uniqueness of solutions of stagnation-point flow towards a stretching surface. Accordingly, researchers in the [10–13] studied the stagnation point flow over a surface. Aforementioned studies were primarily concerned with the laminar flow of a clear fluid. Nanotechnology is an emerging research topic having extensive use in industry due to the unique chemical and physical properties which the nanosized materials possess. These fluids are colloidal suspensions, typically metals, oxides, carbides or carbon nanotubes in a base fluid. The term nanofluid was coined by Choi [14] in his seminal paper presented in 1995 at the ASME Winter Annual Meeting. It refers to fluids containing a dispersion of submicronic solid particles with typical length of the order of 1–50 nm. Kuznetsov and Nield [15] analytically studied the natural convective boundary layer flow of nanofluid past a vertical plate. Khan and Pop [16] first time studied the problem of laminar fluid flow resulting from the stretching of a flat surface in a nanofluid. Mustafa et al. [17] investigated the stagnation point flow of viscous nanofluid towards a stretching surface using homotopy analysis method. Alsaedi et al. [18] examined the influence of heat generation/absorption on the stagnation point flow of nanofluid towards a linear stretching surface. Rahman et al. [19] examined the dynamics of natural convection boundary layer flow of water based nanofluids over a wedge. They discussed the analysis in the presence of a transverse magnetic field with internal heat generation or absorption. Nandy and Mahapatra [20] analysed the effects of velocity slip and heat generation/absorption on magnetohydrodynamic stagnation-point flow and heat transfer over a stretching/shrinking surface and then obtained the solution numerically using fourth order Runga–Kutta method with the help of shooting technique. Different from a stretching sheet, it was found that the solutions for a shrinking sheet are non-unique. Makinde et al. [21] studied the combined effects of buoyancy force, convective heating, Brownian motion and thermophoresis on the stagnation point flow and heat transfer of an electrically conducting nanofluid towards a stretching sheet. Effect of magnetic field on stagnation point flow and heat transfer due to nanofluid towards a stretching sheet has been investigated by Ibrahim et al. [22]. Nadeem et al. [23, 24] reported the numerical solutions of non-Newtonian nanofluid flow over a stretching sheet using the Maxwell fluid model. Further they obtained the analytic solution for non-orthogonal stagnation point flow of a nanosecond grade fluid toward a stretching surface with heat transfer. Hady et al. [25] studied the natural convection boundary layer flow over a downward-pointing vertical cone in a porous medium saturated with a power-law nanofluid in the presence of heat generation or absorption. Unsteady boundary layer flow of viscous nanofluid with thermal radiation has been discussed by Khan et al. [26]. Sheikholeslami et al. [27] examined the natural convection flow of nanofluid in the presence of magnetic field. MHD flow of viscous nanofluid due to rotating disk is addressed by Rashidi et al. [28]. Turkyilmazoglu and Pop [29] discussed thermal radiation effect in unsteady natural convection flow of nanofluids past a vertical infinite plate. Mohamad et al. [30] examined Hiemenz flow of nanofluid due to porous wedge. Turkyilmazoglu [31, 32] explores slip and convection effects in the flow of nanofluids. Nadeem et al. [33] analyzed the flow of three-dimensional water-based nanofluid over an exponentially stretching sheet. Very recently Ramesh and Gireesha [34, 35] studied the heat source/sink effects on Maxwell fluid over a stretching surface with convective boundary condition in the presence of nanoparticles and also obtained the numerical solution of the influence of heat source on stagnation point flow towards a stretching surface of a Jeffrey nanoliquid. Pattnaik et al. [36-40] studied the behaviour of MHD fluid flow and observed some interesting results.

In this paper, we have studied the behavior of the stagnation point flow of Maxwell fluid towards a stretching sheet. The sheet is taken permeable. Similarity transforms are used for this problem and non-dimensionalized equations are solved numerically. Graphical results for various values of the parameters are presented to gain thorough insight towards the physics of the problem. To the best of our knowledge, this problem has not been studied before.

MATHEMATICAL FORMULATION

Consider the flow of an incompressible non-Newtonian Maxwell fluid in the region $y > 0$ driven by a stretching surface located at $y = 0$ with a fixed stagnation point at $x = 0$. The x - and $y-$ axes are chosen along and perpendicular to the sheet. The stretching velocity $U_w(x)$ and the ambient fluid velocity $U(x)$ are assumed to vary linearly from the stagnation point, i.e., $U_w(x) = cx$ and $U(x) = bx$ where b and c are rate constant. We assume that flow is laminar, steady and two dimensional. The sheet is flat and permeable and the temperature T and the nanoparticle fraction C take constant values T_w and C_w respectively. The ambient values attained as y tend to infinity of T and C denoted by T_∞ and C_∞ respectively. All the thermo-physical properties are taken constant.

The flow problem is governed by the following boundary layer equations:

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

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = v\frac{\partial^2 u}{\partial y^2} - \frac{1}{\rho}\frac{\partial p}{\partial x} + k_0\left(u^2\frac{\partial^2 u}{\partial x^2} + v_2\frac{\partial^2 u}{\partial y^2} + 2uv\frac{\partial^2 u}{\partial x \partial y}\right) \tag{2}$$

$$u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \alpha\frac{\partial^2 T}{\partial x^2} + \tau\left[D_B\frac{\partial C}{\partial y}\frac{\partial T}{\partial y} + \left(\frac{D_T}{T_\infty}\right)\left(\frac{\partial T}{\partial y}\right)^2\right] \tag{3}$$

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = D_B\frac{\partial^2 C}{\partial y^2} + \frac{D_T}{T_\infty}\frac{\partial^2 T}{\partial y^2} \tag{4}$$

$$\begin{aligned} &u = U_W(x), v = -V_W(x), T = T_W(x), C = C_W(x) \quad \text{at} \quad y = 0 \\ &u \to U(x), v \to 0, T \to T_\infty, C \to C_\infty \quad \text{as } y \to \infty \end{aligned} \tag{5}$$

To employing the generalized Bernoulli's equation, in the free stream $U(x)=bx$, Eq. (2) reduces to,

$$U\frac{du}{dx}=-\frac{1}{\rho}\frac{dp}{dx} \tag{6}$$

With the help of `stream function` and the following similarity transformation:

$$u=\frac{\partial\psi}{\partial y},v=-\frac{\partial\psi}{\partial x},\eta=y\sqrt{\frac{U_w}{\nu x}},\ f(\eta)=\frac{\psi}{\sqrt{\nu x U_w}},\theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty},\phi(\eta)=\frac{C-C_\infty}{C_w-C_\infty}$$

Eqs. (2)-(4) can be written as,

$$(1-\beta f^2)f'''+ff''-f'^2+A^2+2\beta ff'f''=0 \tag{7}$$

$$\frac{1}{P_r}\theta''+f\theta'+N_b\theta'\phi'+N_t(\theta')^2=0 \tag{8}$$

$$\phi''+\mathrm{P_r}L_e f\phi'+\frac{N_t}{N_b}\theta''=0 \tag{9}$$

where

$$A=\frac{c}{b},\beta=k_0c,\lambda=\frac{V_w}{\sqrt{\upsilon c}},L_e=\frac{\alpha}{D_B},\mathrm{P_r}=\frac{\upsilon}{\alpha}$$
$$N_t=\frac{\tau D_T(T_w-T_\infty)}{\upsilon T_\infty},N_b=\frac{\tau D_B(C_w-C_\infty)}{\upsilon} \tag{10}$$

So the boundary conditions are reduced as:

$$f=\lambda, f'=1,\theta=1,\phi=1 \text{ at } \eta=0$$
$$f'\to A,\ \theta\to 0,\ \phi\to 0 \text{ as } \eta\to\infty \tag{11}$$

Physical quantities:

Skin friction coefficient, Nusselt number and Sherwood number respectively are defined as

$$C_{fx}\sqrt{\mathrm{Re}_x}=(1+\beta)f''(0),N_{ux}/\sqrt{\mathrm{Re}_x}=-\theta'(0),S_{hx}/\sqrt{\mathrm{Re}_x}=-\phi'(0) \tag{12}$$

where $\mathrm{Re}_x=\frac{xU_w(x)}{v}$.

Numerical solutions:

Numerical solutions to the governing ordinary differential Eqs. (7) – (9) with the boundary conditions (11) are obtained using a fourth–fifth order Runge–Kutta method with shooting technique by using MATLAB software. The problem for a regular (non-Newtonian) fluid involves four parameters, namely Maxwell parameter, Prandtl number, suction parameter and velocity ratio parameters. The present extension involves different three more parameters N_b, L_e and N_t. Therefore, we need to be very selective in the choice of the values of the parameters. Since most nanofluids examined to date have large values of the Lewis number L_e, we are interested mainly in the case $L_e\geq 1$. Because the physical domain in this problem is unbounded, whereas the computational domain has to be finite, we apply the far field boundary conditions for the similarity variable at a finite value $\eta_{\max}$. We run our bulk computations with the value $\eta_{\max}=5$. Researchers can solve the above nonlinear differential equations analytically [41,42].

RESULT AND DISCUSSION

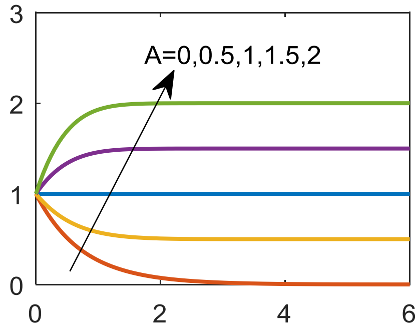
In order to validate the method used in this study and to judge the accuracy of the present analysis, a comparison with available results corresponding to the skin-friction coefficient, Nusselt number and Sherwood number for $N_t = N_b = L_e = 0$, $\beta = 0$ (in the absence of Maxwell parameter) and $\lambda = 0$ (i.e. for stretching impermeable plate) with the available published results of Mahapatra and Gupta [8], Ibrahim et al. [22] and Hayat et al. [43] for various values of different parameters are presented in Figs. (6) - (10). These show a favourable agreement and thus give confidence that the numerical results obtained are accurate. In the present computation the value of the pertinent parameters are considered as $A = \beta = \lambda = 1, N_t = N_b = 0.1, L_e = \mathrm{P_r} = 2$ unless otherwise stated.

Fig. 1(a-c) exhibits the velocity profiles for several values of A, β and λ. It is found in Fig. 1(a) that when the stretching velocity is less than the free stream velocity $A > 1$ the flow has a boundary layer structure, physically saying that the straining motion near the stagnation region increases so the acceleration of the external stream increases which leads to decrease in the thickness of the boundary layer with increase in A. When the stretching velocity cx of the surface exceeds the free stream velocity bx $(A < 1)$ inverted boundary layer structure is formed and for $A = 1$ there is no boundary layer formation because the stretching velocity is equal to the free stream velocity. In Fig. 1(b), it is clear that for $A < 1$, the velocity increases with the increasing values of β. So the boundary layer thickness decreases. Similar effect can be found when $A > 1$.In Fig. 1(c), it is found that for a fixed value of $A < 1$, the velocity decreases with the increase of λ. The velocity profiles tends asymptotically to the horizontal axis and the non-dimensional velocities absorbs maximum at the wall. It is a fact that suction stabilizes the boundary layer growth. For $A > 1$ the velocity increases with the increase of λ .Fig. 2(a-c) shows the variations of temperature profiles for several values of A, β and λ. This fig. is the evidence of the decrement of $\theta(\eta)$ with increasing values of A, β and λ. This is exactly opposite effects for regular Maxwell fluid. It is also interesting to note that there is a significant enhancement of temperature at the wall, when it is porous. The temperature profile starts to decrease monotonically from the very beginning which can be seen in this fig. Fig. 3(a-c) shows the variations of temperature profiles for different values of pertinent parameters $\mathrm{P_r}, N_b$ and N_t .The graph, Fig. 3(a), depicts that the temperature decreases when the values of $\mathrm{P_r}$ increase. This is due to the fact that a higher $\mathrm{P_r}$ fluid has relatively low thermal conductivity, which reduces conduction and thereby the thermal boundary layer thickness, and as a result, temperature decreases. It is found in Fig. 3(b) & (c) that for increasing values of both N_b and N_t are to increase $\theta(\eta)$ in the boundary layer. Fig. 4(a-c) shows the variations of concentration profiles for different values of A, β and λ. It can be seen that $\phi(\eta)$ decreases with increasing values of A, β and λ .The concentration profiles start to decrease monotonically from the very beginning. Fig. 5(a-d) shows the variations of concentration profiles for different values of $N_b, N_t, \mathrm{L_e}$ and $\mathrm{P_r}$. In Fig. 5(a), it is clear that concentration boundary layer reduces as N_b increases which thereby enhances the concentration at the sheet. Fig. 5(b) is the evidence of the fact that increasing values of N_t is to increase the concentration profiles. Fig. 5(c) displays the effect of L_e on concentration profiles. It is noted that the concentration of fluid decreases with increase of L_e. Physically this is due to the fact that mass transfer rate increases as L_e increases. It also reveals that the concentration gradient at surface of the plate increases. Fig. 5(d) shows that for higher values of $\mathrm{P_r}$, concentration profile gets decelerated. Fig. 6(a-c) shows the variations of Skin friction coefficient for several values of A, β and λ .It is clearly observed from this fig. that Skin friction coefficient gets enhanced for increasing values of all the parameters i.e., A, β and λ. Fig. 7(a-c) shows the variations of Nusselt number for several values of β, λ and $\mathrm{P_r}$ .It is interesting to note that, Nusselt number gets accelerated for increasing values of pertinent parameters β, λ and $\mathrm{P_r}$. Fig. 8(a-c) shows the variations of Nusselt number for several values of N_b, N_t and $\mathrm{L_e}$ .It is interesting to note that, Nusselt number gets decelerated for increasing values of pertinent parameters N_b, N_t and $\mathrm{L_e}$. Figs. 9(a-c) and 10(a-c) show the variations of Sherwood number for several values of β, λ and $\mathrm{P_r}$ and N_b, N_t and $\mathrm{L_e}$ .It is very much clear that for increasing values of N_t, Sherwood number gets decelerated but reverse effect is observed for all other parameters. From Fig. 11(a-d), it can be observed that there is no change in Skin friction coefficient for the variations in $N_b, N_t, \mathrm{L_e}$ and $\mathrm{P_r}$.

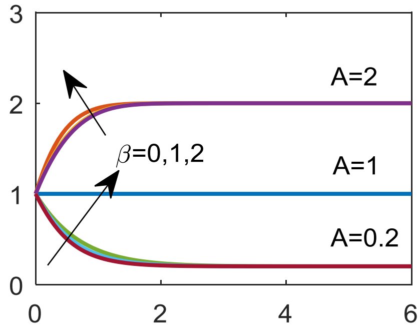
CONCLUSIONS

In the present investigation, the influence of different parameters on the velocity, temperature and concentration profiles is illustrated and discussed. All the graphical results give a view toward understanding the response characteristics of the stagnation point flow of a Maxwell fluid in the presence of suction. It is found that boundary layer is formed when $A > 1$ on the other hand inverted boundary layer is formed when $A < 1$. Some results of thermal characteristics at the wall are usually analyzed in forms of graphs. Analyzing this graphs, it reveals that the effects of increasing the values of β are to increase $f''(0)$ and decrease the $-\theta'(0)$; whereas for $A < 1$, $-\theta'(0)$ increases but decreases at $A > 1$.

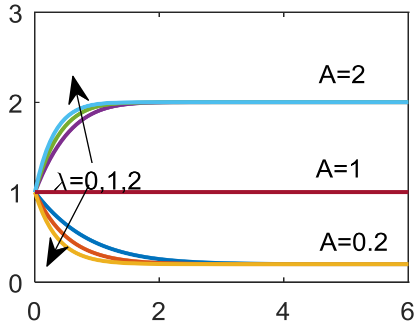
Fig.1 Variation of Velocity profile f '(η)



(a) with A



(b) with β



(c) with λ

Fig.2 Variation of Temperature profile $\theta(\eta)$

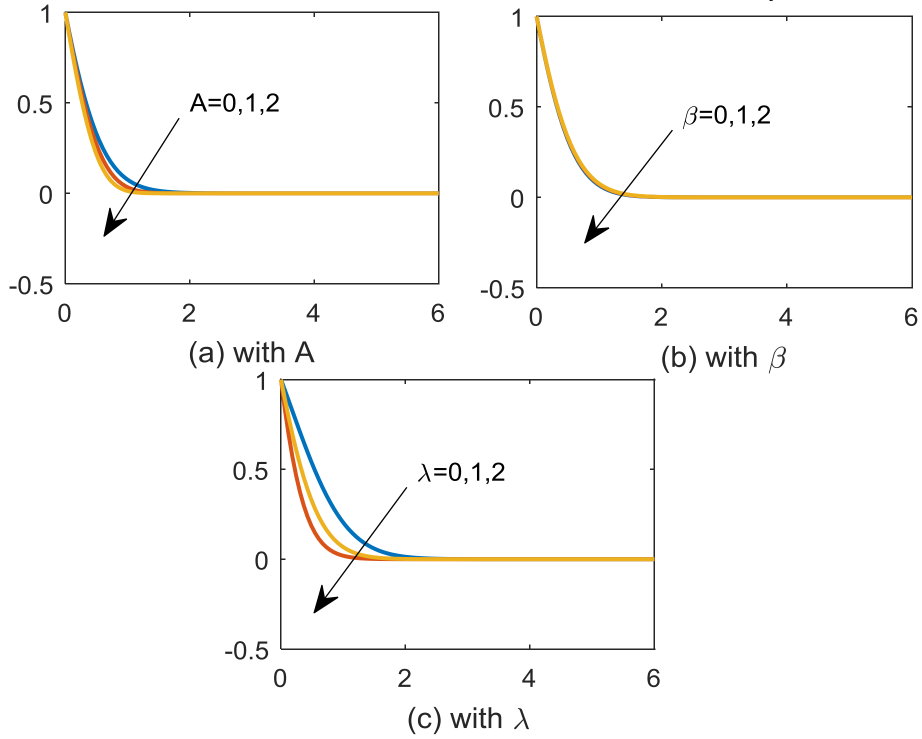


Fig.3 Variation of Temperature profile $\theta(\eta)$

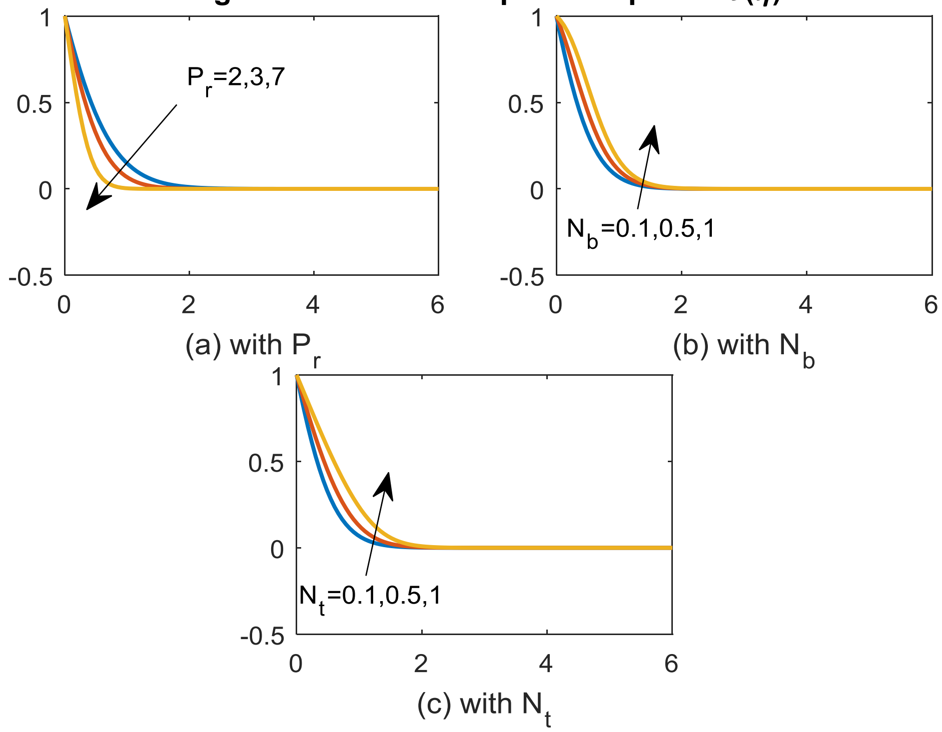


Fig.4 Variation of Temperature profile $\phi(\eta)$

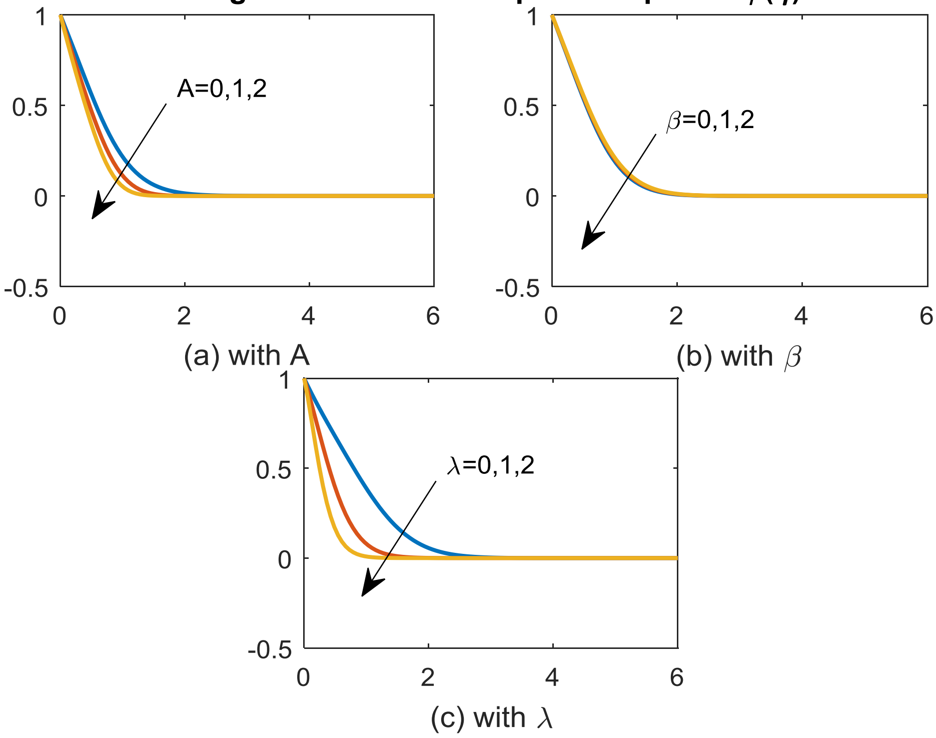


Fig.5 Variation of Temperature profile $\phi(\eta)$

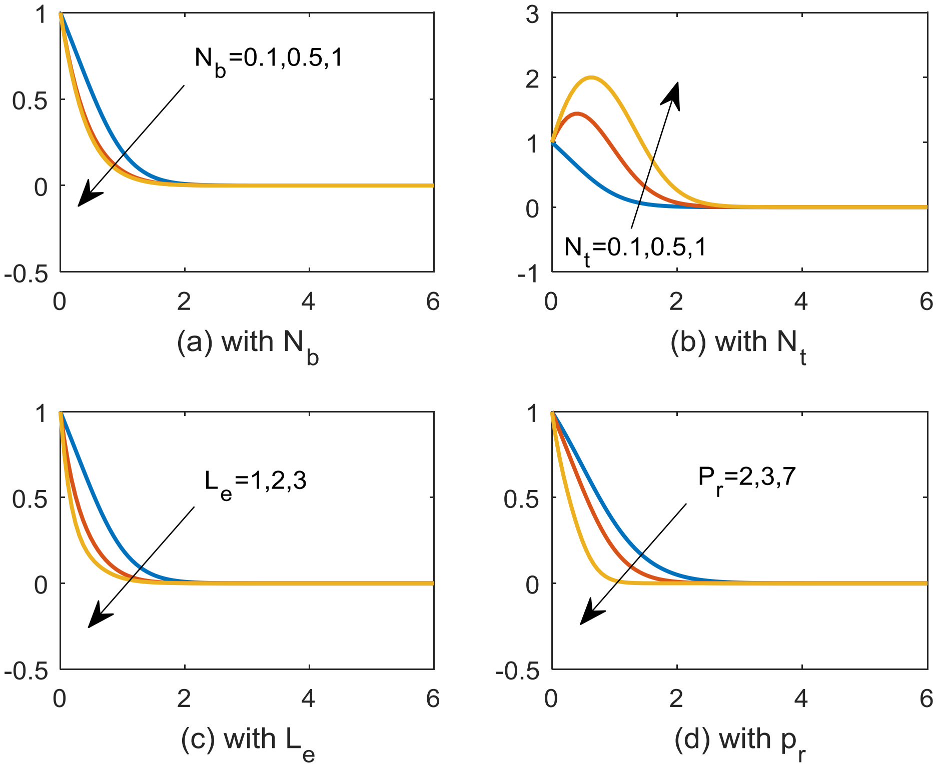


Fig.6 Variation of Skin friction coefficient C_f

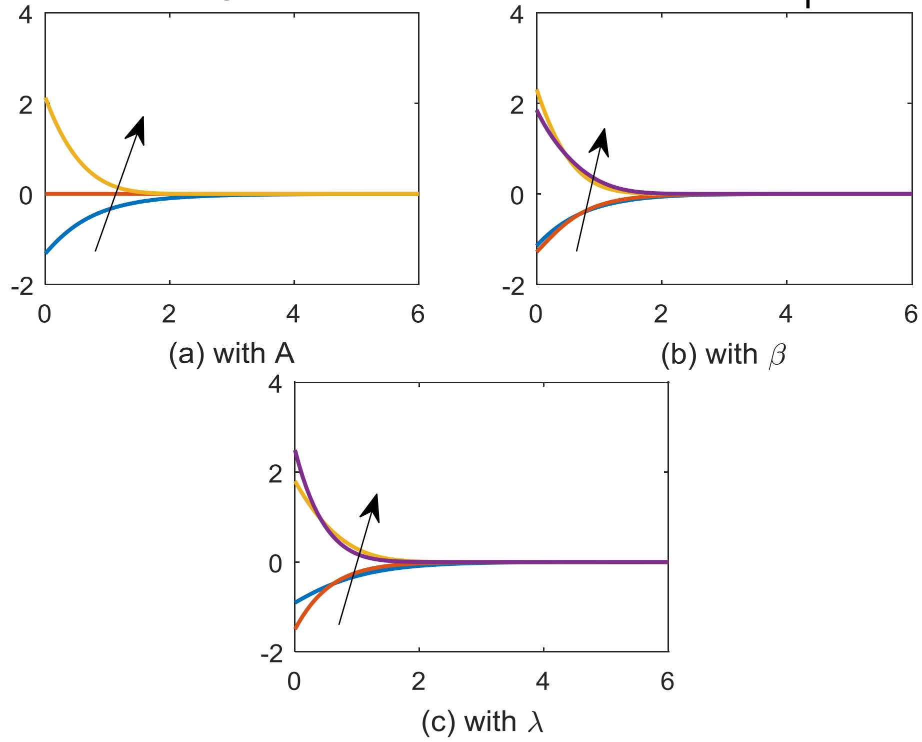


Fig.7 Variation of Nusselt number Nu_x

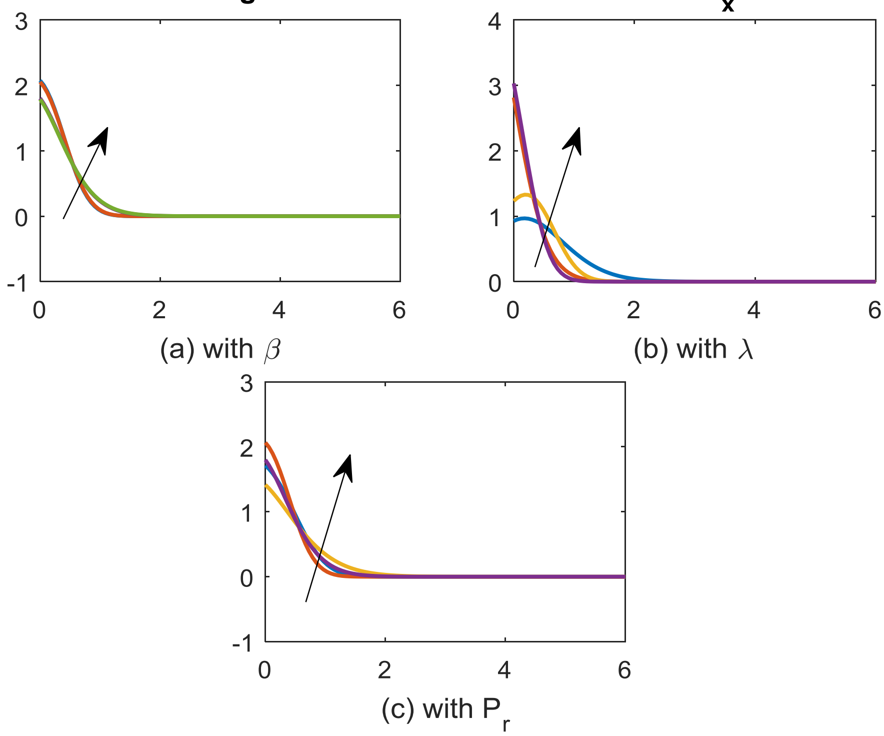


Fig.8 Variation of Nusselt number Nu_x

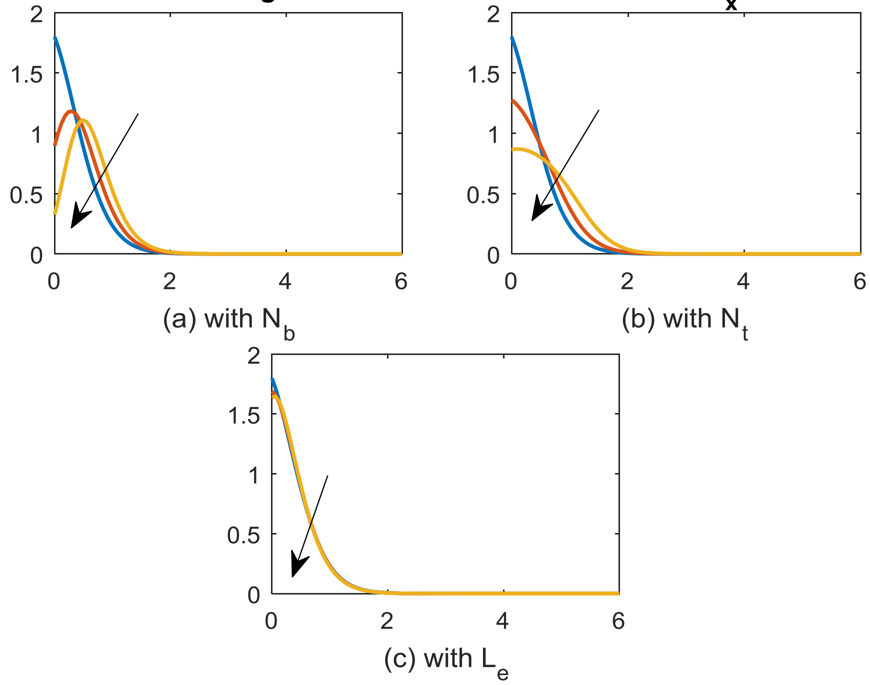


Fig.9 Variation of Sherwood number Sh_x

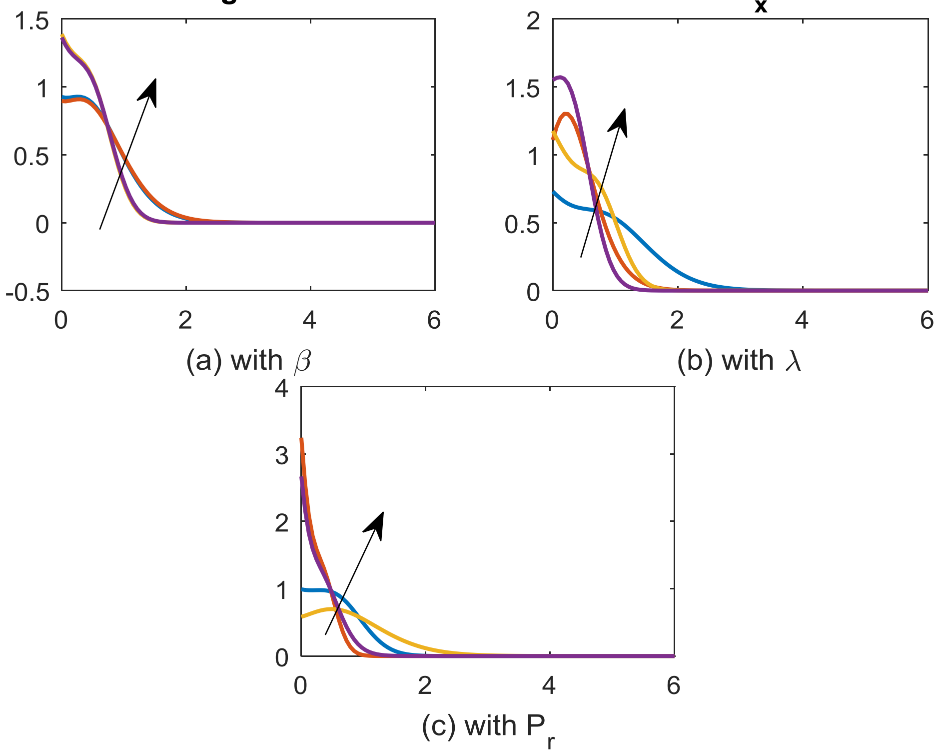


Fig.10 Variation of Sherwood number Sh_x

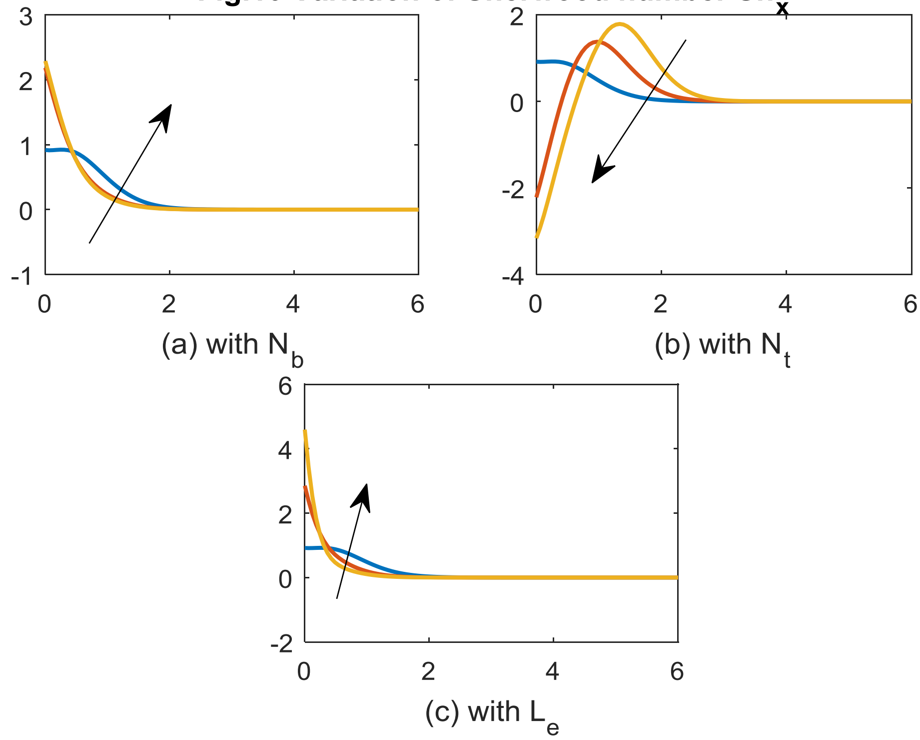
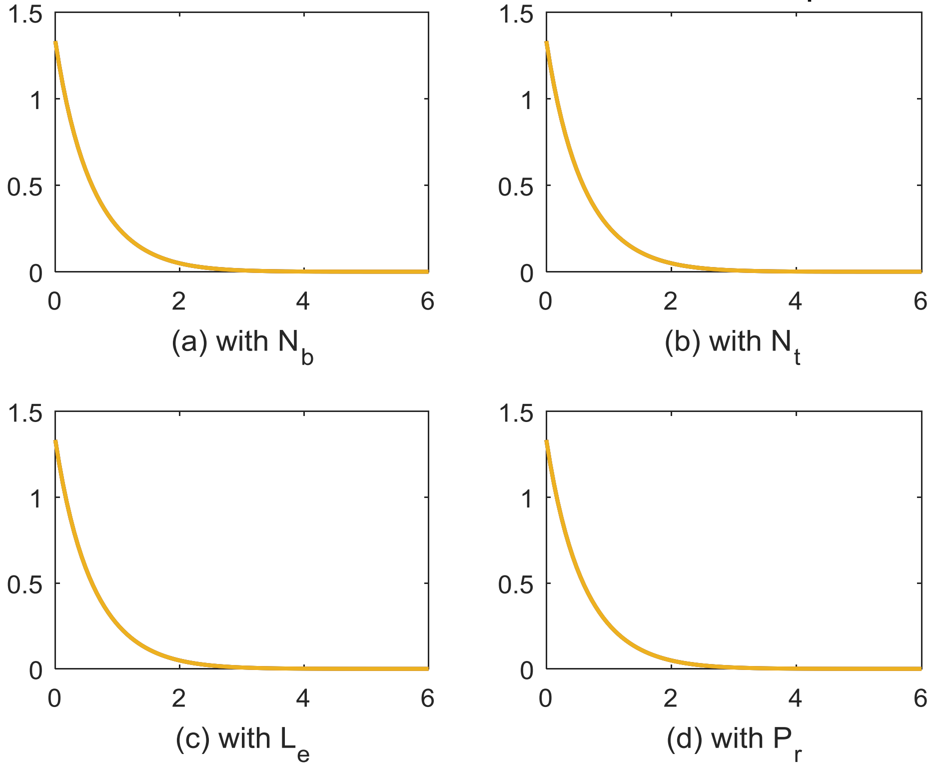


Fig.11 Variation of Skin friction coefficient C_f



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