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SLIP EFFECTS ON UNSTEADY MIXED CONVECTION BOUNDARY LAYER FLOW THROUGH POROUS MEDIUM PAST A VERTICAL STRETCHING SHEET AND ENTROPY GENERATION

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Abstract: In this study, numerical solution to the unsteady laminar mixed convection boundary layer flow through porous medium past a stretching vertical surface is presented .The time dependent forms of the stretching velocity and the sheet surface temperature have been assumed with both partial slip velocity and temperature slip boundary conditions. The governing partial differential equations are transformed into ordinary differential equations using similarity transformations, and then solved numerically. The effects of the various pertinent parameters are examined on the velocity field, temperature field and entropy generation during mixed convection flow, and discussed.

Key Words: *S*lip, porous medium, vertical stretching sheet, entropy generation, mixed convection.

1. Introduction

In many industrial manufacturing processes, such as, production of metal or polymer sheets and in their many practical applications e.g. in packaging industry etc. the fluid dynamics due to shrinking and stretching surfaces is important when these surfaces undergo heating. Several researchers are studying the viscous fluid flow over such surfaces and the associated heat transfer problems because of their wide applications in various areas, such as Aerodynamics, paper production, glass blowing and drawing artificial fibres , and in particular polymer industry where polymer sheets extruded from a die by drawing them through a quiescent viscous fluid. Since the pioneering work of Crane[16] who investigated the steady boundary layer two-dimensional viscous flow due to a stretching sheet in a quiescent fluid, many researchers examined various new aspects of their classical problem of stretching sheet, e.g. Wang[29], Grubka and Bobba[18], Mcleod and Rajgopal[22], Ali[1], Elbashbeshy[17], Chamkha and Issa[8] ,Cortell[15], Ariel[4], Ariel et al.[5], Ali and Magyari[2], Rashidi and Gaji[26], Ishak et el.[20], Patil et el.[25], Chauhan and Agarwal[9], Chauhan and Olkha[12], Vyas and Srivastava[28], Chauhan et al.[14,13].

Most of the studies that deal with the convection in porous medium at various flow thermal situations and boundary conditions are restricted to the analysis of First-law of thermodynamics. However, a Second -law analysis is important in determining the form of irreversibility in terms of entropy generation. In fact, thermodynamic irreversibility is encountered in all heat transfer processes, and different sources, such as heat transfer and viscous dissipation are responsible for entropy generation which destroys the work availability of a thermal system. Bejan[6] examined and discussed the entropy generation, and showed that the optimal design of an engineering thermal system can be achieved by its minimization. In view of this, several researchers, such as Mehmud and Fraser[23], Hooman et al.[19], Chauhan and Kumar[10], Komurgoz et al.[21] have examined heat transfer effects incorporating entropy generation in their studies. Tamayol et al.[27] examined entropy generation in a porous medium over a permeable stretching wall with different power-law thermal boundary conditions. Chauhan and Rastogi[11] investigated entropy generation due to heat transfer, fluid friction and magnetic field during flow through porous medium over a non-isothermal stretching sheet.

The aim of this investigation is to study the unsteady boundary layer viscous fluid flow and heat transfer past a vertical stretching sheet placed in a fluid saturated homogenous highly porous medium, with partially slip boundary conditions. The unsteadiness, in the velocity field and temperature field, is due to the time-dependent stretching velocity and the surface temperature of the sheet. The governing partial differential equations are first transformed into ordinary differential equations using similarity transformations and then solved numerically. The effects of various physical parameters, such as unsteadiness parameter, slip parameters, permeability of the porous medium, Prandtl number, buoyancy parameter, and viscosity ratio parameter, on the flow field, temperature field are examined and discussed graphically. In this analysis, entropy generation due to heat transfer and fluid friction in porous medium have also been included in the presence of the buoyancy force and slip boundary conditions, which further contributes to the existing studies conducted by other researchers in similar stretching sheet problems.

2. Formulation of the Problem

We consider a mixed convection unsteady laminar boundary layer flow through a porous medium adjacent to a vertical stretching sheet .The vertical stretching sheet coincides with the plane $x = 0$ in the upward direction and the porous medium flow is considered in the region $x > 0$. The x-axis is taken along the stretching sheet and the y- axis is taken normal to it in the outward direction into the fluid. It is assumed that for time $t < 0$ the fluid flow and heat flow are steady .The unsteady flows start at $t = 0$, and the vertical stretching sheet moves in its own plane keeping the origin fixed with a velocity $U_\omega(x,t)$, which varies both along the sheet, x and with time, t .It is defined as follows:

$$U_\omega(x,t) = \frac{ax}{1-ct} \tag{1}$$

where a and c are positive constants (with $a > 0$, $c \geq 0$, $ct < 1$),which measure the stretching rate and the unsteadiness respectively, and both have dimension time^{-1} .

The surface temperature distribution $T_\omega(x,t)$ also varies with x and t both and it is defined as follows:

$$T_\omega(x,t) = T_\infty + \frac{bx}{(1-ct)^2} \quad (2)$$

where, T_∞, the ambient temperature; and b , is a constant having dimension temperature/length. Here, $T_\omega(x,t) > T_\infty$ is for heating and $T_\omega(x,t) < T_\infty$ for cooling of the sheet, which correspond to assisting and opposing flows respectively.

The $x-$momentum equation is based on the Brinkman model, and the energy equation, on the local thermal equilibrium assumption (Brinkman[7]; Nield and Bejan[24]). Under the Boussinesq and boundary layer approximations, for unsteady flow and temperature distribution through highly porous medium, the governing partial differential equations for the present problem may be written as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (3)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \upsilon\phi\frac{\partial^2 u}{\partial y^2} - \frac{\upsilon u}{K_0} + g\beta(T - T_\infty) \quad (4)$$

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} = \frac{k}{\rho C_p}\frac{\partial^2 T}{\partial y^2} \quad (5)$$

The corresponding boundary conditions for the present problem are given by

at $y = 0$, $\quad u = U_\omega(t,x) + L_1\frac{\partial u}{\partial y}$

$v = 0$

$T = T_\omega(t,x) + L_2\frac{\partial T}{\partial y}$

as $y \to \infty$, $\quad u \to 0, \quad T \to T_\infty \quad (6)$

where, u and v are the velocity components in x and y directions respectively; T , the temperature ; μ , the viscosity of the clear fluid ; $\bar{\mu}$, the effective viscosity of the fluid in the porous medium; K_0 , the permeability of the porous medium; ρ , the density; C_p , the specific heat at the constant pressure; k , the effective thermal conductivity which depends on the thermal conductivities of the fluid and the porous matrix; L_1 and L_2, the velocity and temperature slip parameters; $\phi = \bar{\mu}/\mu$, the viscosity ratio; g the acceleration due to gravity; β the thermal expansion coefficient; and $\upsilon = \mu/\rho$, the kinematic viscosity.

Let us introduce the similarity transformations, following Andersson et al.[3] and Ishak et al.[20] as follows:

$$u = \frac{ax}{1-ct} f'(\eta), v = -\left(\frac{\upsilon a}{1-ct}\right)^{1/2} f(\eta), \eta = \left(\frac{a}{\upsilon(1-ct)}\right)^{1/2} y, \text{and } \theta(\eta) = \frac{T-T_\infty}{T_\omega - T_\infty}$$

Substituting the above similarity transformations into the partial differential equations (3) to (5) and the boundary conditions (6) , we obtain the following dimensionless system of ordinary differential equations ,

$$\phi f''' - A\left[f' + \frac{\eta}{2} f''\right] - (f')^2 + ff'' + \lambda\theta - \frac{f'}{K} = 0 \tag{7}$$

$$\theta'' - \Pr\left[-\theta' f + f'\theta + A\left(2\theta + \eta\frac{1}{2}\theta'\right)\right] = 0 \tag{8}$$

And the corresponding boundary conditions as follows

at $\eta = 0$, $f(0) = 0$, $f'(0) - 1 = \alpha_1 f''(0)$, $\theta(0) - 1 \ = \alpha_2 \theta'(0)$

as $\eta \to \infty$, $f'(\infty) = 0$, $\theta(\infty) = 0$ (9)

where, , $A = \dfrac{c}{a}$, the unsteadiness parameter ; $\Pr = \dfrac{\mu C_p}{k}$, the Prandtl number;

$K = \dfrac{K_0 a}{\upsilon(1-ct)}$, the Permeability parameter; $\alpha_1 = L_1\left[\dfrac{a}{\upsilon(1-ct)}\right]^{1/2}$, the partial velocity slip parameter; $\alpha_2 = L_2\left[\dfrac{a}{\upsilon(1-ct)}\right]^{1/2}$, the partial temperature slip parameter;

$Gr_x = \dfrac{g\beta(T_\omega - T_\infty)x^3}{\upsilon^2}$, the local Grashof number; $\mathrm{Re}_x = \dfrac{U_\omega x}{\upsilon}$, the local Reynolds number; $\lambda = \dfrac{Gr_x}{\mathrm{Re}_x{}^2} = \dfrac{g\beta b}{a^2}$, the mixed convection parameter.

The local Nusselt number is given by

$$N_{ux} = -\theta'(0)(R_{ex})^{1/2} \tag{10}$$

3. Numerical Solution

For the numerical solution of the present two- point boundary value problem consisting of the set of non linear ordinary differential equations (7) and (8) with the boundary conditions (9) , it is reduced to a system of first order differential equations by defining new variables. The numerical solution of BVP is obtained by using MATLAB BVP solver bvp4c. The asymptotic boundary conditions at $\eta \to \infty$ are replaced by those at a large but finite value of η as a standard practice in the boundary layer analysis, where no considerable variation in velocity, temperature etc. occur .The numerical procedure is repeated until we obtain the results up to the desired accuracy 10^{-6} in all cases.

4. Entropy Generation

The irreversible aspect of the Second law of thermodynamics for the convection flow through porous medium has been studied in this section. The convection process is inherently irreversible. Following Bejan[6] the dimensionless form of entropy generation for viscous fluid flow through porous medium is given as follows:

$$NS = \left[\frac{1}{X^2}\theta^2(\eta) + \theta'^2(\eta) \right] + \frac{Br}{\Omega}\left[\phi\, f''^2(\eta) + \frac{1}{K} f'^2(\eta) \right] \tag{11}$$

where, $X = x\sqrt{\frac{a}{\upsilon(1-ct)}}$,the non-dimensional axial length; T', a reference temperature.; $\Delta T = T_\omega - T_\infty$; $\Omega = \frac{\Delta T}{T'}$, the dimensionless temperature difference; and $Br = \frac{\mu U_\omega^{\ 2}}{k\Delta T}$, the Brinkman number.

Bejan number (Be) is defined as the ratio of the entropy generation due to heat transfer to the total entropy generation (NS).

5. Discussion

The unsteady boundary layer flow through a porous medium adjacent to a vertical stretching sheet with heat transfer has been investigated with velocity and temperature partial slip boundary conditions. In this study, entropy generation analysis have also been conducted and discussed. In figures 1-3, the variation of axial velocity $f'(\eta)$ with η has been plotted for different values of the physical parameters such as, the permeability parameter K, the mixed convection parameter λ, and the partial velocity slip parameter α_1. As expected, an increase in the permeability of the porous medium enhances the flow in the boundary layer since as permeability parameter K increases, the Darcy’s resistance force decreases hence flow increases. Further, it is clear that the velocity component $f'(\eta)$ increases with the increase in the value of the mixed convection parameter λ, since in the case of assisting flow $(\lambda > 0)$, the buoyancy force behaves as favourable pressure gradient to the flow. However, for the opposing flow $(\lambda < 0)$, the buoyancy force reduces the flow in the boundary layer. It is noted that, the velocity slip parameter α_1, causes a decrease in the flow for all values of η in the boundary layer. Figures 4-6, illustrate the temperature distribution $\theta(\eta)$ with η for various values of pertinent parameters. It is clear that temperature $\theta(\eta)$ decreases with an increase in the value of Prandtl number Pr, at all values of η, and therefore the thermal boundary layer thickness decreases. It is observed that with the increase in the value of positive convection parameter λ the fluid temperature decreases, while reverse effect is observed for negative convection parameter λ .It is found that the temperature rises in the flow domain with the increase in the value of the parameter α_1, however a reverse effect is seen by increasing the value of the parameter α_2.

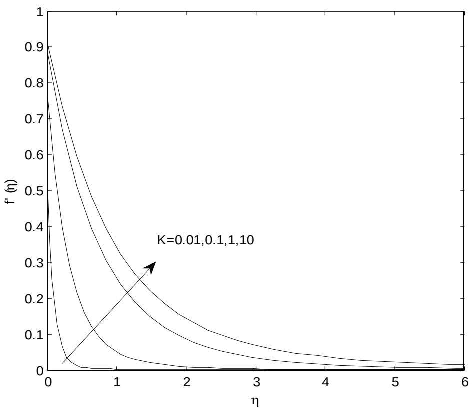

Fig1. Velocity profiles $f'(\eta)$ versus η
for $\mathbf{A = 1, \lambda = 1, Pr = 1, \varphi = 1.25, \alpha_1 = \alpha_2 = 0.1}$

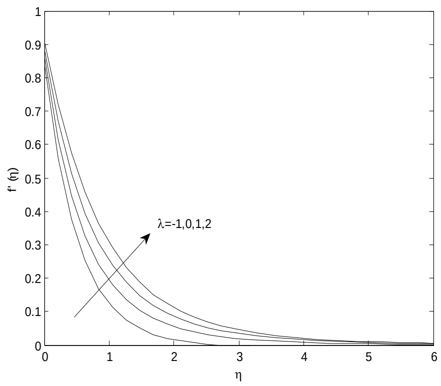

Fig2. Velocity profiles $f'(\eta)$ versus η
for $\mathbf{A = 1, K = 1, Pr = 1, \varphi = 1.25, \alpha_1 = \alpha_2 = 0.1}$

Table 1 illustrates the variation of the non-dimensional rate of heat transfer $-\theta'(0)$ at the stretching sheet for various values of the pertinent parameters. It is observed that the effect of slip parameters α_1 or α_2, is to reduce the rate of heat transfer from the sheet to the fluid in porous medium. However the parameters $\Pr$, A, K or ϕ causes an increase in the rate of heat transfer at the stretching sheet . Further it is noticed that the effect of the positive mixed convection parameter λ is to increase the rate of heat transfer at the sheet while negative mixed convection parameter causes reverse effect at the sheet. For some particular values of the parameters, the result of the present study are also compared with those of Grubka and Bobba[18], Ali[8], Ishak et al.[20], shown in the table, to verify the accuracy of the present numerical approach. It found that our results are in excellent agreement with those reported by other researchers.

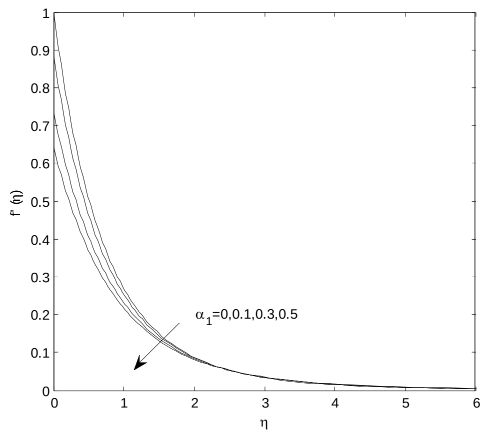

Fig3. Velocity profiles $f'(\eta)$ versus η

for $K=1, \lambda=1, \Pr=1, \varphi=1.25,\ A=1,\ \alpha_2=0.1$

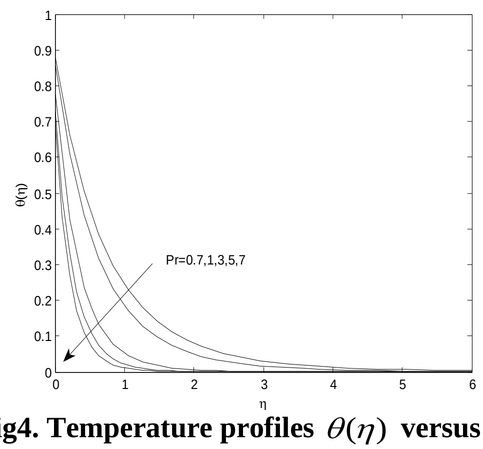

Fig4. Temperature profiles $\theta(\eta)$ versus η

for $A=1, K=1, \lambda=1, \varphi=1.25,\ \alpha_1=\alpha_2=0.1$

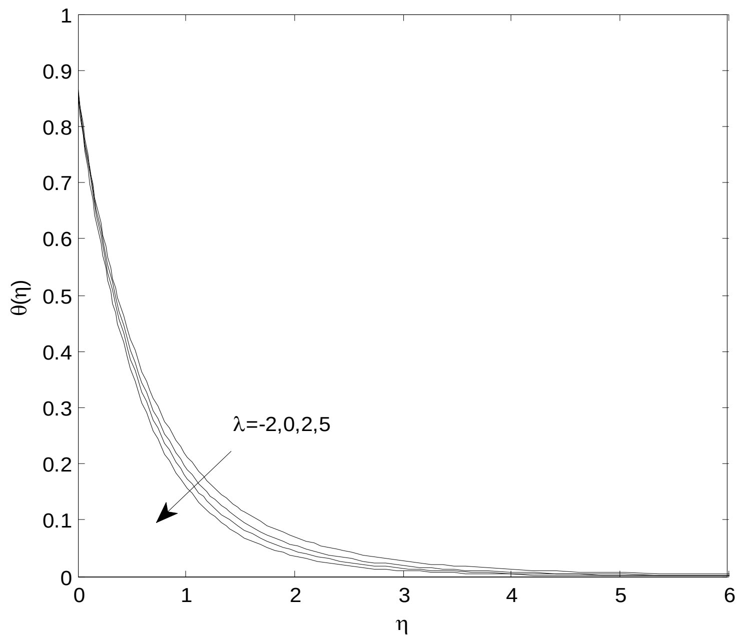

Fig5. Temperature profiles $\theta(\eta)$ versus η
for $\mathbf{A=1, K=1, Pr=1, \lambda=1, \varphi=1.25}$ $\boldsymbol{\alpha_1=\alpha_2=0.1}$

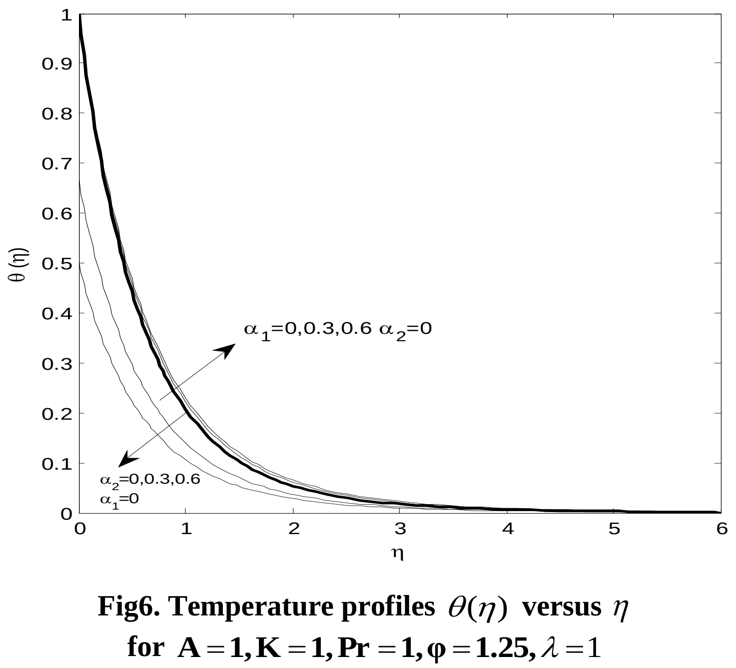

Fig6. Temperature profiles $\theta(\eta)$ versus η
for $\mathbf{A=1, K=1, Pr=1, \varphi=1.25,} \lambda=1$

Table 1: Variations of $-\theta'(0)$, and comparison with results of existing studies for $\alpha_1 = \alpha_2 = 0, \quad K \to \infty, \quad \varphi = 1$

A	λ	Pr	Grubka and Bobba (1985)	Ali(1994)	Ishak et al. (2009)	Present Study					
						$K \to \infty, \phi = 1$	$K = 0.1, \phi = 1.25$			$K = 1, \phi = 1.25$	$K = 1, \phi = 2$
						$\alpha_1 = 0$ $\alpha_2 = 0$	$\alpha_1 = 0.1$ $\alpha_2 = 0.1$	$\alpha_1 = 0.1$ $\alpha_2 = 0.3$	$\alpha_1 = 0.3$ $\alpha_2 = 0.1$	$\alpha_1 = 0.1$ $\alpha_2 = 0.1$	$\alpha_1 = 0.1$ $\alpha_2 = 0.1$
0	0	0.72	0.8086	0.8058	0.8086	0.8087	0.3523	0.3291	0.271	0.6459	0.7114
0	0	1	1	0.9961	1	1	0.4548	0.4169	0.3443	0.7993	0.8662
0	0	3	1.9237	1.9144	1.9237	1.9236	1.0497	0.8676	0.8093	1.4829	1.547
0	0	10	3.7207	3.7006	3.7206	3.7206	2.1503	1.5037	1.7741	2.5593	2.6174
0	1	1			1.0873	1.0873	0.5648	0.5011	0.4848	0.8875	0.9205
0	2	1			1.1423	1.1423	0.6291	0.5491	0.5624	0.9414	0.9594
0	3	1			1.1853	1.1853	0.6775	0.5844	0.6202	0.9827	0.9908
1	0	1			1.682	1.682	1.3222	1.0457	1.2768	1.4011	1.4216
1	1	1			1.7039	1.7039	1.3311	1.0501	1.2887	1.4169	1.433
1	-0.5	10			5.5585	5.5584	3.3675	2.0127	3.2381	3.4997	3.5252
1	0.5	10			5.569	5.5689	3.3732	2.0139	3.2481	3.5055	3.529

In thermal-flow systems entropy production is associated with thermo-dynamic irreversibility, which is common to every type of heat transfer process; therefore, the efficiency of such type of systems can be improved by minimizing it. In this study, we have investigated the effects of various physical parameters on the entropy generation number and NS and the Bejan number Be. In figure 7, the total entropy generation NS is plotted against η for different values of the Brinkman number Br .It is seen that NS increases with the increase in the value of Br for a given η. In fact, Br determines the relative importance of the viscous dissipation effect and the viscous fluid friction increases with the increase in Br value hence NS increases by it. It is also found that the effect of the viscosity ratio parameter ϕ is to increase the entropy generation number NS. However, figures 8 and 9 show that the effect of the unsteadiness parameter A, or the permeability parameter K, or the velocity slip parameter α_1, or the temperature slip parameter α_2 is to reduce the entropy generation number NS .

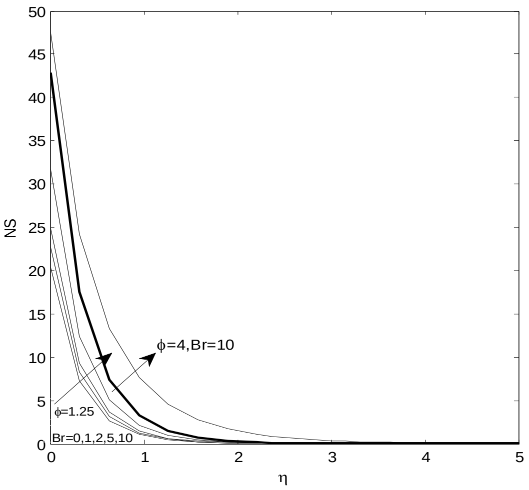

Fig 7. NS **vs** η **for**
$\mathbf{A = 1, K = 1 Pr = 1, \lambda = 1,}$
$\mathbf{X = 0.2, \Omega = 1, \alpha_1 = \alpha_2 = 0.1}$

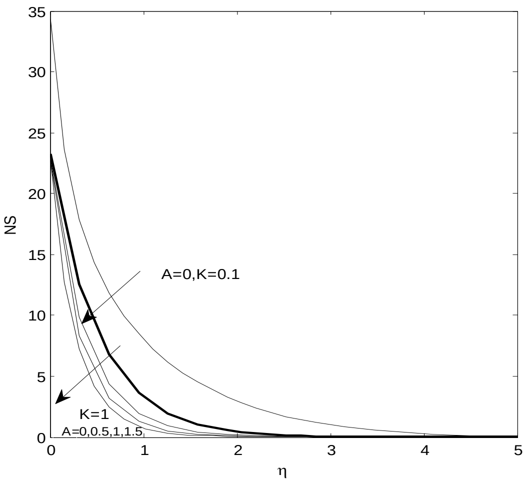

Fig8. NS vs $\boldsymbol{\eta}$ **for**
$\mathbf{A = 1, Br = 1, K = 1,}$
$\mathbf{\varphi = 1.25, Pr = 1, \lambda = 1, X = 0.2, \Omega = 1}$

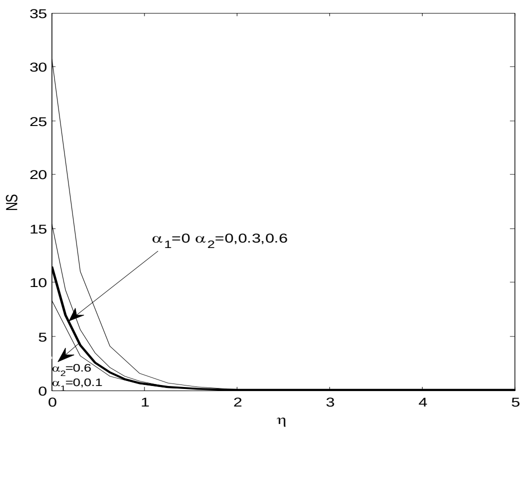

Fig 9. NS vs η **for**
$\mathbf{A = 1, Br = 1, K = 1, \varphi = 1.25,}$
$\mathbf{Pr = 1, \lambda = 1, X = 0.2, \Omega = 1}$

Bejan number is the ratio of the entropy generation due to heat transfer to the total generation, so its range is $0 \le Be \le 1$. $Be > 0.5$ Indicates that the irreversibility due to heat transfer dominates, with $Be = 1$ as the limit at which the irreversibility is solely due to heat transfer. On the other hand when Be is near zero, means fluid friction irreversibility dominates. Figures10-13, illustrate variation of Bejan number with η for various parameters. It is noticed that Bejan number Be decreases significantly with the increase of Brinkman number Br .Since the effect of Br is to increase the viscous dissipation, hence Be which is the ratio of NS_1 to NS , decreases. Its value is maximum, i.e.1, when $Br = 0$ because in that case the contribution of fluid friction irreversibility is zero. The effect of unsteadiness parameter A, the viscosity ratio parameter ϕ, or the temperature slip parameter α_2, is also to reduce the Bejan number Be. However, the velocity slip parameter α_1 causes an increase in the Bejan number Be .

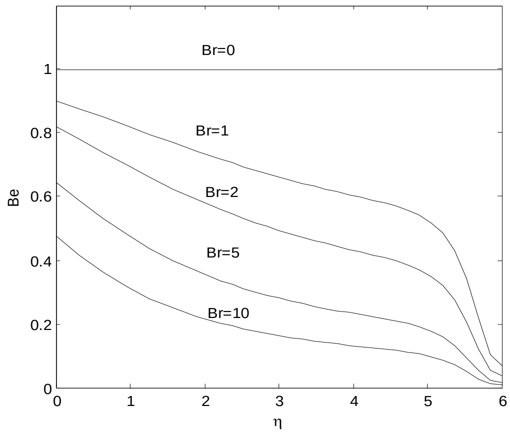

Fig 10. Be **vs** η **for** $\mathbf{A = 1, \varphi = 1.25, \lambda = 1, K = 1,}$ $\mathbf{Pr = 1, X = 0.2, \Omega = 1, \alpha_1 = \alpha_2 = 0.1}$

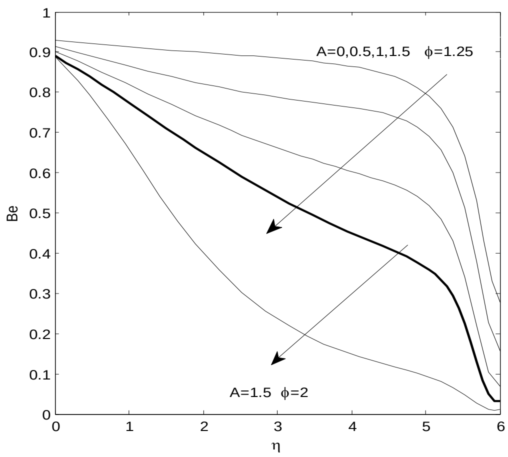

Fig 11. Be **vs** η **for** $\mathbf{Br = 1, \lambda = 1, K = 1,}$ $\mathbf{Pr = 1, X = 0.2, \Omega = 1, \alpha_1 = \alpha_2 = 0.1}$

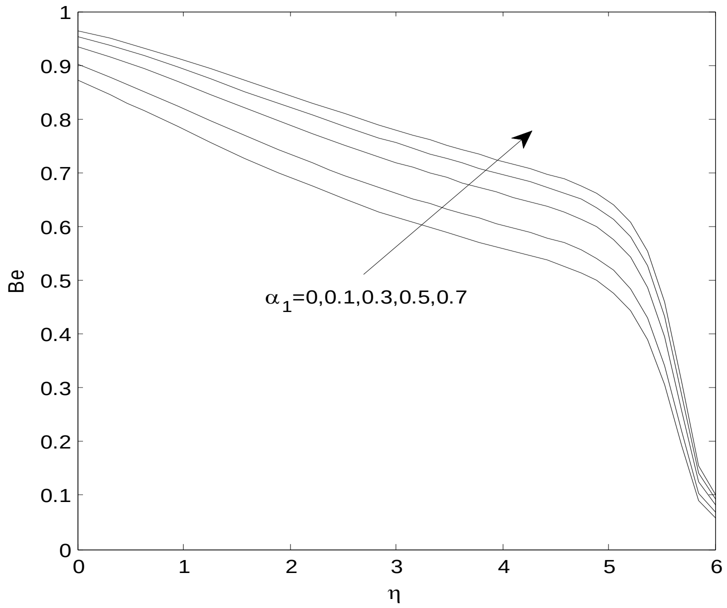

Fig 12. Be **vs** η **for** $\mathbf{A = 1, Br = 1, Pr = 1,}$
$\boldsymbol{\lambda = 1, K = 1, \varphi = 1.25, X = 0.2, \ \Omega = 1, \alpha_2 = 0.1}$

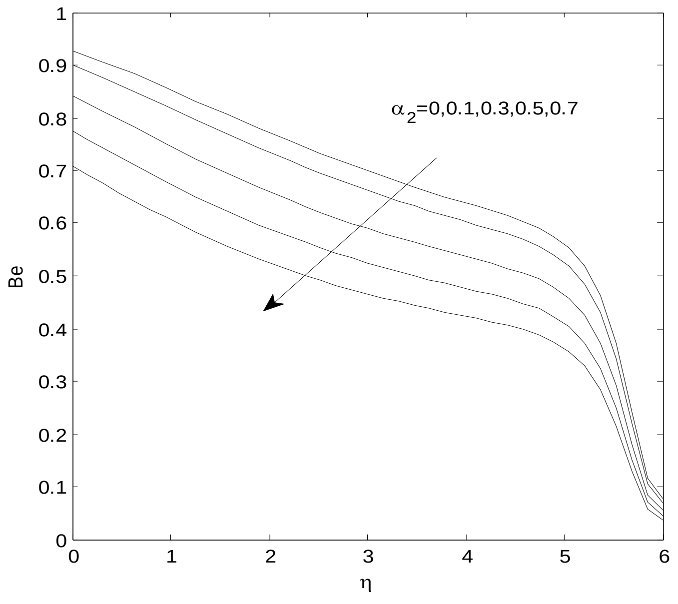

Fig13. Be **vs** η **for** $\mathbf{A = 1, Br = 1, Pr = 1,}$
$\boldsymbol{\lambda = 1, \ K = 1, \varphi = 1.25, X = 0.2, \ \Omega = 1, \alpha_1 = 0.1}$

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