THE EFFECT OF THERMAL STRATIFICATION WITH VARIABLE VISCOSITY AND THERMAL CONDUCTIVITY ON FREE CONVECTION FLOW ALONG A VERTICAL PLATE WITH HEAT SINK

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Abstract: The aim of this paper is to investigate the effect of thermal stratification with linearly varying viscosity and thermal conductivity on steady free convective flow of a viscous incompressible fluid along a non isothermal vertical plate in the presence of heat sink. The governing equations of continuity, momentum and energy are transformed into non linear ordinary differential equations using similarity transformations and then solved by using Runge –Kutta- Gill method along with shooting technique.

Keywords: Thermal Stratification, Variable Viscosity, Heat Sink, Thermal Conductivity, Power Law Index.

Introduction: The study of natural convection process in the presence of heat source / sink is important to engineering applications such as nuclear energy, heat exchanges, petroleum reservoir etc. Cheng and Minkowiycz and Nakayama and Koyama have discussed the flow of heat characteristic of Newtonian fluids over bodies of different geometries embedded in saturated porous medium. Carey and Mollendorfhave analyzed the effect of temperature dependent viscosity on free convective fluid flow. Horne and Sullivan have studied the effect of temperature dependent viscosity and thermal expansion coefficient. Lai and Kulachi have analyzed the effect of variable viscosity on convective heat transfer. Creapeau and Clarksean obtained the similarity solutions of natural heat generation which decays exponentially. Chaim analyzed the heat transfer in fluid flow of low Prandtl number with variable thermal conductivity. Anwar Hossain, Khalil khanafer and KambizVafai have studied the effect of radiation on free convection flow of fluid with variable viscosity. Chamkha and Khaled obtained the similarity solution for hydro magnetic simultaneous heat and mass transfer by natural convection from an inclined plate with internal heat generation or absorption. Seddeck and Salem discussed the effect of variable viscosity and thermal diffusivity. Nakayama and Koyama analyzed the effect of thermal stratification on free convection within a porous medium and discussed the similarity solutions for buoyancy induced flows over non isothermal curved surfaces in a thermally stratified porous medium. Recently Mahanti and Pramod Gaur discussed the effects of varying viscosity and thermal conductivity on steady free convective flow and heat transfer along an isothermal vertical plate in the presence of heat sink. Very recently the authors analyzed the effect of thermal stratification on convective heat transfer past a vertical plate with an applied magnetic field. The present study is devoted to the study of free convection flow and heat transfer along a non isothermal vertical plate in the presence of heat sink together with thermal stratification effect with varying viscosity and thermal conductivity. Hence, the aim of the paper is to investigate the effects of thermal stratification parameter M, the power law index of the surface temperature λ together with the Prandtl number Pr, heat sink term S, thermal conductivity ε and viscosity parameter γ. Numerical values of skin friction, heat transfer rate, Nusselt number, viscous and thermal boundary layer thickness are also obtained for different parameters.

Mathematical Analysis: The free convection flow of viscous incompressible fluid along a non isothermal vertical plate with variable viscosity, thermal conductivity in the presence of heat sink Q together with thermal stratification effect is considered. The x- axis is taken along the plate and y- axis is normal to the plate. Using the Boussinesq approximation and boundary layer approximation, the governing equations of continuity, momentum and energy are given by

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\frac{1}{\rho}\frac{\partial}{\partial y}(\mu^{*}\frac{\partial u}{\partial y})+g\beta(T-T_{\infty}) \quad (2)$$

$$\rho C_{p}(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y})=\frac{\partial}{\partial y}(k^{*}\frac{\partial T}{\partial y})+Q \quad (3)$$

$$T=T_{\infty}(x)=(1-M)T_{0}+MT_{w}(x) \quad (4)$$

together with the boundary conditions

$$y=0,u=0,v=0,T=T_{w}=T_{\infty}+Ax^{\lambda} \quad (5)$$

$$y\to\infty,u=0,T=T_{\infty}(x) \quad (6)$$

the variable viscosity (Carey and Mollendorf (1978)), and thermal conductivity (Kay (1966), Seddeck and Salem (2005)) are considered to vary linearly with temperature as given below, respectively

$$\mu^{*}=\mu(1+\gamma(\theta-\frac{1}{2})) \quad (7)$$

$$k^{*}=k(1+\varepsilon\theta) \quad (8)$$

γ and ε are fluid characteristic and measure of the steepness of relation between the viscosity and thermal conductivity with temperature. Introducing the stream function ψ (x, y) such that

$$u=\frac{\partial\psi}{\partial y} \quad \& \quad v=-\frac{\partial\psi}{\partial x} \quad (9)$$

Where $\psi(x,y)=4\gamma f(\eta)(\frac{Gr}{4})^{\frac{1}{4}}$ (10)

and the similarity variable, $\eta=\frac{y}{x}(\frac{Gr}{4})^{\frac{1}{4}}$ (11)

Following Crepeau and Clarksean, the heat sink is taken as

$$Q=S\{k(\frac{T_{w}-T_{\infty}}{x^{2}})(\frac{Gr}{4})^{\frac{1}{2}}\} \quad (12)$$

where Gr is the Grashof number and S (<0) is heat sink parameter Substitution of these transformations (9 to 12) to equations (2) and (3) along with the equations (4), (7) and (8), the resulting non linear ordinary differential equations are

$$(1+\gamma(\theta-\frac{1}{2}))f'''+f''\theta'\gamma-2f'^{2}+3ff''+\theta=0 \quad (13)$$

$$\theta''(1+\varepsilon\theta)+\theta'^{2}\varepsilon-3\Pr\lambda f'(\theta+\frac{M}{1+M})+3\Pr f\theta'+S\theta=0 \quad (14)$$

together with boundary conditions

$$\eta=0,f=0,f'=0,\theta=1 \quad (15)$$

$$\eta\to\infty,f'=0,\theta=0 \quad (16)$$

Materials and Methods: ***Numerical Solution***: The set of nonlinear ordinary differential equations (13) and (14) with boundary conditions (15) and (16) have been solved by using Ruge – Kutta -Gill method along with shooting technique. The detail of this method is available in Butcher.

The skin friction coefficient at the plate is given by

$$C_{f}=2(1+\frac{\gamma}{2})(Gr)^{-\frac{1}{4}}f''(0) \quad (17)$$

The Nusselt number at the plate is given by

$$Nu_{x}=-(1+\varepsilon)\left(\frac{Gr}{4}\right)^{\frac{1}{4}}\theta'(0) \quad (18)$$

Result and Discussions: The numerical values of skin friction f''(0) and the heat transfer rate -θ'(0) for different values of Prandtl number (Pr), heat sink parameter(S),thermal conductivity parameter (ε), viscosity parameter (γ),thermal stratification parameter (M)and power law index parameter (λ) are given in the Tables 1 & 2 . From the Table 1 it is realized that the decrease in heat sink parameter S causes decrease in the skin friction and increase in the rate of heat transfer. With the increase in the value of thermal conductivity parameter ε causes increase in the skin friction while rate of heat transfer decreases for given values of M, λ, Pr, & γ. From Table 2 it is realized that the increase in the value of viscosity parameter γ causes both the skin friction and heat transfer rate decrease for given values of M, λ, Pr, S and ε. As λ increases, it is seen that the skin friction decreases and rate of heat transfer increases for different values of the parameters.

The viscous and thermal boundary layer thicknesses for different parameters are given in Tables 3 to 5 for different values of M and λ. From Table 3, it is realized that for M=0.25 &0.5 and for selected values of λ the viscous and thermal boundary layer thickness decreases with increase in Prandtl number for γ =0,ε=0,S=0. From Table 4 it is realized that the viscosity parameter γ has no influence on viscous and thermal boundary layer thickness for given values of Pr,S,ε,λ and M. From Table 5, it is realized that the increase in the value of thermal conductivity parameter ε causes increase in the viscous and thermal boundary layer thickness for given values of Pr,γ and λ. Also, it is realized that the decrease in the value of heat sink parameter S causes decrease in viscous and thermal boundary layer thickness for given values of Pr, γ and λ.

It is observed from Table 6 that the numerical values of $f''(0)$ and $\theta'(0)$ for ε=0.0, S=0,λ=0 M=0 and Pr =1.0 for different values of γ obtained in the present paper are in good agreement with those obtained by Hossain et.al (2001), Carey and Mollendorf (1978) and Mahanti&Pramod Gaur (2009).
It is observed from Table 7 that the numerical values of $\theta'(0)$ for γ=0,ε =0,S=0, λ =0 and M =0 for different values of Pr are in good agreement with those obtained by Chamkha et.al (2001), Crepeau and Clarksean (1997) and Mahanti&Pramod Gaur(2009).

The values of $f''(0)$ and $-\theta'(0)$ for different values of ε, γ ,S and Pr for M=0 and λ=0 are compared with those obtained by Mahanti&Pramod Gaur (2009).These results are not presented in order to conserve the space. In all the cases the results are found to be in good agreement.

The velocity and temperature profiles are presented in Figs.1 to10. Figure 1 represents increase in the value of Prandtl number Pr the velocity profile decreases considerably when $0.01 \leq Pr \leq 1$ in the presence of thermal stratification for a given values of M & λ. Figure 2 represents with the increase in the values of Pr the temperature profile decreases in the presence of thermal stratification for a given values of M and λ. From Figure 3 it is observed that the velocity decreases with decrease in the heat sink parameter S in the presence of thermal stratification for a given values of M and λ. From Figure 4 it is observed that the temperature decreases with decrease in the heat sink parameter S for given values of λ and M. From Figure 5 it is observed that the velocity increases with increase in the thermal conductivity parameter ε in the presence of thermal stratification for given values of M and λ. From Figure 6 it is realized that the temperature increases with increase in the thermal conductivity parameter ε in the presence of thermal stratification for given values of M and λ. From Figs. 7 and 8 it is observed that the viscosity variation effect due to temperature variation does not have much effect on both velocity and temperature profiles. From Figs.9 and 10 it is observed that the velocity and temperature decreases as there is an increase in M and λ for given values of Pr, γ, ε &S.

The effect of different parameters on heat transfer rate is presented in Figs.11 to 14.From Figure 11 it is observed that the heat transfer rate increases as Prandtl number Pr increases for given values of M and λ. From Figure 12 it is realized that that the heat transfer rate increases as heat sink parameter S decreases for given values of M and λ.From Figure 13 it is observed that the heat transfer rate decreases as the thermal conductivity parameter ε increases for given values of M and λ.From Figure 14 it is observed that the viscosity parameter γ has negligible effect on heat transfer rate for given values of M and λ.
Conclusion: Free flow with heat transfer in a porous medium over a vertical plate with varying viscosity, thermal conductivity, heat sink and thermal stratification effects are analyzed. The transformed nonlinear ordinary differential equations together with the boundary conditions are solved by Runge-Kutta-Gill method. The results are in very good agreement with Mahanti and Pramod Gaur when M=0 & λ= 0.

- The velocity, temperature, viscous and thermal boundary layer thickness decrease with the increase in Prandtl number in the presence and absence of thermal stratification.
- The velocity, temperature, viscous and thermal boundary layer thickness decrease with the decrease in heat sink parameter S in the presence and absence of thermal stratification.

- The velocity, temperature, viscous and thermal boundary layer thickness increase with the increase in thermal conductivity parameter ε in the presence and absence of thermal stratification.
- The viscosity variation does not have much effect on velocity, temperature, viscous and thermal boundary layer thickness in the presence and absence of thermal stratification.
- The skin – friction coefficient decreases and rate of heat transfer increases with increase in Prandtl number in the presence and absence of thermal stratification.
- The velocity, temperature and skin -friction coefficient decrease and rate of heat transfer increases as the thermal stratification parameter M and power law index parameter λ increases.

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Table 1: Values of f '' (0) and – θ ' (0) for Different Values of ε, S, λ when γ = 0, Pr = 0.023& M= 0.5 (With Thermal Stratification Effect and Power Law Effect)

Pr = 0.023, S = 0.0	γ = 0, ε = 0,		γ = 0, ε = 0.1,		γ = 0, ε = 0.3,	
Λ	f ''(0)	- θ '(0)	f ''(0)	- θ '(0)	f ''(0)	- θ '(0)
0.25	0.9214	0.1661	0.9301	0.1536	0.9435	0.1350
0.5	0.8975	0.2027	0.9071	0.1878	0.9221	0.1657
0.75	0.8781	0.2327	0.8884	0.2158	0.9046	0.1908
1.0	0.8616	0.2585	0.8725	0.2399	0.8898	0.2123
1.25	0.8473	0.2810	0.8588	0.2610	0.8769	0.2312
Pr = 0.023, S = - .1						
0.25	0.8177	0.3501	0.8305	0.3241	0.8507	0.2855
0.5	0.8076	0.3672	0.8207	0.3401	0.8415	0.2999
0.75	0.7983	0.3831	0.8117	0.3550	0.3329	0.3132
1.0	0.7896	0.3979	0.8033	0.3689	0.8250	0.3257
1.25	0.7876	0.4119	0.7954	0.3819	0.8175	0.3375
Pr =0.023, S= - 0.2						
0.25	0.7618	0.4690	0.7763	0.4342	0.7997	0.3824
0.5	0.7553	0.4808	0.7699	0.4453	0.7935	0.3924
0.75	0.7489	0.4921	0.7638	0.4558	0.7877	0.4019
1.0	0.7429	0.5628	0.7599	0.4659	0.7821	0.4110
1.25	0.7372	0.5132	0.7524	0.4756	0.7768	0.4198

Table 2: Values of f '' (0) and – θ ' (0) for Different Values of γ, λ when ε = 0, S = 0, Pr = 0.023 & M = 0.5 (With Thermal Stratification Effect and Power Law Effect)

Pr = 0.023, S = 0, ε = 0, M = 0.5	γ = - 0.4		γ = 0		γ = 0.4	
Λ	f ''(0)	- θ '(0)	f ''(0)	- θ '(0)	f ''(0)	- θ '(0)
0.25	1.07195	0.16784	0.92146	0.1661	0.8140	0.1647
0.5	1.05187	0.20513	0.89756	0.2027	0.7883	0.2006
0.75	1.03518	0.23592	0.87810	0.2328	0.7675	0.2300
1.0	1.02085	0.26236	0.86164	0.2585	0.7502	0.2550
1.25	1.00824	0.28569	0.84734	0.2811	0.7352	0.2770

Table 3: The values of Viscous & Thermal Boundary Layer Thickness for Different Values of λ, Pr when ε = 0, γ = 0, S = 0 for M = 0.25, & 0.50 (With Thermal Stratification Effect and Power Law Effect)

Λ	M = 0.25, γ = 0, ε = 0,Pr = 0.01,S = 0		M= 0.25, γ = 0,ε = 0, Pr = 0.023, S=0		M= 0.5, γ = 0, ε = 0, Pr = 0.01,S = 0		M= 0.5,γ = 0,ε = 0 Pr = 0.023,S = 0	
	η_m	η_T	η_m	η_T	η_m	η_T	η_m	η_T
0.25	28.875	33.875	17.8125	21.3125	27.125	32.5	18.5625	21.6875
0.5	28.1875	32.00	16.9375	21.00	24.6875	30.875	16.5625	19.0
0.75	27.4375	31.00	15.8125	20.9375	23.3125	26.4375	15.5	17.50
1.0	26.000	30.50	13.50	20.875	21.75	23.1875	14.5625	15.625
1.25	25.4375	28.6875	12.125	18.875	20.125	22.25	13.625	14.4375

Table 4: The values of Viscous & Thermal Boundary Layer Thickness for Different Values of λ, γ when S = 0, Pr = 0.023, ε = 0 for M = 0.25 (With Thermal Stratification Effect and Power Law Effect)

Pr = 0.023,S = 0, ε = 0,M = 0.25	γ = - 0.4		γ = 0		γ = 0.4	
Λ	η_m	η_T	η_m	η_T	η_m	η_T
0.25	19.4375	22.4375	19.50	22.50	19.5625	22.50
0.5	18.8750	21.5625	18.9375	21.5625	19.00	21.625
0.75	18.1875	20.6875	18.25	20.6875	18.3125	20.6875
1.0	17.5625	19.8125	17.625	19.8125	17.6875	19.8125
1.25	16.9375	19.00	17.00	19.00	17.00	19.00

Table 5: The Values of Viscous & Thermal Boundary Layer Thickness for Different Values of λ, ε , S when Pr = 0.023,γ = 0 for M = 0.5(With Thermal Stratification Effect and Power Law Effect)

Pr = 0.023, S = 0.0	γ = 0, ε = 0,		γ = 0, ε = 0.1,		γ = 0, ε = 0.3,	
Λ	η_m	η_T	η_m	η_T	η_m	η_T
0.25	18.5625	21.6875	19.3125	22.1875	21.00	24.25
0.5	16.5625	19.00	17.6875	20.0625	19.25	22.00
0.75	15.50	17.50	16.25	18.3125	17.75	20.125
1.0	14.5625	15.625	15.0625	16.875	16.50	18.625
1.25	13.625	14.4375	14.0625	15.6875	15.4375	17.3125
Pr =0.023, S= - 0.1						
0.25	10.875	12.0625	11.375	12.6875	12.375	13.9375
0.5	10.4375	11.5625	11.00	12.1875	11.9375	13.375
0.75	10.0625	11.0625	10.625	11.6875	11.5625	12.875
1.0	9.75	10.6875	10.25	11.3125	11.1875	12.4375
1.25	9.4375	10.3125	9.9375	10.875	10.8125	12.00
Pr =0.023, S= - 0.2						
0.25	8.5625	9.25	9.0625	9.50	9.75	10.75
0.5	8.3125	9.00	9.0000	9.1875	9.50	10.4375
0.75	8.125	8.75	8.3125	9.125	9.3125	10.1875
1.0	7.9375	8.5625	8.1875	9.00	9.125	9.9375
1.25	7.8125	8.3125	8.1250	8.5625	8.9375	9.7500

Table 6: Values of f "(0) and θ ' (0) for different values of γ when Pr =1.0, S = 0, ε = 0, λ = 0 and M= 0 are compared with the results obtained by Hossain et.al (2001), Carey &Mollendorf (1978) &N.C.Mahanti&Pramod Gaur (2009)

γ	Hossain et.al(2001)		Carey &Mollendorf(1978)		N.C.Mahanti&Pramod Gaur(2009)		Present paper	
	f"(0)	θ'(0)	f"(0)	θ'(0)	f"(0)	θ'(0)	f"(0)	θ '(0)
0.0	0.6421	-0.5671	0.6422	-0.5671	0.642187	-0.56714	0.642188	-0.56715
0.8	0.5050	-0.5469	0.5050	-0.5469	0.505014	-0.54694	0.467653	-0.53186
1.6	0.4222	-0.5281	0.4233	-0.5315	0.422341	-0.53153	0.372036	-0.50494
-1.6	2.0411	-0.6514	2.0416	-0.6514	2.041617	-0.65136	3.24605	-0.68396

Table 7: Values of θ ' (0) for Different Values of Pr when γ = 0, ε = 0,S = 0, λ = 0, & M= 0 are Compared with the Results Obtained by Chamkha et. al (2001), Crepeau&Clarksean (1997), &N.C.Mahanti&Pramod Gaur (2009)

Pr	Chamkha et al (2001)	Crepeau&Clarksean (1997)	N.C.Mahanti&Pramod Gaur (2009)	Present paper
	θ '(0)	θ '(0)	θ '(0)	θ '(0)
0.1	-0.2119	-0.2302	-0.230136	-0.23015
1.0	-0.5646	-0.5671	-0.567145	-0.567146
10	-1.1720	-1.169	-1.166270	-1.1693

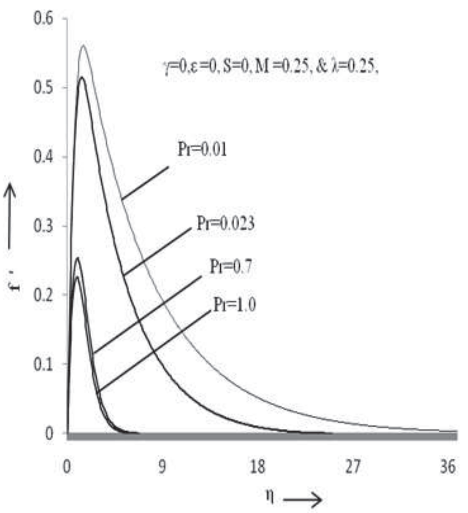

Fig. 1. Velocity Distribution Vs η for Selected Values of Pr

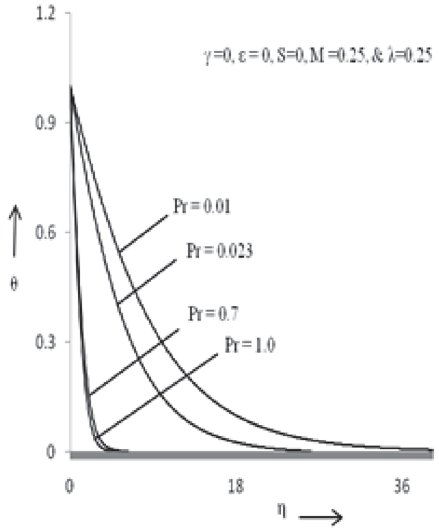

Fig.2. Temperature Distribution Vs η for Selected Values of Pr

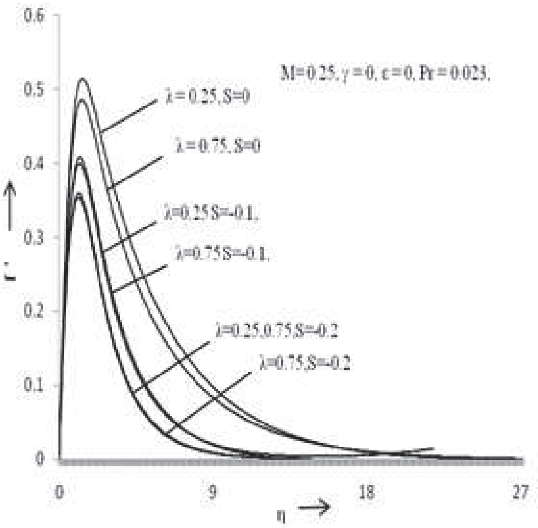

Fig.3. Velocity Distribution Vs η for Selected Values of λ & S

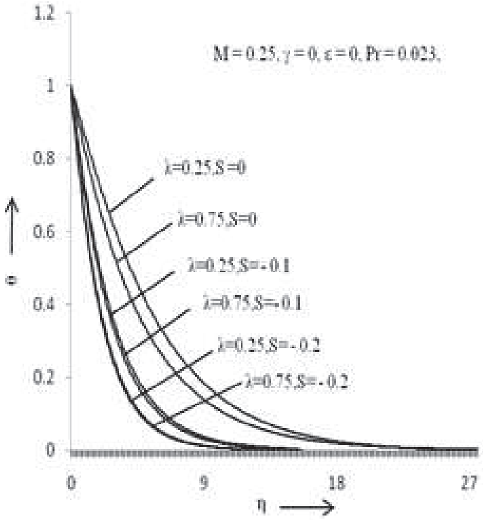

Fig.4 . Temperature Distribution Vs η for Selected Values of λ & S

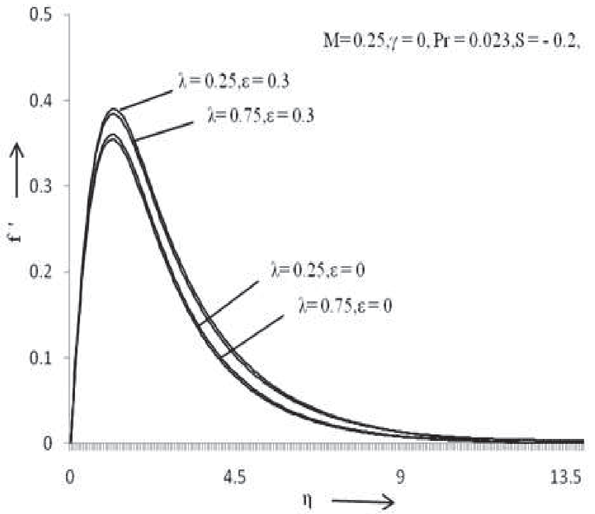

Fig.5 .Velocity Distribution Vs η for Selected Values of λ &ε

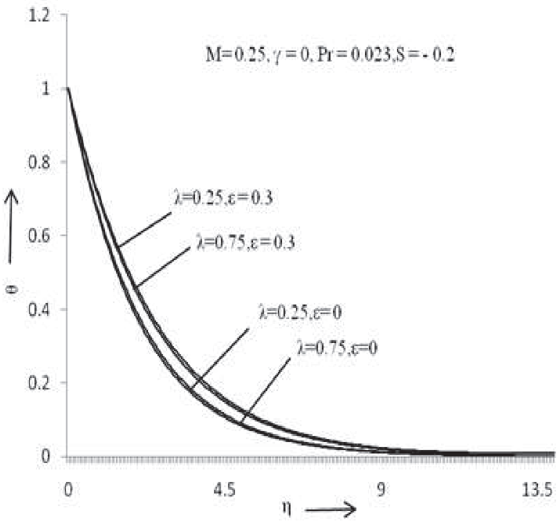

Fig.6.Temperature Distribution Vs η for Selected Values of λ&ε

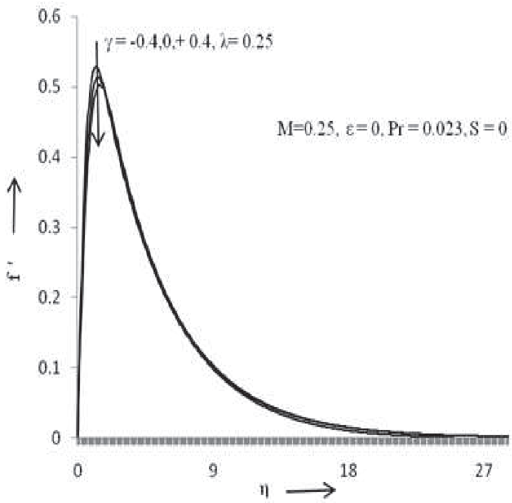

Fig. 7. Velocity Distribution Vs η for Selected Values of λ & γ

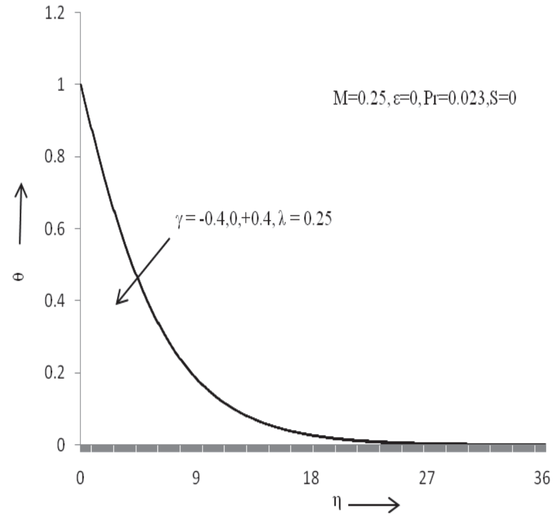

Fig.8.Temperature Distribution Vs η for Selected Values of λ& γ

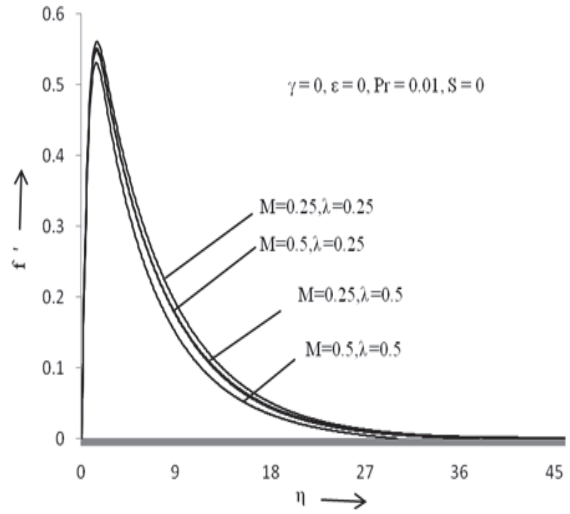

Fig. 9. Velocity Distribution Vs η for Selected Values of M& λ

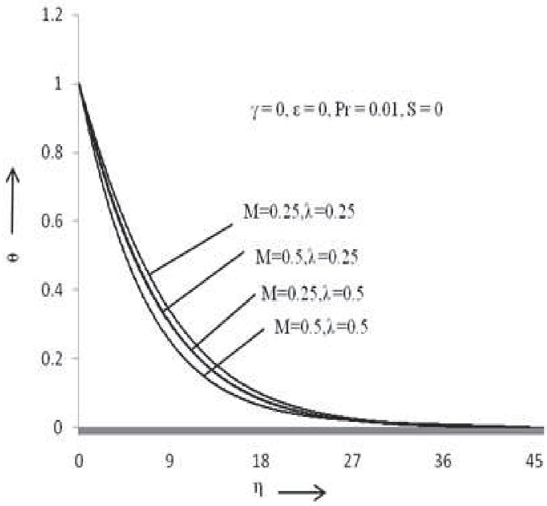

Fig. 10. Temperature Distribution Vs η for Selected Values of M& λ

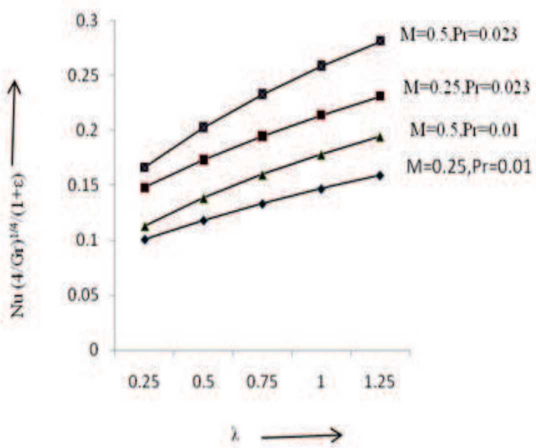

Fig. 11. Values of-θ'(0) Versus λ for Different Values of M&Pr when γ = 0, S = 0, ε = 0

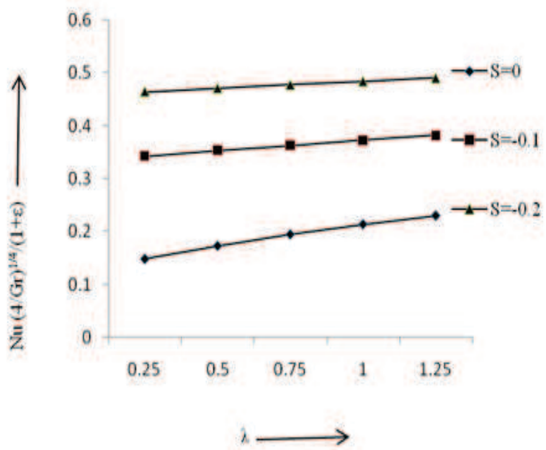

Fig. 12. Values of-θ'(0) Versus λ for Different Values of S when M = 0.25, Pr = 0.023, γ = 0, ε = 0

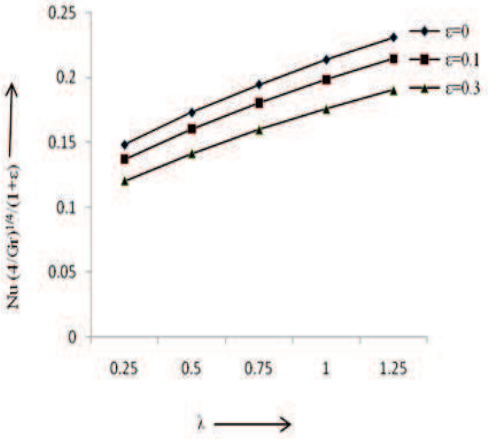

Fig. 13. Values of-θ'(o) Versus λ for Different Values of ε when Pr = 0.023, γ = 0, S = 0, M = 0.25

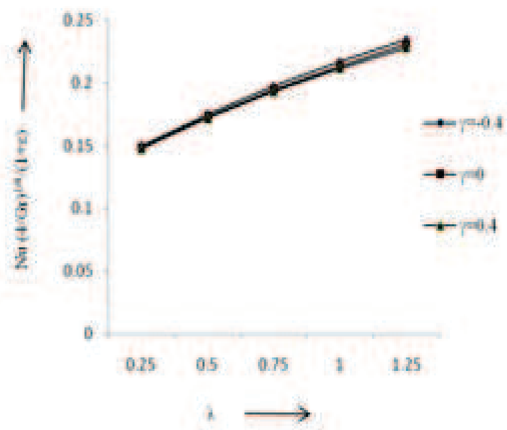

Fig. 14. Values of -θ'(0) Versus λ for γ when ε = 0, Pr = 0.023, S=0 = 0, M =25

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