MIXED CONVECTION SLIP FLOW WITH TEMPERATURE JUMP ALONG A MOVING PLATE IN PRESENCE OF FREE STREAM

by

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In this paper, we examine the mixed convection flow with slip and convective heat transfer along a continuously moving vertical plate in the presence of uniform free stream. The plate and free stream velocity being in the same direction. The governing equations of continuity, momentum and energy for this boundary layer flow are transformed into one set of coupled non-linear ordinary differential equations using the local similarity transformation and are then solved using the fourth-order Runge-Kutta method along with the shooting technique. The fluid flow and heat transfer distributions are discussed and presented graphically. Skin-friction and the Nusselt number at the plate surface are obtained for various values of the physical parameters and presented in tabular form and the physical aspects of these results are discussed.

Key words: *slip flow, temperature jump, convective heat transfer, moving plate, free stream*

Introduction

Recent years have seen rapid advancement in micro- and nanoscale technologies due to numerous applications. In present context, the study of laminar boundary layer flow and heat transfer at micro-level have various engineering applications *e. g.* polishing of internal civilities, heart valves, manufacturing process of micro-electronic mechanical systems, *etc*. At micro-scale level the fluid flow is dominated by fluid surface interaction and belongs to slip flows regime, whereas the momentum equation remains to be Navier-Stokes equation [1]. Therefore many boundary layer fluid flow problems have been revisited with slip boundary condition and different researchers have made significant contribution. To name a few that are particularly important for presented study, Wang [2] studied the influence of partial slip on stretching sheet. Andersson [3] presented exact solution for slip flow past a stretching surface. Ariel *et al.* [4] obtained exact analytical solution for the flow of elastico-viscous fluid along a stretching sheet with partial slip. Martin and Boyd [5] studied the momentum and heat transfer in boundary layer flow of the fluid along a stationary plate in uniform stream employing the Maxwell slip condition. Martin and Boyd [6] analyzed the stagnation point heat transfer with slip flow. Fang *et al.* [7] presented the exact solution of MHD slip flow over a stretching sheet in quiescent fluid. Zhu *et al.* [8] analyzed MHD slip flow about stagnation point over power law stretching sheet using homotopy analysis method. Cao and Baker [9] observed the effect of first order momentum and thermal discontinuities at isothermal vertical wall in mixed convection flow. Zhu *et al.* [10] studied axisymmetric slip stagnation point flow with temperature

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jump using Homotopy analysis method. Zhu *et al.* [11] analyzed the influence of thermal radiation on the stagnation point flow in the presence transverse magnetic field and internal heat generation. Here, we would like to mention the work of Chen [12, 13] who studied the boundary layer flow and heat transfer characteristic on uniformly moving horizontal surface in the presence of uniform free stream, both in the same direction, with no-slip boundary condition. The work of [12] and [13] can be revisited with slip flow and temperature jump boundary condition on a vertical plate. Makinde [14] reported a similarity solution for the hydromagnetic heat and mass transfer over a vertical plate with a convective surface boundary condition. Makinde and Olanrewaju [15] studied the effect of thermal buoyancy on the laminar boundary layer flow about a vertical plate in a uniform stream of fluid under a convective surface boundary condition. Their result revealed that the thermal boundary layer thickness along the plate tends to decrease with increasing buoyancy effect.

Hence, this paper aims at investigating the viscous flow and heat transfer characteristics, with slip and temperature jump boundary conditions [10], of mixed convection flow along a continuously moving vertical plate in the presence of uniform free stream. The plate and free stream velocity being in the same direction. The governing equations of continuity, momentum and energy for this boundary-layer flow are transformed into one set of non-linear ordinary differential equations [16], unlike [12] and [13] who utilized two boundary conditions, using the local similarity transformation.

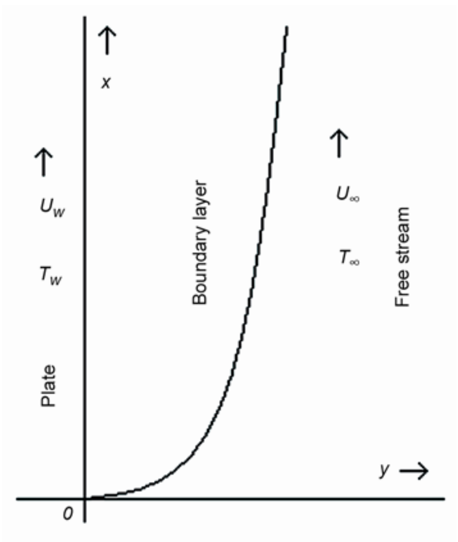

Figure 1. Diagram of flow

Formulation of the problem

Consider a continuous vertical plate at a temperature T_w with uniform velocity U_w in the presence of uniform free stream with velocity U_∞ and temperature T_∞, both in same direction. The x-axis is taken along the plate and the y-axis is taken perpendicular to the plate, as is shown in fig. 1. The fluid experiences the slip and temperature jump at the plate surface.

The governing boundary-layer equations of continuity, momentum, and energy [7-9], [12, 13] are given as:

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

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=\nu\frac{\partial^2 u}{\partial y^2}+g\gamma(T-T_\infty) \tag{2}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\kappa\frac{\partial^2 T}{\partial y^2} \tag{3}$$

Following [10], the boundary conditions for this problem are:

$$y=0:\ u=U_w+\frac{2-\sigma_v}{\sigma_v}\lambda_o\frac{\partial u}{\partial y},\quad v=0,\quad T=T_w+S_o\frac{\partial T}{\partial y};\quad y\to\infty: u=U_\infty,\quad T=T_\infty \tag{4}$$

where λ_o is the mean free path, σ_v – the tangential momentum coefficient, and S_o – the temperature jump coefficient.

Method of solution

Here we introduce the stream function $\psi(x, y)$ such that:

$$u = \frac{\partial \psi}{\partial y} \text{ and } v = -\frac{\partial \psi}{\partial x} \tag{5}$$

where $\psi = \nu\sqrt{\mathrm{Re}}f(\eta)$, and $\eta = y/x\sqrt{\mathrm{Re}}$ is the similarity variable.

It is observed that eq. (1) is identically satisfied by $\psi(x, y)$. Substituting eq. (5) into eqs. (2) and (3), the resulting non-linear coupled ordinary differential equations are:

$$f''' + \frac{1}{2}ff'' + \mathrm{Gr}\theta = 0, \tag{6}$$

and

$$\theta'' + \frac{1}{2}\mathrm{Pr}\, f\,\theta' = 0 \tag{7}$$

The corresponding boundary conditions become:

$$f(0)=0, \quad f'(0) = \left(\frac{U_w}{U_r}\right) + \lambda f''(0), \quad \theta(0) = 1 + \beta\theta'(0), \quad f'(\infty) = \left(\frac{U_\infty}{U_r}\right), \quad \theta(\infty) = 0 \tag{8}$$

where U_r is a reference velocity which is generally taken as:

$$U_r = \begin{cases} U_w & \text{if } U_w > U_\infty \\ U_\infty & \text{if } U_w < U_\infty \end{cases} \tag{9}$$

which leads to formation of two sets of boundary conditions:

$$f(0)=0, \quad f'(0) = 1 + \lambda f''(0), \quad \theta(0) = 1 + \beta\theta'(0), \quad f'(\infty) = \left(\frac{U_\infty}{U_w}\right), \quad \theta(\infty) = 0 \text{ for } U_w > U_\infty \tag{10}$$

and

$$f(0)=0, \quad f'(0) = \left(\frac{U_w}{U_\infty}\right) + \lambda f''(0), \quad \theta(0) = 1 + \beta\theta'(0), \quad f'(\infty) = 1, \quad \theta(\infty) = 0 \text{ for } U_w < U_\infty \tag{11}$$

Following [16], in the present work, U_r is taken as:

$$U_r = U_w + U_\infty \tag{12}$$

which forms one set of boundary conditions:

$$f(0) = 0, \quad f'(0) = (1-\varepsilon) + \lambda f''(0), \quad \theta(0) = 1 + \beta\theta'(0), \quad f'(\infty) = \varepsilon, \quad \theta(\infty) = 0 \tag{13}$$

where $\varepsilon = U_\infty/(U_w + U_\infty) = U_\infty/U_r$ is the velocity parameter.

It should be noted that when the plate velocity and the free stream velocity are in the same direction, this corresponds to $0 < \varepsilon < 1$. In particular, when $0 < \varepsilon < 0.5$ the plate velocity is higher than the free stream velocity, at $\varepsilon = 0.5$, the plate velocity equals to the free stream velocity and when $0.5 < \varepsilon < 1$, the plate velocity is less than the free stream velocity. The governing boundary-layer eqs. (6) and (7) with the boundary conditions (13) are solved numerically using the fourth-order Runge-Kutta technique along with shooting technique [17].

From the process of numerical computation, the expressions for the skin-friction coefficient C_f and the Nusselt number are:

$$C_f = \frac{1}{2(\mathrm{Re})} f''(0), \quad \mathrm{Nu} = -\sqrt{\mathrm{Re}}\,\theta'(0) \tag{14}$$

Results and discussion

We performed the numerical calculations for different values of the thermophysical parameters controlling the fluid dynamics in the flow regime using the fourth-order Runge-Kutta method along with the shooting technique. Table 1 shows the comparison of Makinde and Olanrewaju [15] work with the present work for the case of Prandtl number Pr = 0.72, stationary plate (ε = 1) and no velocity slip at the plate surface (λ = 0). It is noteworthy that there is a perfect agreement. This serves as a numerical validation and benchmark for the accuracy of our present results. It is seen from tab. 2 that with the increase in velocity parameter ε, skin friction at the plate, measure of drag, $f''(0)$, increases while the fluid velocity at the plate, $f'(0)$, decreases. The rate of heat transfer, $-\theta'(0)$, at the plate decreases and plate temperature, $\theta(0)$, increases. Table 3 has two sets of data, ε = 0.1 when plate velocity is higher than free stream velocity and ε = 0.8 when free stream velocity is higher than plate velocity, to suitably represent the flow phenomena. It is seen from tab. 3 that with the increase in velocity slip parameter λ, the skin friction decreases, fluid velocity at plate surface increases, the rate of heat transfer increases and plate temperature decrease for ε = 0.1 and 0.8. It is interesting to note that for ε = 0.1 and 0.8 the fluid velocity at plate is higher than plate velocity, due to slip. Table 3 shows that with the increase in temperature jump parameter β, the skin friction, fluid velocity at plate, rate of heat transfer and plate temperature decrease for ε = 0.1 and 0.8. Further, with the increase in buoyancy parameter, Gr, the skin-friction, fluid velocity and the rate of heat transfer increases while the plate temperature decreases for ε = 0.1 and 0.8. The increase in Prandtl number results in decrease of skin-friction, fluid velocity at plate and plate temperature while the rate of heat transfer at plate increases for ε = 0.1 and 0.8.

Table 1. Computations showing comparison with Makinde and Olanrewaju [5] results

	Gr = 0.1, ε = 1, Pr = 0.72, λ = 0					
	$f''(0)$ [5]	$-\theta'(0)$ [5]	$\theta(0)$ [5]	$f''(0)$ Present	$-\theta'(0)$ Present	$\theta(0)$ Present
β = 10	0.36881	0.07507	0.24922	0.36881	0.07507	0.24922
β = 1	0.44036	0.23750	0.76249	0.44036	0.23750	0.76249
β = 0.1	0.46792	0.30559	0.96944	0.46792	0.30559	0.96944

Table 2. Numerical values of $f''(0)$, $f'(0)$, $-\theta'(0)$, and $\theta(0)$ for different values of ε

	Gr = 2.0, Pr = 0.71, λ = 0.1, β = 0.1			
	$f''(0)$	$f'(0)$	$-\theta'(0)$	$\theta(0)$
ε = 0.1	1.097835	1.009783	0.482571	0.951742
ε = 0.2	1.202531	0.920253	0.479690	0.952030
ε = 0.3	1.306593	0.830659	0.476751	0.952324
ε = 0.6	1.612940	0.561294	0.467403	0.953259
ε = 0.7	1.712566	0.471256	0.464069	0.953593
ε = 0.8	1.810711	0.381071	0.460610	0.953938

Table 3. Numerical values of $f''(0)$, $f'(0)$, $-\theta'(0)$, and $\theta(0)$ for different values parameters

	ε = 0.1				ε = 0.8			
	$f''(0)$	$f'(0)$	$-\theta'(0)$	$\theta(0)$	$f''(0)$	$f'(0)$	$-\theta'(0)$	$\theta(0)$
	Gr = 2.0, Pr = 0.71, β = 0.1				Gr = 2.0, Pr = 0.71, β = 0.1			
λ = 0.1	1.097835	1.009783	0.482571	0.951742	1.810711	0.381071	0.460610	0.953938
λ = 0.5	0.813255	1.306627	0.507795	0.949220	1.404449	0.902224	0.509250	0.949074
λ = 1.0	0.609283	1.509283	0.524555	0.947544	1.077142	1.277142	0.542212	0.945787
λ = 2.0	0.403327	1.706655	0.540537	0.945946	0.724738	1.649476	0.573201	0.942679
λ = 5.0	0.199193	1.895967	0.555562	0.944443	0.361476	2.007380	0.601743	0.939825
	Gr = 2.0, Pr = 0.71, λ = 0.1				Gr = 2.0, Pr = 0.71, λ = 0.1			
β = 0.1	1.097838	1.009783	0.482571	0.951742	1.810711	0.381071	0.460610	0.953938
β = 0.5	0.910997	0.991099	0.395317	0.802341	1.615262	0.361526	0.379523	0.810213
β = 1.0	0.746974	0.974697	0.323991	0.676008	1.441184	0.344118	0.312679	0.687320
β = 2.0	0.535736	0.953573	0.239726	0.520546	1.213251	0.321325	0.232866	0.534266
	β = 0.1, Pr = 0.71, λ = 0.1				β = 0.1, Pr = 0.71, λ = 0.1			
Gr = 2	1.097835	1.009783	0.482571	0.951742	1.810711	0.381071	0.460610	0.953938
Gr = 4	2.155147	1.115514	0.543761	0.945623	2.948767	0.494876	0.524714	0.947528
Gr = 6	3.081855	1.208185	0.586627	0.941337	3.932705	0.593270	0.569380	0.943061
	Gr = 2.0, β = 0.1, λ = 0.1				Gr = 2.0, β = 0.1, λ = 0.1			
Pr = 0.71	1.097835	1.009783	0.482571	0.951742	1.810711	0.381071	0.460610	0.953938
Pr = 5	0.381231	0.938123	1.088804	0.891119	1.156496	0.315649	0.887708	0.912291
Pr = 10	0.191205	0.919120	1.447943	0.855205	0.966183	0.296618	1.112367	0.888763

It is seen in fig. 2 that when plate velocity is higher than free stream velocity ($0 < \varepsilon < 0.5$), the velocity profile attains its maximum nearer to the plate with respect to when plate velocity is less than free stream velocity ($0.5 < \varepsilon < 1.0$) (shown with the help of dotted line). Also boundary layer is thicker when plate velocity is higher than free stream velocity. It is also seen, that with the decrease in parameter ε the fluid velocity decreases. Figure 3 shows that with the increase parameter ε the fluid temperature decreases however the decrease is not

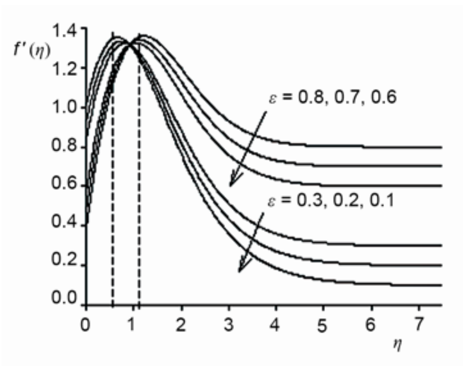

Figure 2. Velocity distribution *vs.* η when Gr = 2.0, Pr = 0.71, λ = 0.1, and β = 0.1

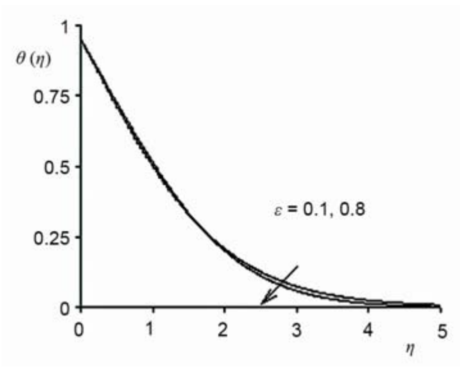

Figure 3. Temperature distribution *vs.* η when Gr = 2.0, Pr = 0.71, λ = 0.1, and β = 0.1

substantial. Figures 4 and 5 show that for higher values of slip parameter λ, the fluid velocity at plate is higher *i. e*. skin friction observed is less (as is also seen in tab. 3). It is also seen that the point at which the maximum of velocity profile is attained is nearer to the plate for higher values of λ (shown with dotted line in fig. 4). Adding, once the maximum is achieved the dip in the profile is higher for higher values of λ. It is seen in figs. 6 and 7 that fluid temperature decreases with the increase in parameter λ. This happens because as λ increases fluid velocity

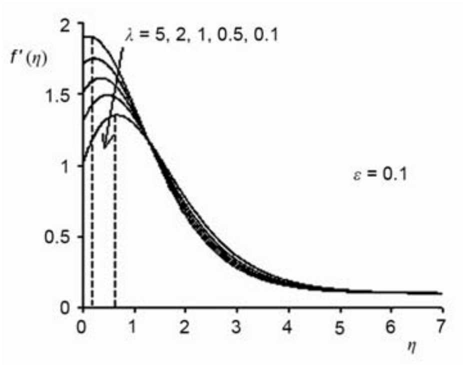

Figure 4. Velocity distribution *vs.* η when Gr = 2.0, Pr = 0.71, and β = 0.1

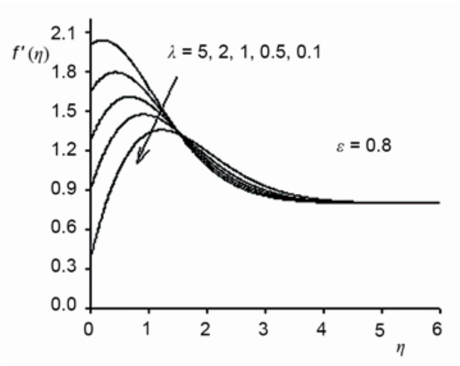

Figure 5. Velocity distribution *vs.* η when Gr = 2.0, Pr = 0.71, and β = 0.1

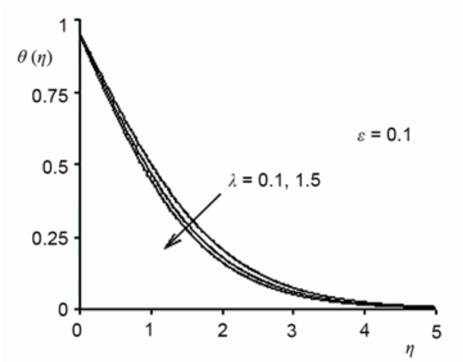

Figure 6. Temperature distribution *vs.* η when Gr = 2.0, Pr = 0.71, and β = 0.1

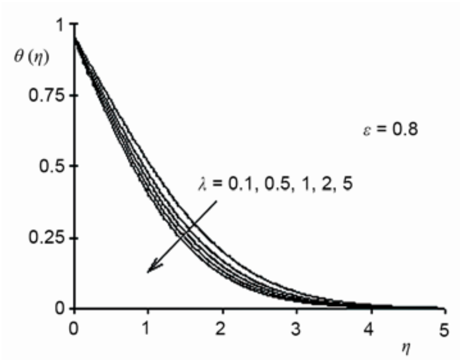

Figure 7. Temperature distribution *vs.* η when Gr = 2.0, Pr = 0.71, and β = 0.1

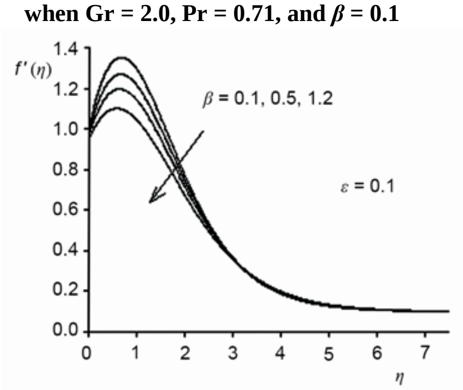

Figure 8. Velocity distribution *vs.* η when Gr = 2.0, Pr = 0.71, and λ = 0.1

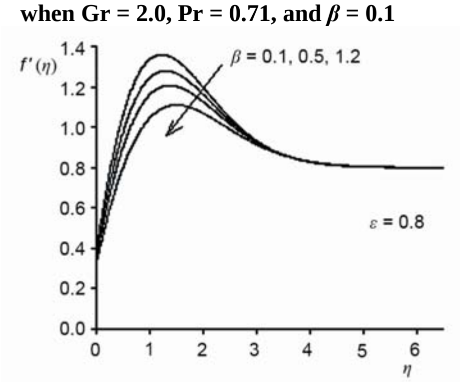

Figure 9. Velocity distribution *vs.* η when Gr = 2.0, Pr = 0.71, and λ = 0.1

increases which then convects heat readily. For the same reason plate temperature also decreases with the increase in parameter λ. Figures 8 and 9 show that with the increase in value of temperature jump parameter β the fluid velocity at the plate and fluid velocity decrease. Figures 10 and 11 depict that as β increases the fluid temperature and plate temperature decrease. The decrease in fluid temperature results in reduced buoyancy force and therefore the fluid velocity decrease, which is seen in figs. 8 and 9. Figures 12 and 13 depict that with the

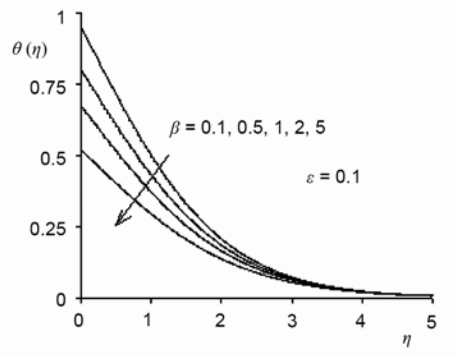

Figure 10. Temperature distribution *vs.* η when Gr = 2.0, Pr = 0.71, and λ = 0.1

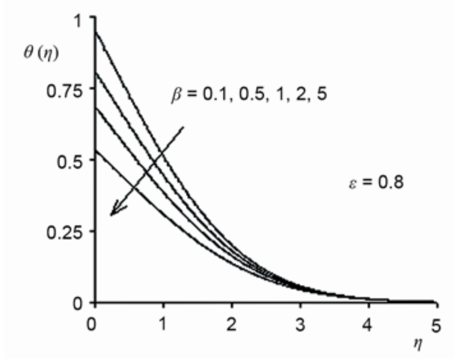

Figure 11. Temperature distribution *vs.* η when Gr = 2.0, Pr = 0.71, and λ = 0.1

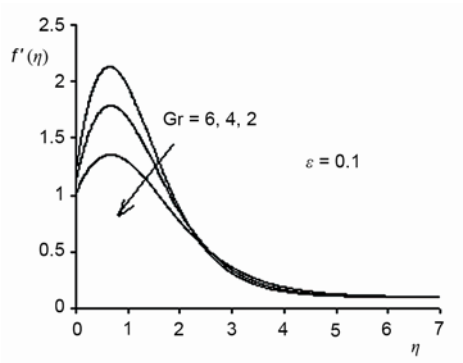

Figure 12. Velocity distribution *vs.* η when β = 0.1, Pr = 0.71, and λ = 0.1

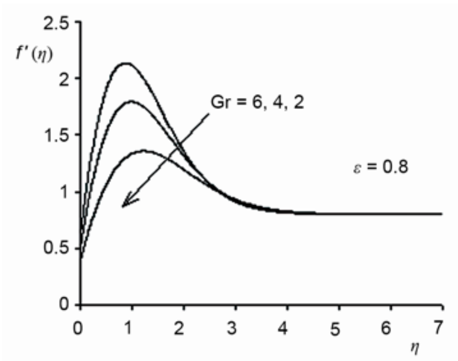

Figure 13. Velocity distribution *vs.* η when β = 0.1, Pr = 0.71, and λ = 0.1

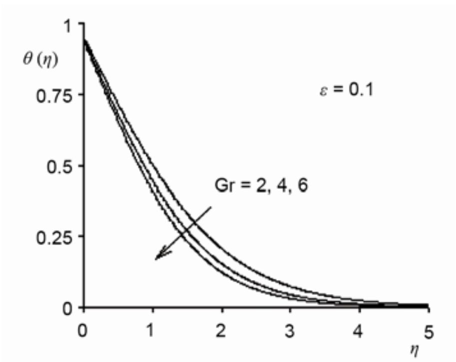

Figure 14. Temperature distribution *vs.* η when β = 0.1, Pr = 0.71, and λ = 0.1

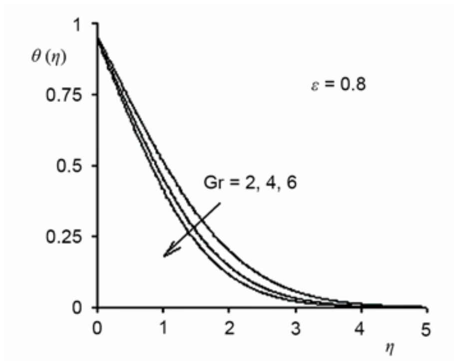

Figure 15. Temperature distribution *vs.* η when β = 0.1, Pr = 0.71, and λ = 0.1

increase in Gr, the fluid velocity along with the fluid velocity at plate surface increases. The increase in fluid velocity leads to better convection and hence fluid temperature and plate temperature decreases with increase in Gr, which is seen in figs. 14 and 15. It is observed from figs. 16 and 17 that with the increase in Prandtl number, fluid velocity and fluid velocity at plate decreases. Figures 18 and 19 show that the fluid temperature decreases with the increase in Prandtl number. In general, low Prandtl number fluid has higher thermal conductivity and hence attains higher temperature. Higher temperature leads to increase in buoyancy force hence fluid velocity also increases.

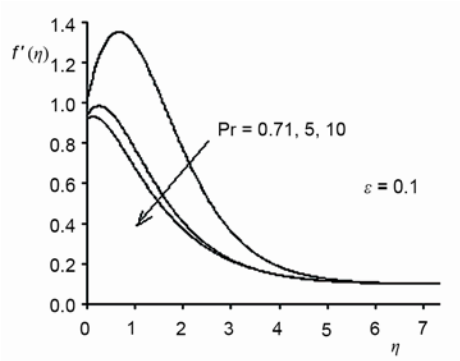

Figure 16. Velocity distribution *vs.* η when Gr = 2.0, β = 0.1, and λ = 0.1

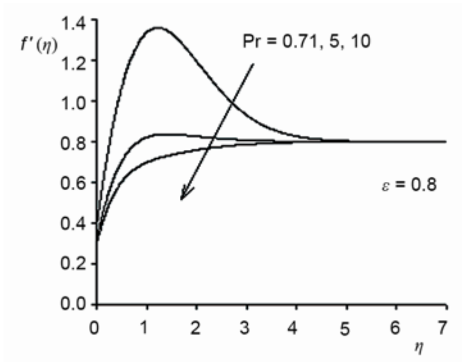

Figure 17. Velocity distribution *vs.* η when Gr = 2.0, β = 0.1, and λ = 0.1

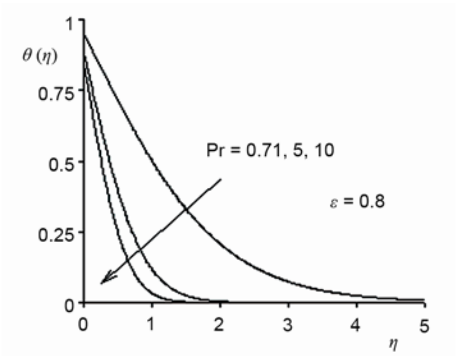

Figure 18. Temperature distribution *vs.* η when Gr = 2.0, β = 0.1, and λ = 0.1

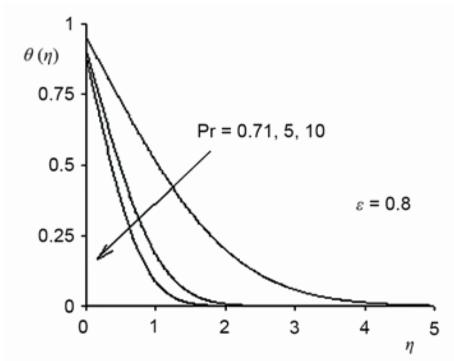

Figure 19. Temperature distribution *vs.* η when Gr = 2.0, β = 0.1, and λ = 0.1

Conclusions

The paper investigated the combined effects of velocity slip, buoyancy force and convective heating on the boundary layer flow over a vertical plate with a convective surface boundary condition. A similarity solution for the momentum and the thermal boundary layer equations were obtained. The thermal boundary layer thickness along the plate reduces with increasing buoyancy effects and convective heat transfer. Moreover, the effect of parameters ε, λ, β, Gr, and Pr on both velocity and temperature profiles have been discussed above. It is noted that effects of moving plate parameter $0 < \varepsilon < 0.5$ or $0.5 < \varepsilon < 1.0$ are similar on the flow and heat transfer. This comparison is possible because one set boundary condition has been taken.

Nomenclature

C_p – specific heat at constant pressure, [$Jkg^{-1}K^{-1}$]
f – dimensionless stream function, [–]
Gr – buoyancy parameter (Grashof number) $\{= [g\gamma(T_w - T_\infty)^2 x^3]/\nu^2\}(1/Re^2)$, [–]
g –gravity acceleration, [ms^{-2}]
Nu – Nusselt number, [–]
Pr – Prandtl number ($= \mu C_p/\kappa$), [–]
Re – Reynolds number ($= U_r x/\nu$), [–]
S_o – temperature jump coefficient, [m]
T – temperature of the fluid, [K]
T_w – temperature of the plate, [K]
T_∞ – temperature of free stream, [K]
u, v – velocity components along x- and y-directions, [ms^{-1}]
U_r – reference velocity ($= U_w + U_\infty$), [ms^{-1}]
U_w – velocity of plate, [ms^{-1}]
U_∞ – free stream velocity, [ms^{-1}]
x, y – Cartesian co-ordinates, [m]

Greek symbols

β – temperature jump parameter [$= (S_o/x)Re^{1/2}$], [–]
γ – coefficient of thermal expansion, [K^{-1}]
ε – velocity parameter [$= U_\infty/(U_W + U_\infty) = U_\infty/U_r$], [–]
η – similarity variable, [–]
θ – dimensionless temperature [$= (T - T_\infty)/(T_w + U_\infty)$], [–]
κ – coefficient of thermal conductivity, [$Wm^{-1}K^{-1}$]
κ_n – local Knudsen number [$= (\lambda o/x)$ $(0.01 < \kappa_n < 0.1)$], [–]
λ – velocity slip parameter $\{= [(2 - \sigma_v)\sigma_v] \cdot \kappa_n Re^{1/2}\}$, [–]
λ_o – mean free path, [m]
μ – coefficient of viscosity [$kgms^{-1}$]
ν – kinematic viscosity ($= \mu/\rho$), [m^2s^{-1}]
σ_v – tangential momentum coefficient, [–]
ρ – fluid density [kgm^{-3}]
ψ – stream function, [–]

Superscript

′ – differentiation with respect to η

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