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Mixed convection boundary layer flow along a stretching cylinder in porous medium

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ABSTRACT

This paper presents an axi-symmetric laminar boundary layer mixed convection flow of a viscous incompressible fluid and heat transfer towards a stretching cylinder embedded in porous medium. Variable surface temperature is assumed. The partial differential equations corresponding to the momentum equations are converted into highly non-linear ordinary differential equations with the help of similarity transformations. Numerical solutions of these equations are obtained by shooting method. It is found that the velocity decreases but the temperature increases with increasing permeability parameter. With the increasing values of mixed convection parameter, velocity is found to increase for buoyancy aided flow but opposite nature is noted for buoyancy opposed flow. The skin friction as well as the heat transfer rate at the surface is larger for a cylinder compared to a flat plate. Thermal boundary layer thickness decreases with increasing Prandtl number.

1. Introduction

Flow and heat transfer due to a stretching cylinder or a flat plate in a quiescent or moving fluid is important in number of industrial manufacturing processes that includes both metal and polymer sheets. It is worth mentioning that there are several practical applications in which significant temperature differences between the body-surface and the ambient fluid exist. The temperature differences cause density gradients in the fluid medium and free convection effects become more important in presence of gravitational force. There arise some situations where the stretching cylinder moves vertically in the cooling liquid. In this situation, the fluid flow and the heat transfer characteristics are determined by two mechanisms namely, the motion of stretching cylinder and the buoyancy force. The thermal buoyancy generated due to heating/cooling of a vertically moving stretching cylinder has a large impact on the flow and heat transfer characteristics. Convection heat transfer and fluid flow through porous medium is a phenomenon of great interest from both theoretical and practical point of view because of its applications in many engineering and geophysical fields such as geothermal and petroleum resources, solid matrix heat exchanges, thermal insulation drying of porous solids, enhanced oil recovery, cooling of nuclear reactors and other practical interesting designs (Rabadi and Hamdan, 2000; Mukhopadhyay and Layek, 2009; Mukhopadhyay et al., 2012).

Flow over cylinders are considered to be two-dimensional if the body radius is large compared to the boundary layer thickness. On the other hand for a thin or slender cylinder, the radius of the cylinder may be of the same order as that of the boundary layer thickness. Therefore, the flow may be considered as axi-symmetric instead of two-dimensional (Datta et al., 2006; Elbarbary and Elgazery, 2005; Kumari and Nath, 2004). The study of steady flow in a viscous and incompressible fluid outside of a stretching hollow cylinder in an ambient fluid at rest has been done by Wang (1988). The effect of slot suction/injection over a thin cylinder as studied by Datta et al. (2006) and Kumari and Nath (2004) may be useful in the cooling of nuclear reactors during emergency shutdown, where a part of the surface can be cooled by injecting a coolant (Ishak et al., 2008). Lin and Shih (1980, 1981) considered the laminar boundary layer and heat transfer along horizontally and vertically moving cylinders with constant velocity and found that the similarity solutions could not be obtained due to the curvature effect of the cylinder. Ishak and Nazar (2009) showed that the similarity solutions may be obtained by assuming that the cylinder is stretched with linear velocity in the axial direction and claimed that their study may be regarded as the extension of the papers by Grubka and Bobba (1985) and Ali (1994), from a stretching sheet to a stretching cylinder.

The study of hydrodynamic flow and heat transfer in porous medium becomes much more interesting due to its vast applications on the boundary layer flow control. Heat removal from

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nuclear fuel debris, underground disposal of radioactive waste material, storage of food stuffs and exothermic and/or endothermic chemical reactions and dissociating fluids in the packed-bed reactors etc. are some porous media applications. It is well known that Darcy's law is an empirical formula relating the pressure gradient, the bulk viscous fluid resistance and the gravitational force for a forced convective flow in a porous medium. Deviations from the Darcy's law occur when the Reynolds number based on the pore diameter is within the range of 1–10 (Ishak et al., 2006).

No attempt has been made yet to analyze the flow and thermal characteristics of mixed convection boundary layer axi-symmetric flow and heat transfer along a stretching cylinder in porous medium. Therefore an attempt is made to study the steady mixed convection flow and heat transfer past a stretching cylinder placed in a fluid-saturated porous medium using the Darcy model. Using similarity transformation, a third order ordinary differential equation corresponding to the momentum equation and a second order ordinary differential equation corresponding to heat equation are derived. Using shooting method numerical calculations up to desired level of accuracy were carried out for different values of dimensionless parameters of the problem under consideration for the purpose of illustrating the results graphically. The results obtained are then compared with those of Grubka and Bobba (1985), Ali (1994) and Ishak and Nazar (2009) who reported the results for some special case of the present study. The analysis of the results obtained shows that the flow field is influenced appreciably by the permeability parameter. Estimations of skin friction and heat transfer coefficients which are very important from the industrial application point of view are also presented in the analysis. It is hoped that the results obtained will not only provide useful information for applications, but also serve as a complement to the previous studies.

2. Equations of motion

Consider the steady axi-symmetric mixed convection flow of an incompressible viscous fluid along a vertical stretching cylinder in porous medium (see Fig. 1). The continuity, momentum and energy equations governing such type of flow are written as

$$\frac{\partial(ru)}{\partial x}+\frac{\partial(r\upsilon)}{\partial r}=0, \tag{1}$$

$$u\frac{\partial u}{\partial x}+\upsilon\frac{\partial u}{\partial r}=\frac{\nu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)-\frac{\nu}{K}u+g\beta(T-T_\infty), \tag{2}$$

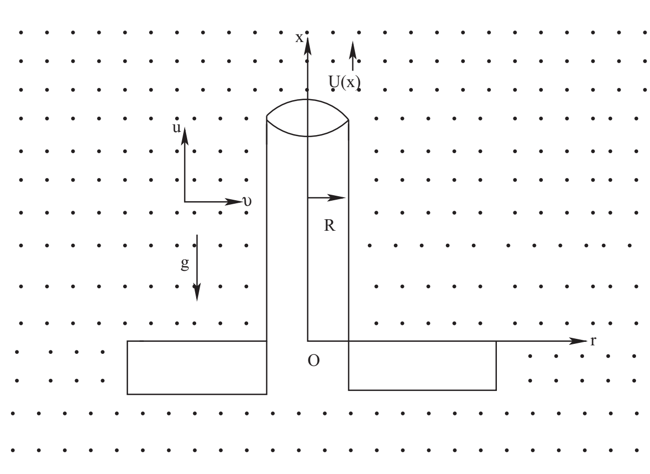

Fig. 1. Sketch of physical flow problem.

$$u\frac{\partial T}{\partial x}+\upsilon\frac{\partial T}{\partial r}=\frac{\kappa}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{3}$$

where u and υ are the components of velocity respectively in the x and r directions, $\nu=\mu/\rho$ is the kinematic viscosity, ρ is the fluid density, μ is the coefficient of fluid viscosity, K is the permeability of the medium, κ is the thermal diffusivity of the fluid, T is the fluid temperature, β is the volumetric coefficient of thermal expansion, g is the gravity field, T_∞ is the ambient temperature.

2.1. Boundary conditions

The appropriate boundary conditions for the problem are given by

$$u=U(x),\ \upsilon=0,\ T=T_w(x)\quad \text{at } r=R, \tag{4}$$

$$u\to 0,\ T\to T_\infty,\quad \text{as } r\to\infty \tag{5}$$

Here $U(x)=U_0(x/L)$ is the stretching velocity, $T_w(x)=T_\infty+T_0(x/L)^N$ is the prescribed surface temperature (for forced convection case), N is the temperature exponent, $N=1$ is considered for mixed convection case. U_0, T_0 are the reference velocity and temperature respectively, L is the characteristic length.

2.2. Method of solution

The continuity equation is automatically satisfied by the introduction of stream function ψ as

$$u=\frac{1}{r}\frac{\partial\psi}{\partial r},\ \upsilon=-\frac{1}{r}\frac{\partial\psi}{\partial x}$$

Introducing the similarity variables as

$$\eta=\frac{r^2-R^2}{2R}\left(\frac{U}{\nu x}\right)^{1/2},\ \psi=(U\nu x)^{1/2}Rf(\eta),\ \theta(\eta)=\frac{T-T_\infty}{T_w-T_\infty} \tag{6}$$

and upon substitution of (6) in Eqs. (2)–(5) the governing equations and the boundary conditions reduce to

$$(1+2M\eta)f'''+2Mf''+ff''-f'^2-k_1f'+\lambda\theta=0, \tag{7}$$

$$(1+2M\eta)\theta''+2M\theta'+\Pr(f\theta'-f'\theta)=0 \tag{8}$$

$$f'=1,\ f=0,\ \theta=1,\quad \text{at } \eta=0 \tag{9}$$

and

$$f'\to 0,\ \theta\to 0\quad \text{as } \eta\to\infty \tag{10}$$

where the prime denotes differentiation with respect to η, $k_1=\nu L/U_0 K$ is the permeability parameter of the porous medium, $M=(\nu L/U_0R^2)^{1/2}$ is the curvature parameter, $\lambda=g\beta T_0L/U_0^2$ is the mixed convection parameter. The case of non-porous medium is recovered for $k_1=0$. k_1^{-1} will reflect the effect of Darcian flow on the present problem.

One can note that if $M=0$ (i.e., $R\to\infty$), the problem under consideration (with $k_1=0$, $\lambda=0$) reduces to the boundary layer flow along a stretching flat plate considered by Ali (1994), with $m=1$ in that paper. Moreover, when $M=0$ (stretching flat plate) subjected to (9) with $k_1=0$ (i.e., for non-porous medium), $\lambda=0$ (i.e., for forced convection), the analytical solutions of Eqs. (7) and (8) are given by Crane (1970) and Grubka and Bobba (1985), respectively.

3. Numerical method for solution

A number of methods can be used to solve linear boundary-value problems. Method of differences works reasonably well in such cases. Other methods attempt to obtain linearly independent solutions and to combine them in such a way as to satisfy the boundary conditions. But these methods cannot be used in case of nonlinear equations. Difference method can be adapted for such problems but it requires guessing at a tentative solution and then improving this by an iterative process. The shooting method, used in this problem, can be used for both linear and nonlinear problems. Though there is no guarantee of convergence, but the method is easy to apply and when it does converge, it is usually more efficient than other methods.

In case of applying the initial-value methods to solve a second order boundary-value problem $y^{//}(x)=y(x)$ subjected to $y(0)=0$, $y(1)=1$ we must know $y(0)$ and $y^{/}(0)$. As $y^{/}(0)$ is not prescribed, we consider it as a parameter, say α, which must be determined so that the resulting solutions yield the prescribed value $y(1)$ to some desired accuracy. We therefore guess at the initial slope and an iterative procedure is set up for converging to the correct slope. A normally better approximation to α can now be obtained by linear interpolation formula

$$\alpha_2=\alpha_0+(\alpha_1-\alpha_0)\frac{y(1)-y(\alpha_0;1)}{y(\alpha_1;1)-y(\alpha_0;1)}$$

where α_0,α_1 are two guesses at the initial slope $y^{/}(0)$ and $y(\alpha_0;1)$, $y(\alpha_1;1)$ are values of y at $x=1$. We now integrate the differential equation using the initial values $y(0)=0$, $y^{/}(0)=\alpha_2$ to obtain $y(\alpha_2;1)$. Using linear interpolation based on α_1, α_2 we can obtain a next approximation α_3. This process is repeated until convergence is obtained. The rapidity of convergence depends upon the good initial guesses (Conte and Boor, 1981).

Using the above procedure, Eqs. (7) and (8) along with boundary conditions (9) and (10) are solved by converting them to an initial value problem. We set

$$f^{/}=z,\ z^{/}=p,\ p^{/}=[z^2+k_1z-fp-2Mp-\lambda\theta]/(1+2M\eta) \tag{11}$$

$$\theta^{/}=q,\ q^{/}=-[\Pr(fq-z\theta)+2Mq]/((1+2M\eta) \tag{12}$$

with the boundary conditions

$$f(0)=0,\ f^{/}(0)=1,\ \theta(0)=1 \tag{13}$$

In order to integrate (11) and (12) as initial value problems one requires a value for $p(0)$ i.e. $f^{//}(0)$ and a value for $q(0)$ i.e. $\theta^{/}(0)$ but no such values are given at the boundary. The suitable guess values for $f^{//}(0)$ and $\theta^{/}(0)$ are chosen and then integration is carried out. Comparing the calculated values for $f^{/}$ and θ at $\eta=10$ (say) with the given boundary conditions $f^{/}(10)=0$ and $\theta(10)=0$ and adjusting the estimated values, $f^{//}(0)$ and $\theta^{/}(0)$, a better approximation for the solution is given.

Taking the series of values for $f^{//}(0)$ and $\theta^{/}(0)$ and applying the fourth order classical Runge–Kutta method with step-size $h=0.01$, the above procedure is repeated until the results up to the desired degree of accuracy (10^{-5}) are obtained.

4. Results and discussions

For the verification of accuracy of the applied numerical scheme, a comparison of the present results for forced convection case ($\lambda=0$) corresponding to the heat transfer coefficient $[-\theta^{/}(0)]$ for $k_1=0$ (i.e., in case of non-porous medium) and $M=0$ (i.e., for stretching flat plate) with the available published results of Ishak and Nazar (2009), Grubka and Bobba (1985) and Ali (1994) is made and presented in Table 1. The results are found in excellent agreement.

In order to analyse the results, numerical computation has been carried out using the method described in the previous section for various values of the curvature parameter (M), mixed convection parameter (λ), permeability parameter (k_1) and Prandtl number (Pr). For illustrations of the results, numerical values are plotted in the Fig. 2(a) to Fig. 7(b).

Table 1
Values of $[-\theta^{/}(0)]$ for several values of temperature exponent N for forced convection ($\lambda=0$) in a plate ($M=0$) in non-porous medium ($k_1=0$) and Pr=1.

N	Ishak and Nazar (2009)	Grubka and Bobba (1985)	Ali (1994)	Present study
0	0.5820	0.5820	0.5801	0.5821
1	1.0000	1.0000	0.9961	1.0000
2	1.3333	1.3333	1.3269	1.3332

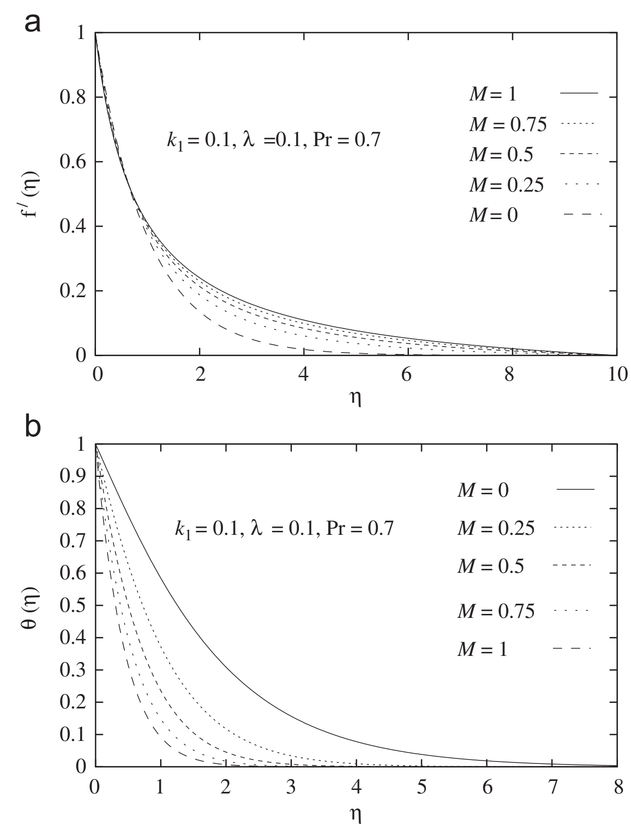

Fig. 2. (a) Variation of velocity $f^{/}(\eta)$ with η for several values of curvature parameter M of the stretching cylinder. (b) Variation of temperature $\theta(\eta)$ with η for several values of curvature parameter M of the stretching cylinder.

Let us first concentrate on the effects of curvature parameter M on velocity distribution in presence of porous medium. In Fig. 2(a), horizontal velocity profiles are shown for different values of M. The horizontal velocity curves show that the rate of transport decreases with the increasing distance (η) of the sheet. In all cases the velocity vanishes at some large distance from the sheet (at $\eta=10$). The velocity increases with increasing values of M. The velocity gradient at the surface is larger for larger values of M, which produces larger skin friction coefficient.

Effects of curvature parameter on the temperature distribution are presented in Fig. 2(b). Temperature is found to decrease with the increasing curvature parameter M. The thermal boundary layer thickness decreases as M increases, which implies increase in the wall temperature gradient and in turn the surface heat transfer rate increases. Hence, the local Nusselt number Nu_x, defined as $Nu_x=(-x(\partial T/\partial r)_{r=R})/(T_w-T_\infty)=-\mathrm{Re}_x^{1/2}\theta^{/}(0)$, $\mathrm{Re}_x=Ux/\nu$ being the local Reynolds number, increases as M increases.

Fig. 3(a)–(d) displays the effects of the mixed convection parameter on velocity, shear stress, temperature and temperature gradient for flat plate and stretching cylinder. Fig. 3(a) and (b) demonstrate the effects of mixed convection parameter (λ) on

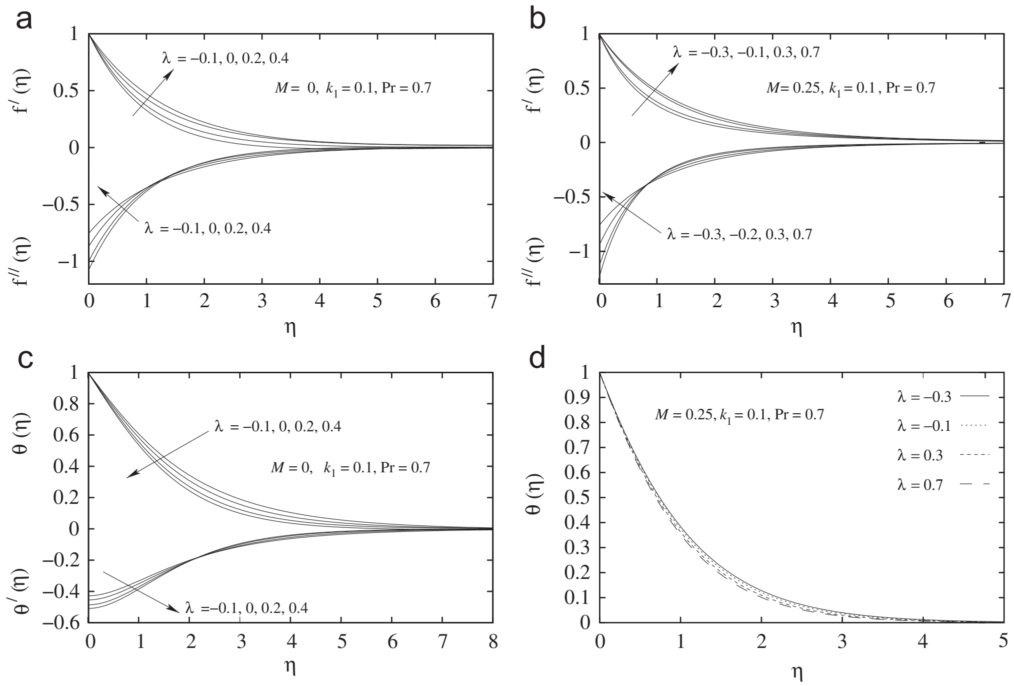

Fig. 3. (a) Variation of velocity $f^{/}(\eta)$ and shear stress $f^{//}(\eta)$ with η for several values of mixed convection parameter λ for flat plate. (b) Variation of velocity $f^{/}(\eta)$ and shear stress $f^{//}(\eta)$ with η for several values of mixed convection parameter λ for stretching cylinder. (c) Variation of temperature $\theta(\eta)$ and temperature gradient $\theta^{/}(\eta)$ with η for several values of mixed convection parameter λ for flat plate. (d) Variation of temperature $\theta(\eta)$ with η for several values of mixed convection parameter λ for stretching cylinder.

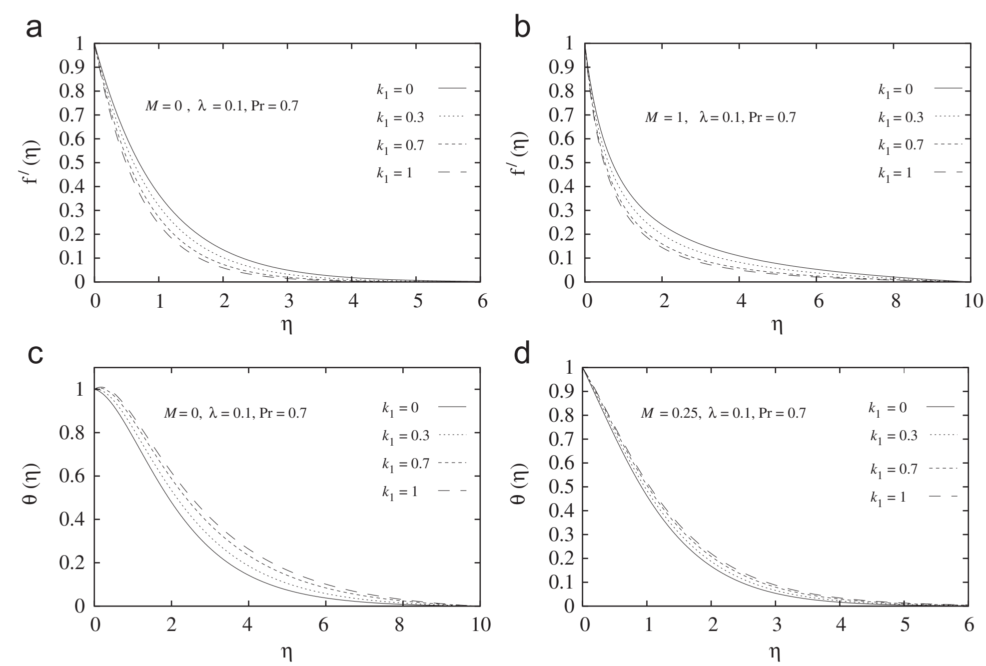

Fig. 4. (a) Variation of velocity $f^{/}(\eta)$ with η for several values of permeability parameter k_1 for flat plate with $M=0$. (b) Variation of velocity $f^{\prime}(\eta)$ with η for several values of permeability parameter k_1 for stretching cylinder with $M=1$. (c) Variation of temperature $\theta(\eta)$ with η for several values of permeability parameter k_1 for flat plate with $M=0$. (d) Variation of temperature $\theta(\eta)$ with η for several values of permeability parameter k_1 for stretching cylinder with $M=0.25$.

velocity and shear stress profiles respectively for a stretching flat plate (i.e., for $M=0$) and a stretching cylinder (for $M=0.25$). With the increasing λ, the horizontal velocity is found to increase for buoyancy aided flow ($\lambda>0$) but decreases for buoyancy opposed flow ($\lambda<0$) [Fig. 3(a) and (b)]. It is noted that λ has a substantial effect on the solutions. Also, with the increasing values of mixed convection parameter λ, the shear stress $f^{//}(\eta)$ increases for buoyancy opposed flow but decreases in case of buoyancy aided flow. $\lambda=0$ corresponds to the forced convection case. For $\lambda>0$, there is a favourable pressure gradient due to the buoyancy forces, which results in the flow being accelerated.

Physically $\lambda>0$ means heating of the fluid or cooling of the surface (assisting flow), $\lambda<0$ means cooling of the fluid or heating of the surface (opposing flow). Also, an increase in the value of λ can lead to an increase in the temperature difference T_w-T_∞.

This leads to an enhancement of the velocity due to the enhanced convection currents and thus an increase in the boundary layer thickness.

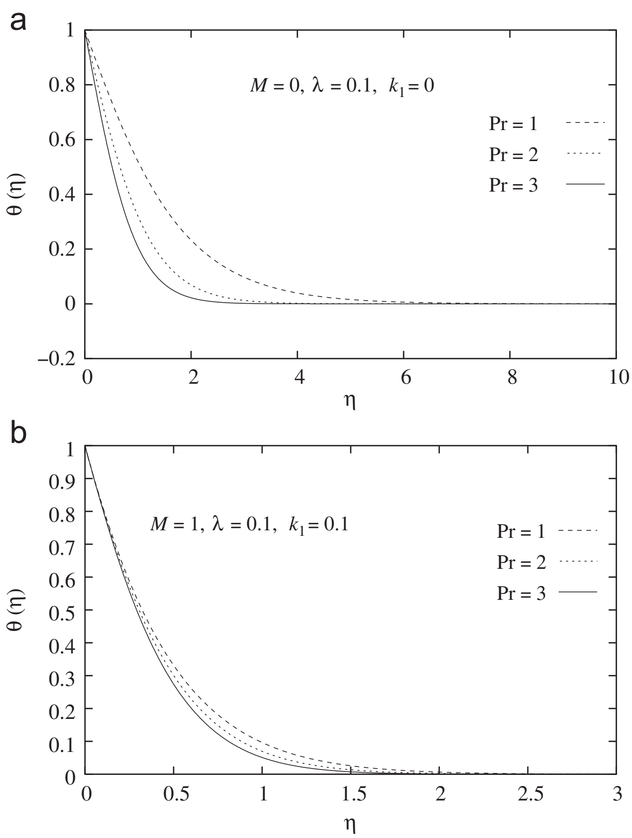

Fig. 5. (a) Variation of temperature $\theta(\eta)$ with η for several values of Prandtl number Pr for flat plate with $M=0$. (b) Variation of temperature $\theta(\eta)$ with η for several values of Prandtl number Pr for stretching cylinder with $M=1$.

Variation of temperature $\theta(\eta)$ and temperature gradient $\theta^{/}(\eta)$ with η for several values of mixed convection parameter λ for flat plate are shown in Fig. 3(c). Temperature decreases with increasing λ for buoyancy aided flow but increases in case of buoyancy opposed flow. Opposite behaviour is noted for temperature gradient. Fig. 3(d) presents the nature of temperature profiles for various values of λ in case of stretching cylinder. With increasing λ temperature is found to decrease in the buoyancy aided flow and temperature increases with λ in buoyancy opposed flow. An increase in the value of mixed convection parameter λ results in a decrease in the thermal boundary layer

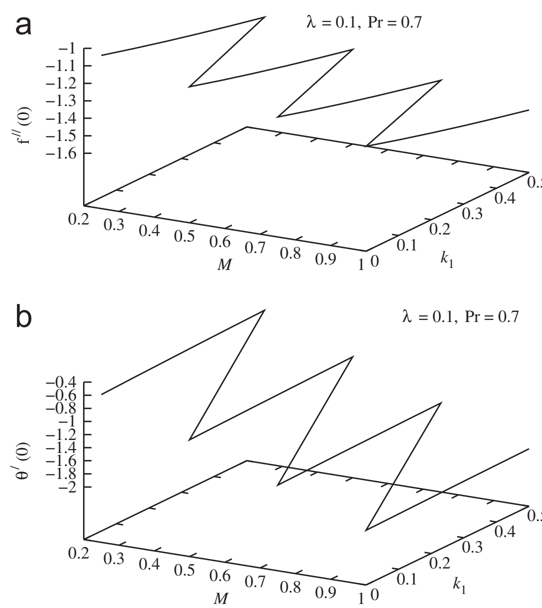

Fig. 7. (a) Variations of skin friction coefficient $f^{//}(0)$ with permeability parameter k_1 and curvature parameter M. (b) Variations of heat transfer coefficient $\theta'(0)$ with permeability parameter k_1 and curvature parameter M.

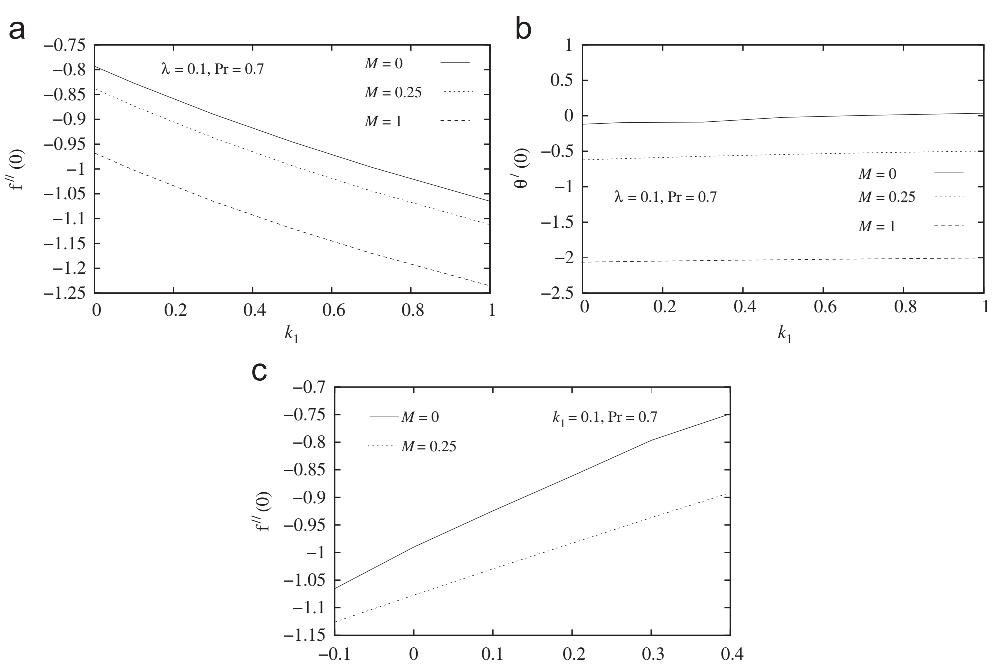

Fig. 6. (a) Variation of skin friction coefficient $f^{//}(0)$ with permeability parameter k_1 for several values of curvature parameter M. (b) Variation of heat transfer coefficient $\theta'(0)$ with permeability parameter k_1 for several values of curvature parameter M. (c) Skin friction coefficient $f^{//}(0)$ against mixed convection parameter λ for two values of curvature parameter M.

thickness and this results in an increase in the magnitude of the wall temperature gradient. This in turn produces an increase in the surface heat transfer rate.

Now the velocity profiles are presented for the variation of permeability parameter for flat plate and stretching cylinder. Fig. 4(a) and (c) demonstrate the effects of permeability parameter (k_1) for a stretching flat plate (i.e., for $M=0$) on velocity and temperature respectively. With the increasing k_1, the horizontal velocity is found to decrease [Fig. 4(a)] but the temperature increases in this case [Fig. 4(c)]. This feature prevails up to certain heights and then the process is slowed down. It is noted that k_1 has a substantial effect on the solutions. It is obvious that the presence of porous medium causes higher restriction to the fluid, which reduces the fluid velocity [Fig. 4(a)] and enhances the temperature [Fig. 4(c)]. The porous medium presents resistance to the flow, thus, the flow becomes slower. Therefore, as the inverse Darcy number (k_1^{-1}) increases, the resistance due to the porous medium increases and the surface velocity gradient increases. In this case, skin friction increases monotonically. $k_1=0$ corresponds to the case of non-porous medium. Fig. 4(b) and (d) present the effects of permeability parameter k_1 on velocity and temperature for the stretching cylinder ($M=1$). Here also velocity decreases with k_1 whereas the temperature increases with increasing k_1 [Fig. 4(d)].

It is noted that temperature decreases with increasing Pr. An increase in Prandtl number reduces the thermal boundary layer thickness. It is also observed that the effects of Pr are much more prominent for flat plate [Fig. 5(a)] compared to stretching cylinder [Fig. 5(b)]. Prandtl number signifies the ratio of momentum diffusivity to thermal diffusivity. Fluids with lower Prandtl number will possess higher thermal conductivities (and thicker thermal boundary layer structures) so that heat can diffuse from the wall faster than for higher Pr fluids (thinner boundary layers). Hence Prandtl number can be used to increase the rate of cooling in conducting flows.

Fig. 6(a) and (b) present the behaviour of skin friction and heat transfer coefficients with the permeability parameter k_1 of the porous medium for three values of curvature parameter. Magnitude of the skin friction coefficient increases with increasing permeability parameter k_1 and also with the curvature parameter M which also supports the earlier findings in Fig. 2(a). These features are also exhibited in Fig. 7(a). From the figure it is very clear that shear stress at the wall is negative here. Physically, negative sign of $f''(0)$ implies that surface exerts a dragging force on the fluid and positive sign implies the opposite. This is consistent with the present case as a stretching cylinder which induces the flow that is considered here. From Fig. 6(b) it is very clear that the magnitude of heat transfer coefficient decreases with permeability parameter k_1 but increases with the curvature parameter M which is consistent with the findings in Fig. 2(b). Fig. 7(b) also supports these features. The skin-friction coefficient increases with increasing mixed convection parameter λ [Fig. 6(c)].

5. Conclusions

The present study gives the numerical solutions for steady boundary layer mixed convection flow and heat transfer along a stretching cylinder embedded in porous medium. The rate of transport is considerably reduced with increasing values of curvature parameter. The results pertaining to the present study indicate that due to increasing permeability parameter, velocity decreases whereas the temperature increases. The surface shear stress and the heat transfer rate at the surface increase as the curvature parameter increases. Fluid velocity is found to increase with increasing mixed convection parameter for buoyancy aided flow but it decreases for buoyancy opposed flow. Prandtl number can be used to increase the rate of cooling.

In fine, it can be concluded that the problem resembles the conditions experienced around well bores in oil reservoirs and therefore is useful in petroleum science & engineering.

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