

Research Article

Reactive Solute Diffusion in Boundary Layer Flow through a Porous Medium over a Permeable Flat Plate with Power-Law Variation in Surface Concentration

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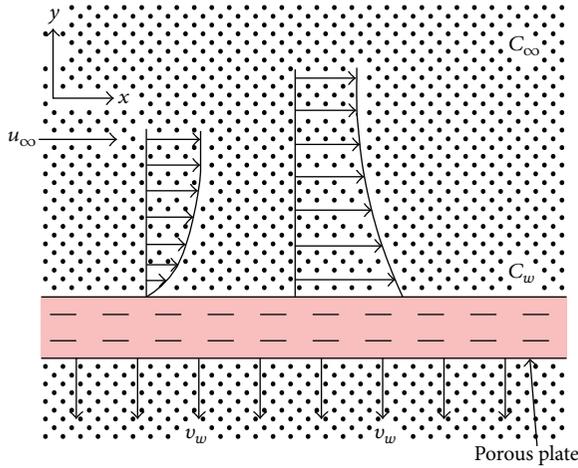
The solute diffusion in boundary layer flow of an incompressible fluid through a porous medium over a porous flat plate with first-order chemical reaction and with variable surface concentration is studied. The reaction rate of the solute is also taken as variable. The self-similar ordinary differential equations are obtained from the governing partial differential equations using similarity transformations, and then those self-similar equations are solved by shooting technique using fourth-order Runge-Kutta method. The analysis shows that the velocity increases with the increase of permeability of the porous medium, whereas the concentration decreases. The thicknesses of momentum and solute boundary layers reduce for suction, and the effect of blowing is opposite. For the inverse variation of wall concentration along the surface, mass absorption at the surface is found in all cases, and in direct variation mass transfer is found. For increase of both the Schmidt number and the reaction rate parameter, the concentration as well as the solute boundary layer thickness decreases.

1. Introduction

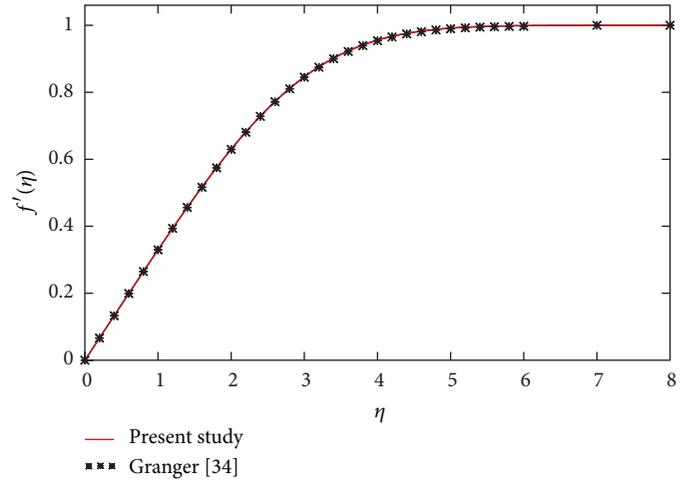
The study of the steady flow of viscous incompressible fluid has acquired significant attention because of its wide range of engineering applications, and the flow over a flat plate is one of such important problems in fluid dynamics. Blasius [1] first investigated the steady laminar boundary layer viscous flow over a flat plate. The numerical solution for Blasius problem was obtained by Howarth [2]. The existence of a solution for the flow past a flat plate was established by Abu-Sitta [3]. Further some important aspects of boundary layer flow over flat plate were studied by Bataller [4], Cortell [5], Wang [6], Bhattacharyya and Layek [7], Bhattacharyya et al. [8], and Bhattacharyya [9].

The solute transfer analysis in fluid flow has great importance in expansion of the theory of separation processes and chemical kinetics. Chambré and Young [10] presented the diffusion of a chemically reactive species in a laminar boundary layer flow past a flat plate. The mass transfer effects on the flow over an impulsively started infinite vertical plate under

various physical conditions were discussed by Soundalgekar [11], Soundalgekar et al. [12] and Das et al. [13]. Whereas Afzal and Hussain [14] and Yao [15] studied the mixed convection flows on a flat plate. Fan et al. [16] reported the similarity solution of diffusion of chemically reactive species in mixed convective flow over a horizontal moving plate. Anjalidavi and Kandasamy [17] studied the effects of chemical reaction, heat and mass transfer on laminar flow along a semi-infinite horizontal plate. Makinde and Ogulu [18] investigated the MHD flow with heat and mass transfer past a vertical porous plate in presence of thermal radiation with variable viscosity fluid. Ibrahim and Makinde [19] illustrated the effect of thermal radiation on chemically reacting MHD boundary layer flow of heat and mass transfer past a porous vertical flat plate. The effects of chemical reaction on flow due to the stretching/shrinking of flat sheet were discussed by Andersson et al. [20], Chamkha et al. [21], El-Aziz [22], Bhattacharyya and Layek [23, 24], Bhattacharyya [25, 26], and Bhattacharyya et al. [27, 28].



(a)



(b)

FIGURE 1: (a) Physical model of the boundary layer flow through porous medium on a flat plate. (b) Velocity profile $f'(\eta)$ for $k^* = 0$ and $S = 0$.

Mass and heat transfer phenomenon in porous medium grabbed the attention of modern researchers due to its huge applications in chemical industries, reservoir engineering, and many other technological processes. Also, a better understanding of convection through porous medium can benefit several areas like insulation design, underground nuclear waste storage sites, grain storage, heat exchangers, filtering devices, metal processing, catalytic reactors, and so forth. Lai and Kulacki [29] showed the coupled heat and mass transfer by mixed convection from a vertical plate in a saturated porous medium. Postelnicu [30] studied the influence of chemical reaction on heat and mass transfer by natural convection from vertical surface in porous media with the Soret and Dufour effects. Mukhopadhyay and Layek [31] described the effects of thermal radiation on forced convective flow and heat transfer over a porous flat plate in a porous medium. Makinde [32] investigated the MHD boundary-layer flow and mass transfer past a vertical plate in a porous medium with constant heat flux. Recently, Bhattacharyya et al. [33] have discussed the effects of velocity and thermal slips on the boundary layer flow and heat transfer over a permeable plate in porous medium.

In this paper, the effect of diffusion of reactive solute on boundary layer flow over a permeable flat plate in porous medium with power-law surface concentration will be discussed. The reaction rate is taken as variable. Using similarity transformations, self-similar ordinary differential equations are obtained from the governing partial differential equations. The transformed ODEs are then solved numerically using well-known shooting method for the solution of boundary value problems. Obtained numerical results are presented in some figures for various values of physical parameter, and the flow and solute transfer characteristics are discussed in detail.

2. Formulation of the Problem

Consider the steady two-dimensional laminar boundary layer flow of viscous incompressible fluid and solute transfer with first-order chemical reaction over a permeable flat plate in porous medium with the surface concentration varying as $C_w = C_\infty + C_0 x^n$, where C_0 is a real constant and n is a power-law exponent that signifies the change of amount of solute along the surface. The external flow consists of a uniform-free stream velocity u_∞ parallel to the plate and concentration C_∞ . The x -axis is taken along the plate and the y -axis is considered normal to the plate. A sketch of the physical flow problem through porous medium is plotted in Figure 1(a). The governing equations for the flow and the solute distribution may be written in usual notation as

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

$$u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = \nu \frac{\partial^2 u}{\partial y^2} - \frac{\nu}{k} (u - u_\infty), \quad (2)$$

$$u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - R(C - C_\infty), \quad (3)$$

where u is the velocity component in x direction, v is the velocity component y direction, $\nu (= \mu/\rho)$ is the kinematic fluid viscosity, ρ is the fluid density, μ is the coefficient of fluid viscosity, k is the permeability of the porous medium, C is the concentration, and D is the diffusion coefficient. $R(x)$ is the variable reaction rate and is given by $R(x) = LR_0/x$, L is the reference length, and R_0 is a constant.

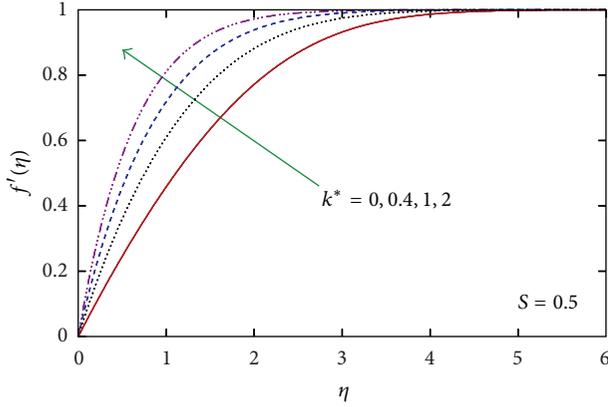


FIGURE 2: Velocity profiles $f'(\eta)$ for different values of k^* .

2.1. Boundary Conditions. The appropriate boundary conditions for the velocity components and the concentration are given by

$$u = 0, \quad v = v_w \quad \text{at } y = 0 \quad (4)$$

$$u \rightarrow u_\infty \quad \text{as } y \rightarrow \infty,$$

$$C = C_w = C_\infty + C_0 x^n \quad \text{at } y = 0 \quad (5)$$

$$C \rightarrow C_\infty \quad \text{as } y \rightarrow \infty,$$

where v_w is prescribed suction or blowing through the porous plate and is given by $v_w = v_0/(x)^{1/2}$, v_0 is a constant with $v_0 < 0$ for suction, and $v_0 > 0$ for blowing.

3. Method of Solution

We now introduce the stream function $\psi(x, y)$ as

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x}. \quad (6)$$

Now, using relation (6), (1) is automatically satisfied and (2) and (3) become

$$\frac{\partial \psi}{\partial y} \frac{\partial^2 \psi}{\partial x \partial y} - \frac{\partial \psi}{\partial x} \frac{\partial^2 \psi}{\partial y^2} = v \frac{\partial^3 \psi}{\partial y^3} - \frac{v}{k} \left(\frac{\partial \psi}{\partial y} - u_\infty \right), \quad (7)$$

$$\frac{\partial \psi}{\partial y} \frac{\partial C}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - \frac{LR_0}{x} (C - C_\infty).$$

The boundary conditions in (4) for the flow reduce to

$$\frac{\partial \psi}{\partial y} = 0, \quad \frac{\partial \psi}{\partial x} = -v_w \quad \text{at } y = 0 \quad (8)$$

$$\frac{\partial \psi}{\partial y} \rightarrow u_\infty \quad \text{as } y \rightarrow \infty.$$

3.1. Similarity Technique. We shall introduce the dimensionless variables for ψ and C as given below

$$\psi = \sqrt{u_\infty v x} f(\eta), \quad C = C_\infty + (C_w - C_\infty) \phi(\eta), \quad (9)$$

where the similarity variable η is defined as $\eta = (y/x) \sqrt{\text{Re}_x}$, $\text{Re}_x = u_\infty x / \nu$ being the local Reynolds number.

In view of relations in (9) we finally obtain the self-similar equations in the following form:

$$f''' + \frac{1}{2} f f'' - \frac{1}{\text{Da}_x \text{Re}_x} (f' - 1) = 0, \quad (10)$$

$$\phi'' + \frac{1}{2} \text{Sc} f \phi' - \text{Sc} (n f' + \beta) \phi = 0, \quad (11)$$

where $\text{Da}_x = k/x^2 = k_0/x$ is the local Darcy number, $k = k_0 x$, k_0 is a constant, $\text{Sc} = \nu/D$ is the Schmidt number, and $\beta = LR_0/u_\infty$ is the reaction rate parameter. It is important to note that the chemical reaction is of destructive type if $\beta > 0$, the chemical reaction is of constructive type if $\beta < 0$, and when $\beta = 0$, it is the case for non-reactive solute.

Equation (10) can be written as

$$f''' + \frac{1}{2} f f'' - k^* (f' - 1) = 0, \quad (12)$$

where $k^* = 1/\text{Da}_x \text{Re}_x$ is the permeability parameter of the porous medium (Mukhopadhyay and Layek [31]).

The boundary conditions (8) and (5) finally become

$$f(\eta) = S, \quad f'(\eta) = 0 \quad \text{at } \eta = 0 \quad (13)$$

$$f'(\eta) \rightarrow 1 \quad \text{as } \eta \rightarrow \infty,$$

$$\phi(\eta) = 1 \quad \text{at } \eta = 0 \quad (14)$$

$$\phi(\eta) \rightarrow 0 \quad \text{as } \eta \rightarrow \infty,$$

where $S = (-2v_w/u_\infty)(\text{Re}_x)^{1/2} = -2v_0/(u_\infty v)^{1/2}$ is the suction or blowing parameter, $S > 0$ (i.e., $v_0 < 0$) is corresponding to suction, and $S < 0$ (i.e., $v_0 > 0$) is corresponding to blowing.

3.2. Numerical Method. The nonlinear self-similar coupled ordinary differential equations (12) and (11) along with the boundary conditions (13) and (14) form a boundary value problem (BVP) and are solved using shooting method [8, 32, 33], by converting it into an initial value problem (IVP). In this method, we have to choose a suitable finite value of $\eta \rightarrow \infty$, say η_∞ . We set the following first-order systems:

$$f' = p, \quad p' = q, \quad q' = -\frac{1}{2} f q + k^* (p - 1), \quad (15)$$

$$\phi' = z, \quad z' = -\frac{1}{2} \text{Sc} f z + \text{Sc} (n p + \beta) \phi \quad (16)$$

with the boundary conditions

$$f(0) = S, \quad p(0) = 0, \quad \phi(0) = 1. \quad (17)$$

To integrate (15) and (16) with (17) as an IVP the values for $q(0)$, that is, $f''(0)$ and $z(0)$, that is, $\phi'(0)$ are needed, but no such values are given. The initial guess values for $f''(0)$ and $\phi'(0)$ are chosen and applying fourth-order Runge-Kutta method a solution is obtained. We compare the calculated

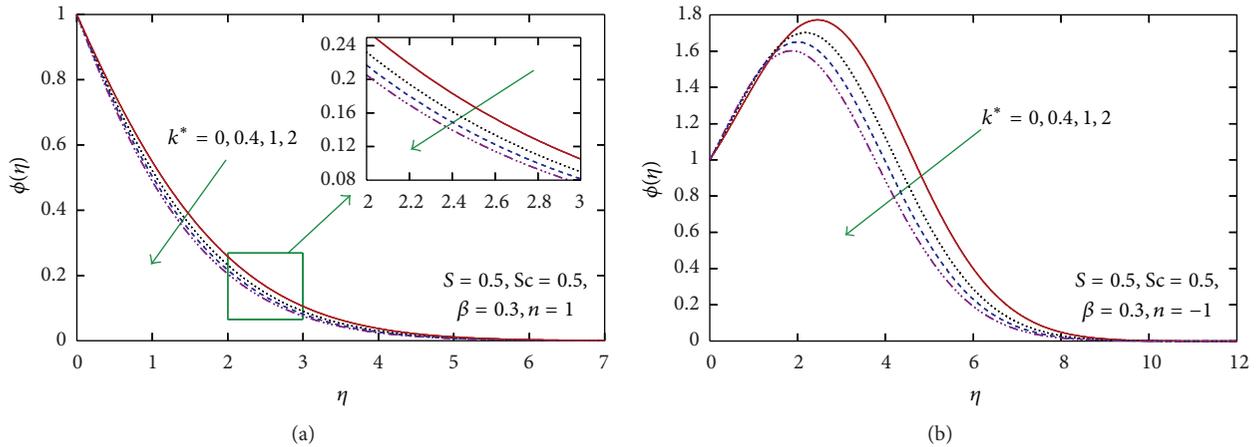


FIGURE 3: (a) Concentration profiles $\phi(\eta)$ for different values of k^* with $n > 0$. (b) Concentration profiles $\phi(\eta)$ for different values of k^* with $n < 0$.

values of $f'(\eta)$ and $\phi(\eta)$ at $\eta_{\infty} (= 20)$ with the given boundary conditions $f'(\eta_{\infty}) = 1$ and $\phi(\eta_{\infty}) = 0$ and adjust values of $f''(0)$ and $\phi'(0)$ using “secant method” to give better approximation for the solution. The step size is taken as $\Delta\eta = 0.01$. This process is repeated until we get the results asymptotically correct up to the desired accuracy of 10^{-6} level.

4. Results and Discussion

The computed solutions of self-similar ODEs are obtained for several values of parameters involved, namely, the permeability parameter k^* , the suction or blowing parameter S , the Schmidt number Sc , the reaction rate parameter β , and power-law exponent n . The variations in velocity and temperature distributions for the variations in the parameters are presented in some figures. Also, to ensure the accuracy of numerical scheme, a comparison of the velocity profile $f'(\eta)$ for $k^* = 0$ and $S = 0$ (i.e., for nonporous medium) with the available data provided by Granger [34] in Figure 1(b) and those are found in excellent agreement.

The velocity and concentration distributions for several value of the permeability parameter k^* are plotted in Figures 2, 3(a) and 3(b). The increase in permeability of the porous medium causes the enhancement of the velocity $f'(\eta)$ at a fixed η (Figure 2), because the momentum boundary layer thickness is reduced due to the increase in k^* . Two figures of concentration profiles (Figures 3(a) and 3(b)) are shown: one for direct variation of surface concentration ($n > 0$) and the other for inverse variation of surface concentration ($n < 0$). For direct variation solute transfer is found from the surface to the fluid, and for inverse variation solute absorption at the surface occurs with concentration overshoot. In both cases, the concentration decreases with increase of permeability parameter. The concentration overshoot reduces with permeability of the porous medium.

Next, the effect of suction or blowing through the permeable plate is discussed. For various values of the suction or blowing parameter S , the dimensionless velocity and

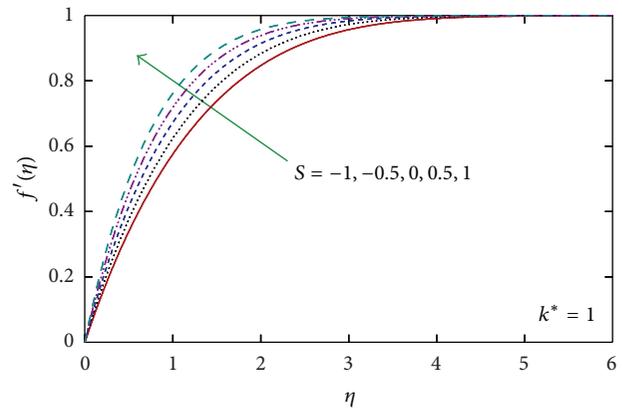


FIGURE 4: Velocity profiles $f'(\eta)$ for different values of S .

concentration profiles are plotted in Figures 4, 5(a), and 5(b). For the increase of applied suction, the velocity at a fixed point increases, and, with increasing blowing, the velocity decreases. On the other hand, the concentration decreases with suction and increases with blowing. The concentration overshoot in inverse variation of surface concentration reduces with suction and enhances with blowing. Also, it is important to note that fluid suction causes reduction in solute boundary layer thickness and due to blowing it becomes thicker.

The effect of the Schmidt number Sc on the solute distribution for positive (direct variation) and negative (inverse variation) values of n is depicted in Figures 6(a) and 6(b), respectively. In both cases, with increasing values of Sc , the concentration $\phi(\eta)$ at a point and solute boundary layer thickness rapidly decrease. Schmidt number is inversely proportional to the diffusion coefficient and so increase of Schmidt number means a decrease in diffusion coefficient, which acts to reduce the solute boundary layer thickness. Here also, concentration overshoot is found when the surface concentration varies inversely along the plate and the overshoot, that is, mass absorption is suppressed with the increase in the Schmidt number Sc . Actually, due to increasing

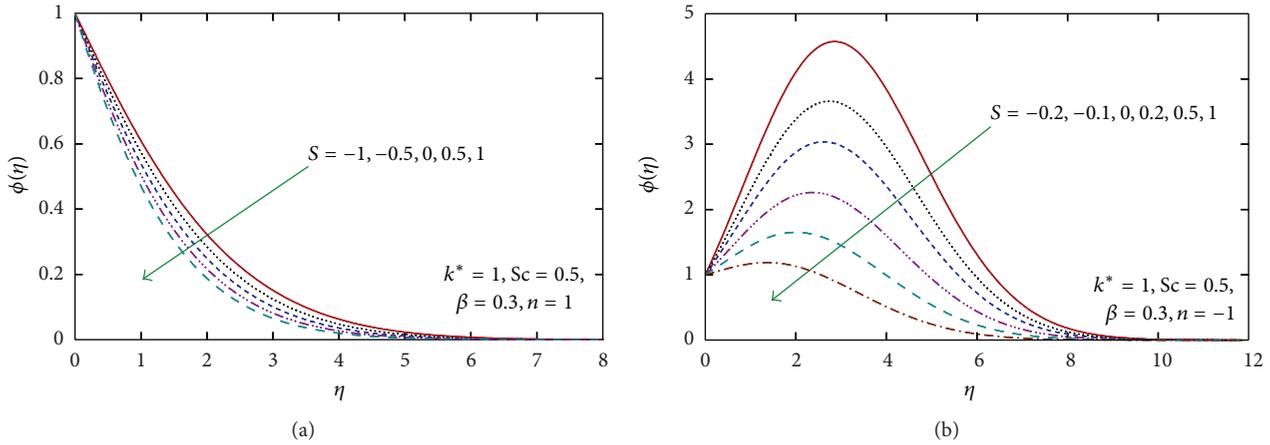


FIGURE 5: (a) Concentration profiles $\phi(\eta)$ for different values of S with $n > 0$. (b) Concentration profiles $\phi(\eta)$ for different values of S with $n < 0$.

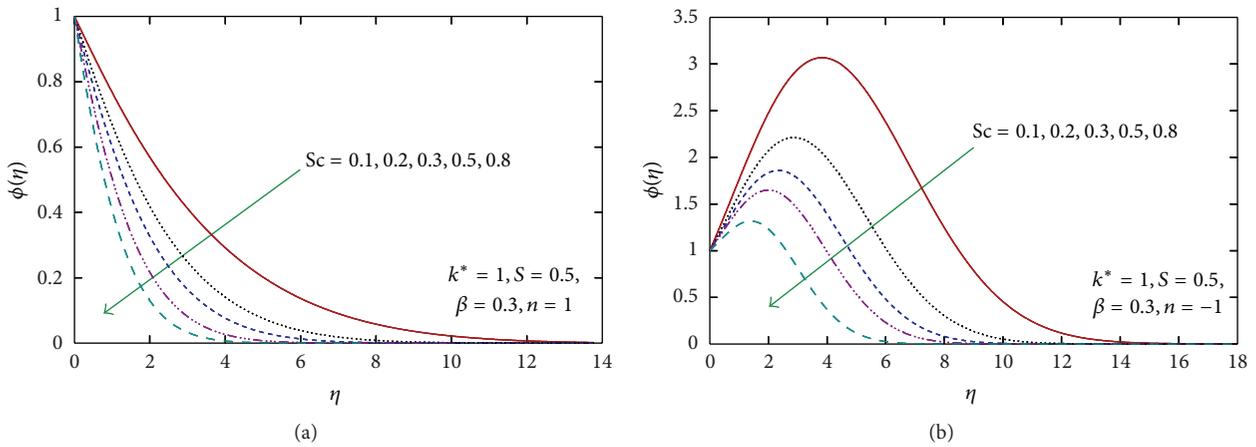


FIGURE 6: (a) Concentration profiles $\phi(\eta)$ for different values of Sc with $n > 0$. (b) Concentration profiles $\phi(\eta)$ for different values of Sc with $n < 0$.

Schmidt number the rate of mass transfer from the surface to the fluid increases.

The first-order chemical reaction of solute affects the diffusion dynamics. In Figures 7(a) and 7(b), the reactive concentration profiles $\phi(\eta)$ for several values of reaction rate parameter β of the first-order reaction are illustrated. In both cases, positive and negative values of n , the concentration overshoot is observed. For direct variation ($n > 0$) the overshoot can be seen only for higher negative values reaction rate parameter, that is, for higher constructive chemical reaction. But, for inverse variation ($n < 0$) the overshoot is appeared in destructive reaction, and it reduces with higher destructive chemical reaction. Thus destructive reaction causes mass transfer from the surface and constructive reaction results mass absorption at the surface. Also, due to increase in β , the solute boundary layer thickness reduces.

Now, it is important to note down the influence of variable surface concentration on the solute distribution. The graphical representations of the concentration profiles for different values of n are demonstrated in Figures 8(a) and 8(b). For direct variation, the concentration $\phi(\eta)$ and solute boundary layer thickness decrease with mass transfer from

the surface when n increases, that is, when the concentration increases along the surface. For inverse variation, the concentration along the surface decreases with increasing magnitude of $n(< 0)$, and the effect of inverse variation is opposite to that of direct variation. Also, in inverse variation the mass absorption is found and with increasing magnitude of $n(< 0)$ mass absorption becomes larger.

The local skin friction coefficient $f''(0)$ for various values of permeability parameter k^* and suction or blowing parameter S is plotted in Figure 9. It is worth noting that the local skin friction coefficient increases with increase suction parameter and permeability parameter, whereas it reduces with increasing blowing.

5. Concluding Remarks

The investigation focuses on the reactive species diffusion with first-order reaction in boundary layer flow over a porous flat plate in porous medium with power-law variation in surface concentration. Using similarity transformations, self-similar equations are obtained from the governing equations, and then those are solved by shooting method.

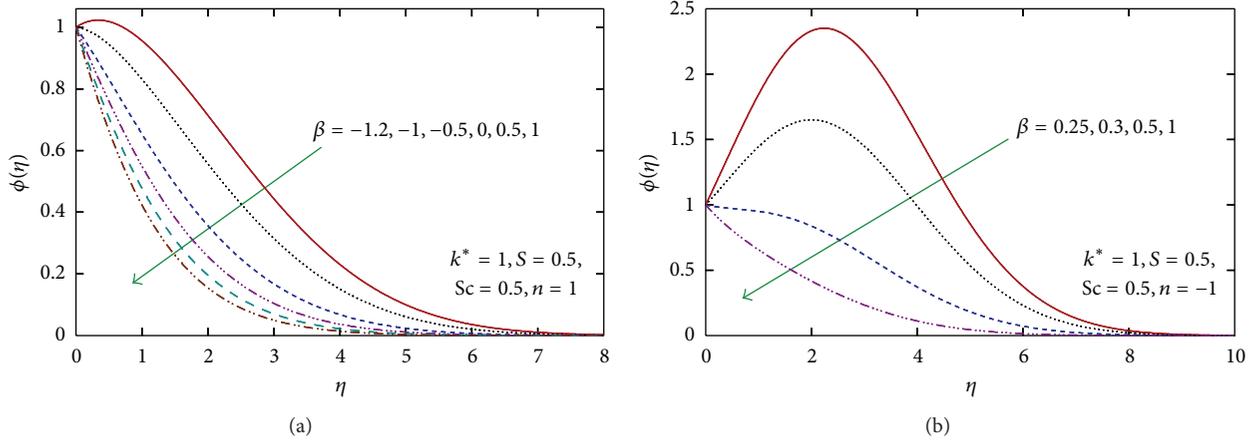


FIGURE 7: (a) Concentration profiles $\phi(\eta)$ for different values of β with $n > 0$. (b) Concentration profiles $\phi(\eta)$ for different values of β with $n < 0$.

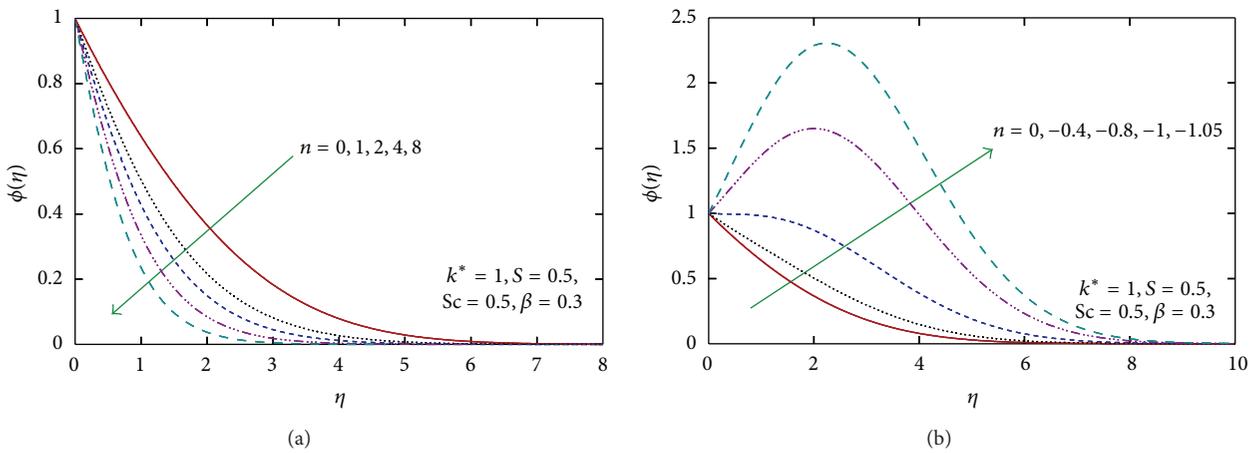


FIGURE 8: (a) Concentration profiles $\phi(\eta)$ for different values of $n (> 0)$. (b) Concentration profiles $\phi(\eta)$ for different values of $n (< 0)$.

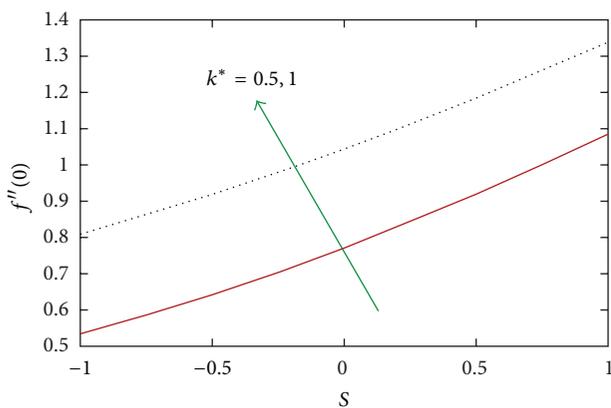


FIGURE 9: Local skin friction coefficient $f''(0)$ versus S for different values of k^* .

The study reveals that, with the increase permeability of the porous medium, the velocity increases and the concentration decreases. The suction through the porous plate causes decrease in the momentum and solute boundary layer thicknesses, while due to blowing both boundary layers become

thicker. For the increase in Schmidt number and reaction rate parameter the concentration reduces. Due to inverse variation of surface concentration (negative value of power-law exponent of surface concentration) mass absorption at the surface is observed in all cases, and mass transfer from the surface is found for direction variation (positive value of power-law exponent of surface concentration). But for higher constructive chemical reaction, mass absorption is seen even in direct variation of surface concentration along the surface.

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