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Flow Over an Exponentially Stretching Porous Sheet with Cross-diffusion Effects and Convective Thermal Conditions

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ABSTRACT

This article investigates the influence of cross-diffusion on the viscous fluid flow over a porous sheet stretching exponentially by applying the convective thermal conditions. Velocity slip at the boundary is considered. The numerical solutions to the governing equations are evaluated using successive linearisation procedure and Chebyshev collocation method. It is observed from this study that the rate of heat transfer escalated with enhance in the Biot number and reduced with increase in dufour number. While, the rate of mass transfer from the sheet to the fluid reduced with increase in both soret and Biot numbers. Finally, the obtained results for rate of heat transfer are compared with the published results in the literature for special cases. The influence of the pertinent parameters on the physical quantities are displayed through graphs.

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1. INTRODUCTION

The investigation of flow over a sheet elongated exponentially is of considerable interest because of its applications in industrial and technological processes, such as, fluid film condensation process, aerodynamic extrusion of plastic sheets, crystal growth, the cooling process of metallic sheets, design of chemical processing equipment and various heat exchangers and glass and polymer industries. The pioneering works of Sakiadis [1, 2], motivated the several researchers to investigate the stretched flow problem. Crane [3] is one among them, who extended the work of Sakiadis [1, 2]. Since then several researchers, to mention a few, Rohni et al. [4], Nadeem and Hussain [5], Khan et al. [6], Hayat et al. [7], Adeniyan and Adigun [8], Srinivasacharya and Jagadeeshwar [9], etc., investigated this flow problem for different geometries under different physical conditions.

The energy flux originated by a concentration gradient is termed as the diffusion-thermo or Dufour effect. While, the thermal-diffusion or Soret effect corresponds to mass fluxes created by temperature gradients. When the temperature and concentration gradients are considerably very large in areas such as petrology, hydrology, high-speed aerodynamics, geosciences, and so forth, the soret and dufour effects may just become strong despite recognising as second order phenomena. However, in most of the studies the importance of soret and dufour effects are neglected. Eckert and Drake [10] recognized in many instances, that the importance of these effects cannot be neglected. Inspite of engineering and industrial applications of these flows, a little attention (Srinivasacharya and Ramreddy [11], Sulochana et al. [12] etc,) is focussed on the flow over the sheets stretching exponentially including the soret and dufour effects.

Generally, accepted boundary condition on the solid surface is no-slip condition. However, Navier [13] suggested that fluid slips at the solid boundary and slip velocity depends linearly on the shear stress. The fluid slippage phenomenon at the solid boundary appear in numerous applications, for example, in nanochannels or microchannels and the cleaning of simulated heart valves, internal cavities. Using this velocity-slip conditions, Su and Zheng [14] reported the effects of Joule heating and Hall currents on the flow of nanofluid

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over a stretching wedge. Bhatnagar [15] studied the influence of the shape of stenosis and slip velocity on non-Newtonian flow of blood through a stenosed arterial segment. Sarabandi and Moghadam [16] considered the steady-state fully-developed laminar flow of non-Newtonian power-law fluids in a circular microchannel with slip boundary condition under an imposed constant wall heat flux. On the other hand, a novel technique for the heating process by providing the heat with finite capacity to the convecting fluid through the bounding surface has attracted by numerous researchers. This type of thermal boundary condition, called convective boundary condition, results in the rate of exchange of heat across the boundary being proportional to the difference in local temperature with the ambient conditions [17]. Due to the realistic nature of the convective thermal condition, the investigation of heat transfer with this condition has rich significance in mechanical and designing fields, for example, heat exchangers, atomic plants, gas turbines, and so forth. Hayat et al. [18] investigated the impact of convective thermal conditions on the MHD flow of nano-fluid over an stretching surface in porous medium. Rahman et al. [19] studied numerically the steady flow, thermal and solutal transfer process of a nano-fluid past a permeable exponentially shrinking surface using the Buongiorno's model. Recently, Srinivasacharya and Jagadeeshwar [20] investigated the slip flow of viscous fluid over a sheet stretching exponentially with convective thermal conditions. Though, there is considerable literature available on the flow, thermal and solutal transport towards a stretching surface, a significant investigations have not been carried out with convective thermal conditions in different physical situations.

Therefore, motivated by the above investigations and importance of these flows in engineering and manufacturing process, we made an attempt to analyse the cross-diffusion effects on the flow over a permeable stretching sheet with convective thermal conditions. In addition to these physical conditions, velocity slip at the surface and suction/injection are also considered.

2. MATHEMATICAL FORMULATION

Consider a stretching sheet in an incompressible viscous fluid with a temperature and concentration as T_∞ and C_∞, respectively. The Cartesian framework is selected by taking positive $\tilde{x}$-axis which is along the sheet and $\tilde{y}$-axis which is orthogonal to the sheet. The stretching velocity of the sheet is assumed as $U_*(\tilde{x}) = U_0\, e^{\tilde{x}/L}$ where $\tilde{x}$ the distance from the slit. Assume that the sheet is either cooled or heated convectively through a fluid with temperature T_f and which induces a heat transfer coefficient h_f, where $h_f = h\sqrt{U_0/2L}\; e^{\tilde{x}/2L}$. ($\tilde{u}_x$, $\tilde{u}_y$) is the velocity vector, $\tilde{C}$ is the concentration and $\tilde{T}$ is the temperature. The suction/injection velocity of the fluid through the sheet is $V_*(\tilde{x}) = V_0\, e^{\tilde{x}/2L}$, where V_0 is the strength of suction/injection. Further, the slip velocity of the fluid is assumed as $N(\tilde{x}) = N_0\, e^{-\tilde{x}/2L}$, where N_0 is the velocity slip factor. Hence, the following equations which governs the present flow with cross-diffusion effects [21, 22] are:

$$\frac{\partial \tilde{u}_x}{\partial \tilde{x}} + \frac{\partial \tilde{u}_y}{\partial \tilde{y}} = 0 \tag{1}$$

$$\tilde{u}_x \frac{\partial \tilde{u}_x}{\partial \tilde{x}} + \tilde{u}_y \frac{\partial \tilde{u}_x}{\partial \tilde{y}} = \nu \frac{\partial^2 \tilde{u}_x}{\partial \tilde{y}^2} \tag{2}$$

$$\tilde{u}_x \frac{\partial \tilde{T}}{\partial \tilde{x}} + \tilde{u}_y \frac{\partial \tilde{T}}{\partial \tilde{y}} = \alpha \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2} + \frac{D\kappa_T}{c_s\, c_p} \frac{\partial^2 \tilde{C}}{\partial \tilde{y}^2} \tag{3}$$

$$\tilde{u}_x \frac{\partial \tilde{C}}{\partial \tilde{x}} + \tilde{u}_y \frac{\partial \tilde{C}}{\partial \tilde{y}} = D \frac{\partial^2 \tilde{C}}{\partial \tilde{y}^2} + \frac{D\kappa_T}{T_m} \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2} \tag{4}$$

where υ, ρ, c_p, c_s, T_m, κ_T, α and D are respectively, the kinematic viscosity, the density, the specific heat capacity at the constant pressure, the concentration susceptibility, the mean fluid temperature, the thermal diffusion ratio, the thermal diffusivity and the mass diffusivity.

The conditions at the boundary are:

$$\left.\begin{array}{l} \tilde{u}_x = U_* + N\nu \dfrac{\partial \tilde{u}_x}{\partial \tilde{y}}, \tilde{u}_y = -V_*(\tilde{x}), \\ h_f(T_f - \tilde{T}) = -\kappa \dfrac{\partial \tilde{T}}{\partial \tilde{y}}, \tilde{C} = C_w \quad \text{at} \quad \tilde{y} = 0 \\ \tilde{u}_x \to 0, \tilde{T} \to T_\infty, \tilde{C} \to C_\infty \quad \text{as} \quad \tilde{y} \to \infty \end{array}\right\} \tag{5}$$

Substituting the stream functions $\tilde{u}_x = -\partial\psi/\partial\tilde{y}$ and $\tilde{u}_y = \partial\psi/\partial\tilde{x}$ and then the following dimensionless variables:

$$\left.\begin{array}{l} y = \tilde{y}\sqrt{U_0/(2\nu L)}\,e^{\frac{\tilde{x}}{2L}}, \quad \psi = \sqrt{2\nu L U_0}\,e^{\frac{\tilde{x}}{2L}} F(x,y), \\ \tilde{T} = T_\infty + (T_f - T_\infty)T(x,y), \\ \tilde{C} = C_\infty + (C_w - C_\infty)C(x,y) \end{array}\right\} \tag{6}$$

into Equations (1) - (4), we attain:

$$F''' + FF'' - 2F'^2 = 0 \tag{7}$$

$$\frac{1}{Pr}T'' + FT' + D_f\, C'' = 0 \tag{8}$$

$$\frac{1}{Sc}C'' + FC' + S_r\, T'' = 0 \tag{9}$$

The conditions at the boundary reduces to:

$$\left.\begin{aligned} &F(0) = S, \quad F'(0) = 1 + \lambda F''(0), \\ &T'(0) = -Bi(1 - T(0)), \quad C(0) = 1 \ \text{at} \quad y = 0 \\ &F'(\infty) \to 0, \quad T(\infty) \to 0, \quad C(\infty) \to 0 \ \text{as} \quad y \to \infty \end{aligned}\right\} \tag{10}$$

where $Bi = \frac{h}{\kappa}\sqrt{\nu}$ is the Biot number, $Pr = \nu / \alpha$ is the Prandtl number, $S_r = D\kappa_T\, T_0/(\upsilon C_0 T_m)$ is the soret number, $S = V_0\sqrt{2L/\nu U_0}$ is the suction/injection parameter according as $S > 0$ or $S < 0$ respectively, $D_f = D\ \kappa_T\ C_0/\ \upsilon C_s C_p T_0$ is the Dufor parameter, $\lambda = N_0\sqrt{\nu U_0 / 2L}$ is the velocity slip parameter, $Sc = \nu / D$ is the Schmidt number and the prime symbolizes the derivative with respect to y.

The local Nusselt number $Nu_{\tilde{x}} = \tilde{x}\, q_w/\kappa(T_f - T_\infty)$, and local Sherwood number $Sh_{\tilde{x}} = \tilde{x}\, q_m/\kappa(C_w - C_\infty)$, are given by:

$$\left. Nu_{\tilde{x}} = -\sqrt{\frac{\tilde{x}}{2L}}\sqrt{Re_{\tilde{x}}}\,T'(0) \ \text{and} \ Sh_{\tilde{x}} = -\sqrt{\frac{\tilde{x}}{2L}}\sqrt{Re_{\tilde{x}}}\,C'(0) \right\} \tag{11}$$

where $Re_{\tilde{x}} = \tilde{x}\, U_*(\tilde{x})/\upsilon$ is the local Reynolds number.

3. NUMERICAL SOLUTION

The system of Equations (7)–(9) is linearized using successive linearisation method (SLM) [23, 24]. In this method, the functions *F(y)*, *T(y)* and *C(y)* are expressed as:

$$\begin{aligned} &F(y) = F_r(y) + \sum_{i=0}^{r-1} F_i(y), T(y) = T_r(y) + \sum_{i=0}^{r-1} T_i(y), \\ &\text{and } C(y) = C_r(y) + \sum_{i=0}^{r-1} C_i(y) \end{aligned} \tag{12}$$

where $F_r(y)$, $T_r(y)$ and $C_r(y)$ (r = 1, 2, 3, ...) are functions, which are not known and $F_i(y)$, $T_i(y)$ and $C_i(y)$ ($i > 1$) are approximations. Substituting Equation (12) in Equations (7) to (9) and taking the linear part, we get:

$$F_i''' + \chi_{11,i-1}F_i'' + \chi_{12,i-1}F_i' + \chi_{13,i-1}F_i = \zeta_{1,i-1} \tag{13}$$

$$\chi_{21,i-1}F_i + \frac{1}{\Pr}T_i'' + \chi_{22,i-1}T_i' + D_f C_i'' = \zeta_{2,i-1} \tag{14}$$

$$\chi_{31,i-1}F_i + S_r T_i'' + \frac{1}{Sc}C_i'' + \chi_{32,i-1}C_i' = \zeta_{3,i-1} \tag{15}$$

where the coefficients $\chi_{lk,r-1}$ and $\zeta_{k,i-1}$, (l, k = 1, 2, 3) are in terms of the approximations F_i, T_i and C_i, ($i = 1,2,3,..., r-1$) and their derivatives.

The boundary associated conditions are:

$$\left.\begin{aligned} &F_r(0) = \lambda F_r''(0) - F_r'(0) = F_r'(\infty) = 0, \\ &T_r'(0) - Bi T_r(0) = T_r(\infty) = C_r(0) = C_r(\infty) = 0 \end{aligned}\right\} \tag{16}$$

Choosing the initial approximation $F_0(y)$, $T_0(y)$ and $C_0(y)$ satisfy the conditions (10) and solving the linear Equations (13) to (15) recursively, we get the solutions for $F_r(y)$, $T_r(y)$ and $C_r(y)$ ($r > 1$) and hence, *F(y)*, *T(y)* and *C(y)*.

To solve Equations (13) to (15) along with the boundary conditions (16), Chebyshev spectral collocation method [25] is used. The problem is solved for *[0, L]* instead of *[0, ∞)*, where the parameter *L* is used to recover the conditions at infinity.

To apply Chebyshev spectral collocation method, the domain under consideration *[0, L]* is transformed to *[-1, 1]* by the transformation $\xi = (2\eta / L) - 1, \quad -1 \le \xi \le 1$.

The unknown functions $F_r(y)$, $T_r(y)$ and $C_r(y)$ (r = 1, 2, 3, ...) and their derivatives are expressed in terms of Chebyshev polynomials $\Upsilon_k(\xi) = \cos(k\cos^{-1}(\xi))$ at N+1 Gauss-Lobatto collocation points $\xi_k = \cos(\pi k / N)$, $k = 1, 2, \ldots N$ as:

$$\begin{aligned} &\Gamma_r(\xi) = \sum_{k=0}^{N} \Gamma_r(\xi_k)\Upsilon_k(\xi_m) \quad \text{and} \\ &\frac{d^{\mathbf{a}}\Gamma_r}{dy^{\mathbf{a}}} = \sum_{k=0}^{N} \mathbf{D}^{\mathbf{a}}_{\mathbf{km}}\Gamma_i(\tilde{\tau}_k), \end{aligned} \tag{17}$$

where $\Gamma_r(y) = F_r(y)$ or $T_r(y)$ or $C_r(y)$, **D**= $2\mathcal{D}$/L with $\mathcal{D}$ is the Chebyshev derivative matrix and **a** is the order of the derivative.

Substituting in (17) in (13) - (15) leads to the matrix equation (for details see ([23, 24]). Incorporating boundary conditions and solving the resulting matrix system, we get the solution.

4. RESULTS AND DISCUSSION

Numerical values for $-T'(0)$ of Magyari and Keller [22] are compared with the results of current method for particular values of $D_f = 0$, $\lambda = 0$, $S_r = 0$, $S = 0$ and $Bi \to \infty$ shown in Table 1 and found to be in good agreement.

To elucidate the significance of relevant parameters, the numerical calculations are carried out by taking $S = 0.5$, $D_f = 0.03$, $Sc = 0.22$, $Pr = 1.0$, $\lambda = 1.0$, $S_r = 0.5$, $Bi = 1.0$, $N = 100$ and $L = 20$ unless otherwise mentioned.

TABLE 1. Comparative analysis for *–T'(0)* by the current method for for $S_r = 0$, $\lambda = 0$, $D_f = 0$, $S = 0$ and $Bi \to \infty$

	Nusselt number –*T'(0)*		
Pr	**Magyari and Keller [26]**	**Present**	**Error Percent**
0.5	0.330493	0.330537	0.013313
1	0.549643	0.549643	0.000000
3	1.122188	1.122086	0.009089
5	1.521240	1.521238	0.000131
8	1.991847	1.991836	0.000552
10	2.257429	2.257422	0.000310

The influence of slip and suction/injection parameters on the fluid velocity is portrayed in the Figures 1(a) – 1(b). It is evident from the Figures 1(a) and 1(b) that raise in slipperiness and fluid suction diminishes the fluid velocity while injection is enhancing the velocity.

The variation of temperature distribution with Bi, λ, S, and D_f is plotted through the Figures 2(a) – 2(d). Figure 2(a) illustrates that the temperature is enhancing with raise in the value of Bi and hence gain in thickness of thermal boundary. Further, for large value of Biot number, the convective thermal condition from (10) transforms to $T(0) \to 1$, which signifies the constant wall condition.

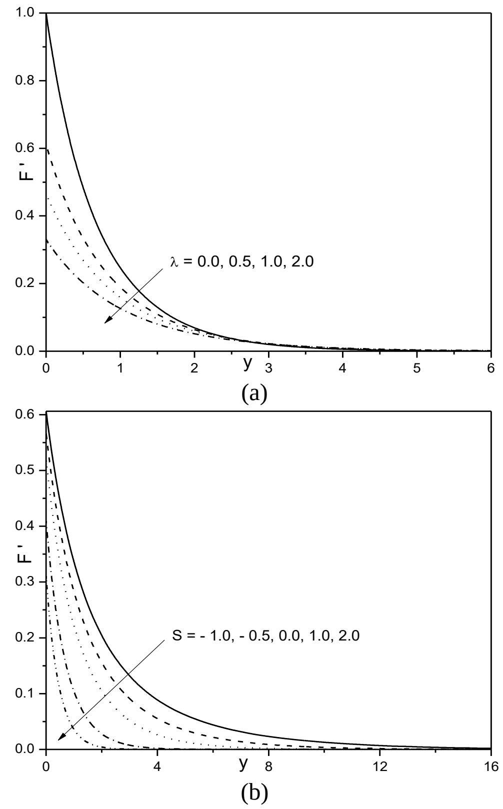


Figure 1. (a) Influence of λ on F', (b) Influence of S on F'

It is evident from the Figure 2(b) that temperature enhanced with a raise in slipperiness.

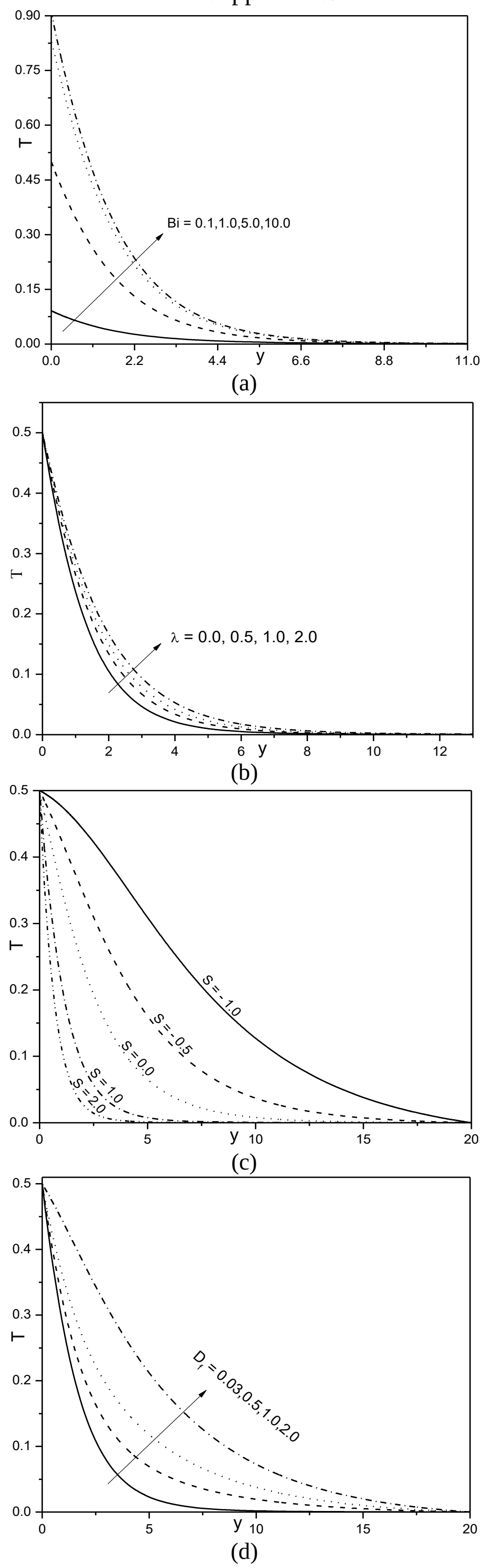
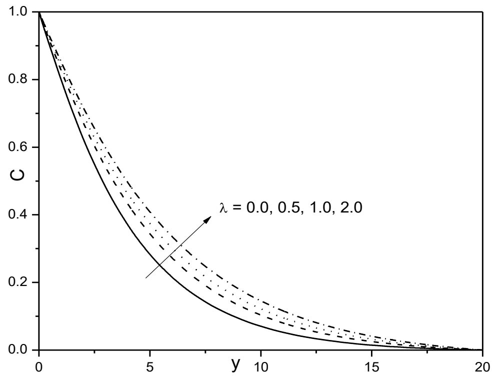


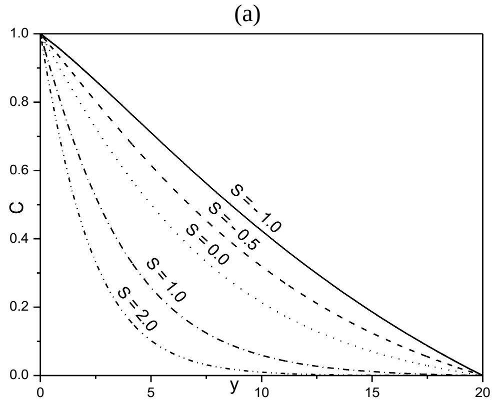
Figure 2. (a) Influence of Bi on T , (b) Influence of λ on T, (c) Influence of S on T, (d) Influence of D_f on T

It is well known fact that wall suction reduces the thickness of thermal boundary layer and hence, reduction in temperature arises. This phenomenon is graphically presented in the Figure 2(c). However, the wall injection produces the exact contradictory nature. It is observed from the figures that the thickness of the thermal boundary layer is increased with an increase in the values of Dufour number as shown in Figure 2(d).

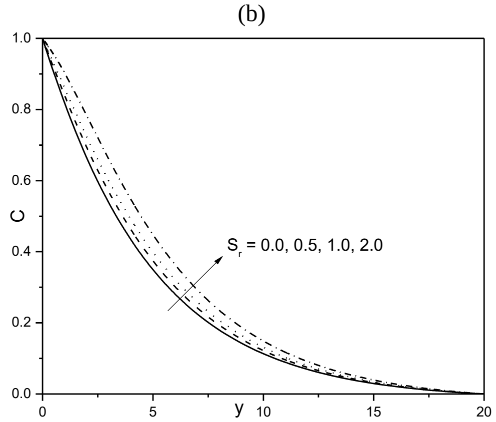
The influence of λ, S, S_r and Bi on concentration of the fluid is shown graphically in Figures 3(a) – 3(d). It is clear from the Figure 3(a) that the increase in slipperiness rises the concentration. On the other hand, the wall injection enhanced the fluid concentration and suction reduced the concentration as shown in the Figure 3(b).



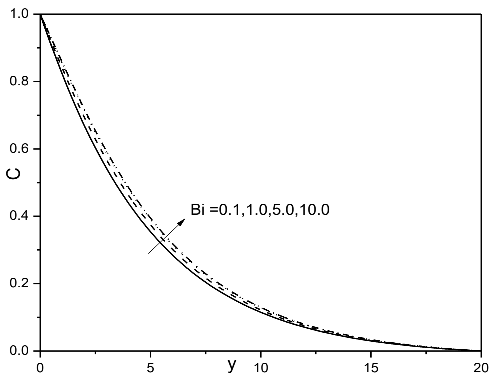
(a)



(b)



(c)

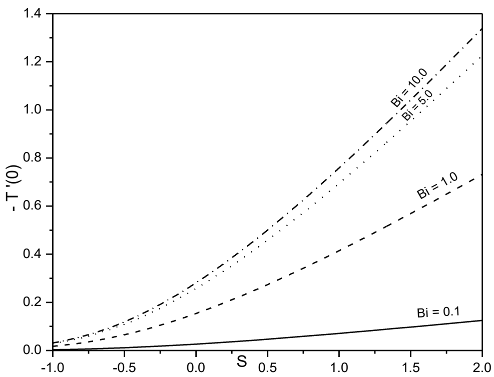


(d)

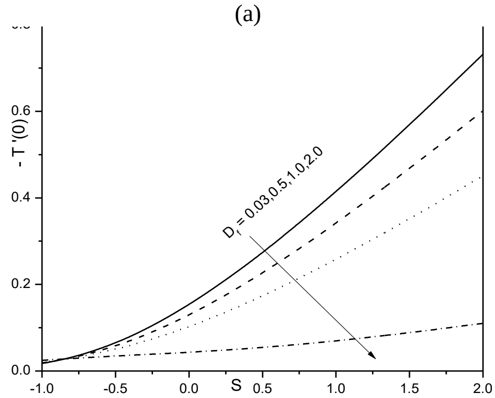
Figure 3. (a) Influence of λ on C, (b) Influence of S on C (c) Influence of S_r on C, (d) Influence of Bi on C

The impact of Soret number on concentration profile is presented in Figure 3(c). It is apparent from this figure that the concentration is increased with an increase in S_r. Figure 3(d) illustrates that the concentration is enhanced with a raise in the value of Bi and hence gain in thickness of the concentration boundary. However, the enhancement in concentration is less compared to that temperature with a rise in Biot number as shown in the Figure 2(a).

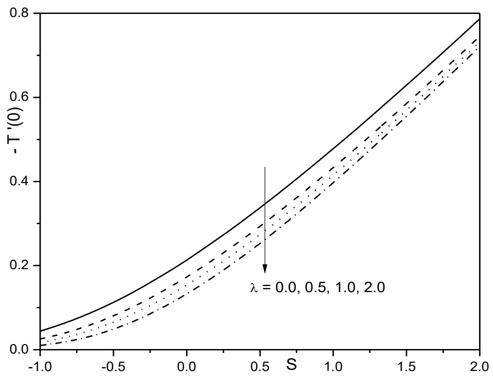
The influence of Bi, D_f and λ on the rate of heat transfer with S are depicted through the Figures 4(a) – 4(c). Figure 4(a) demonstrates that the rate of heat transfer is increased with a rise in Bi.



(a)



(b)



(c)

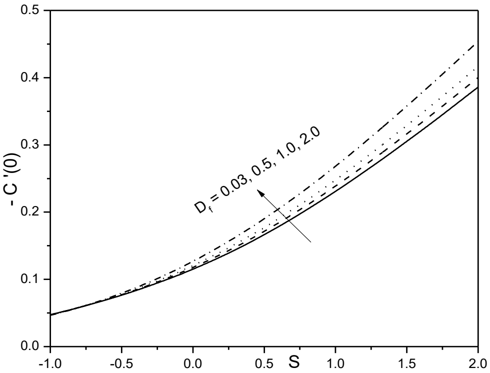
Figure 4. (a) Influence of *Bi* on *–T'(0)*, (b) Influence of D_f on *–T'(0)* (c). Influence of λ on *–T'(0)*

On the other hand, Figures 4(b) and 4(c) depict the behaviour of rate of heat transfer for different values of Dufour number and slip parameter. It is clear from these figures that the rate of heat transfer decreases with increasing values of Dufour number and slip parameter. Further, it is noticed that the rate of heat transfer is enhancing with fluid suction in the presence all pertinent parameters.

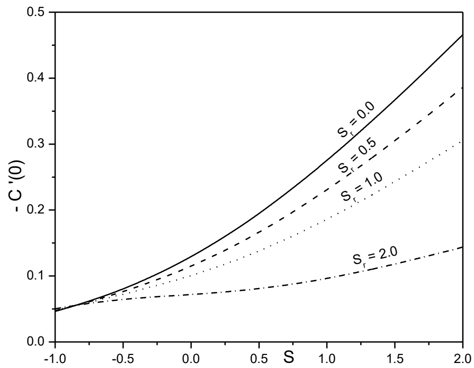
The rate of mass transfer under the influence of Dufour, Soret, Biot numbers and velocity slip parameter is represented in Figures 5(a) - 5(d). It is noticed from the Figure 5(a) that the rate of mass transfer is enhanced with an enhancement in the value of D_f. While, reduction in the rate of mass transfer is observed with the rise in S_r as portrayed in Figure 5(b). Figures 5(c) and 5(d) depict that the rate of mass transfer is diminishing with rise in Biot number and slip parameter. On the other hand, the rate of mass transfer from the sheet to the fluid is enhancing with fluid suction.

5. CONCLUSION

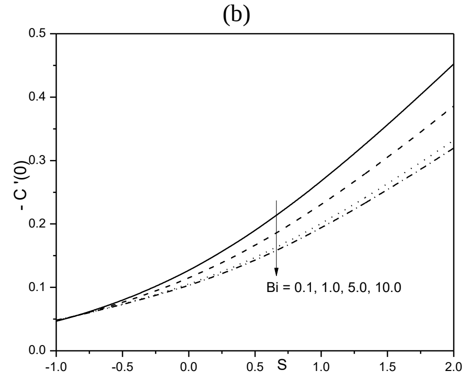
The influence of cross-diffusion effects on the flow over a sheet stretching exponentially in presence of convective thermal conditions has been studied.



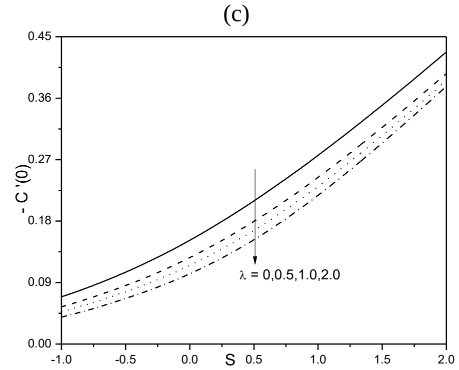
(a)



(b)



(c)



(d)

Figure 5. (a) Influence of D_f on *–C'(0)*, (b) Influence of S_r on *–C'(0),* (c) Influence of *Bi* on *–C'(0)* (d). Influence of λ on *–C'(0)*

Successive linearization method along with the Chebyshev collocation method is used to solve the governing equations.

- Velocity of the fluid is reduced with a decrease in slip and fluid suction. Skin-friction diminished with a rise in the suction and enhanced with slip.
- Fluid temperature is escalated with a rise in Dufour, Biot numbers and slip parameter and decelerated with fluid suction.
- Fluid concentration is enriched with a rise in Biot and soret numbers and reduced with an increase in slip parameter.
- Rate of heat transfer is enhanced with a rise in Biot number and fluid suction. It decreased with an increase in the Dufour number and slip.

- An increase in suction and Dufour number escalated the rate of mass transfer. It diminished with increase in Soret, Biot numbers and velocity slip.

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Flow Over an Exponentially Stretching Porous Sheet with Cross-diffusion Effects and Convective Thermal Conditions

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چکیده

این مقاله تأثیر نفوذ عرضی را بر روی جریان مایع چسبنده بر روی یک ورقه متخلخل کششی به طور نمادین با استفاده از شرایط حرارتی کنتراست مورد بررسی داده است. لغزش سرعت در مرز در نظر گرفته شده است. راه حل های عددی برای معادلات حاکم با استفاده از روش خطی سازی متوالی و روش جابجایی Chebyshev ارزیابی می شود. از این مطالعه مشاهده می شود که میزان انتقال حرارت با افزایش عدد بیو افزایش می یابد و با افزایش عدد dufour کاهش می یابد. در حالی که سرعت انتقال جرم از ورق به مایع با افزایش هر دو عدد بیو و soret کاهش می یابد. در نهایت، نتایج به دست آمده برای میزان انتقال حرارت با نتایج منتشر شده در پیشینه ادبیات برای موارد خاص مقایسه می شود. تأثیر پارامترهای مربوط به مقادیر فیزیکی از طریق نمودارها نمایش داده می شود.

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