J Ther Eng, Vol. 12, No. 2, pp. 656–664, March, 2026

Journal of Thermal Engineering
Web page info: https://jten.yildiz.edu.tr
DOI: 10.14744/thermal.0001108

Research Article

Influence of viscous dissipation, chemical reaction, thermophoresis and heat absorption on the flow via an exponentially stretching sheet

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ARTICLE INFO

Article history
Received: 26 November 2024
Accept: 17 January 2025

Keywords:
Heat Absorption, Chemical Reaction, Thermophoresis, Viscous Dissipation, Eckert Number, Schmidt Number

ABSTRACT

The effects of convective boundary conditions on the flow of a viscous fluid through a porous sheet that is expanding exponentially are studied in this study, along with additional factors such as heat absorption, viscous dissipation, thermophoresis, chemical reactions, and others. The numerical solutions to the governing equations are evaluated using the bvp4c technique in conjunction with similarity requirements. The effect of different parameters on different physical variables are depicted using graphs. The fluid›s velocity increases with the increase in thermophoretic parameter. The temperature profile decreases with the rise in Grashof number and Schmidt number. While the concentration profile escalates with the rise in Schmidt number. Many real-world situations involve the co-existence of thermophoresis, viscous dissipation, chemical processes, heat absorption etc.

Cite this article as: Mudoi S, Sarma D. Influence of viscous dissipation, chemical reaction, thermophoresis and heat absorption on the flow via an exponentially stretching Sheet. J Ther Eng 2026;12(2):656–664.

INTRODUCTION

A common issue in fluid dynamics is fluid flow over stretched surfaces, which has substantial importance to several industrial and technical uses. Not only does the dynamic interaction between a fluid and a stretched surface shed light on fundamental fluid mechanics, but it also plays a crucial part in the optimisation of mass and heat transfer processes. When considering how various physical phenomena, such as heat absorption, chemical reactions, viscous dissipation, thermophoresis, etc., interact with one another, the research of this issue becomes more complex.

The impact of heat absorption or generation is crucial in many real-world scenarios. This could be from internal exothermic chemical reactions taking place in the fluid or by heating the system from outside sources. For processes to be optimised in fields ranging from materials processing to renewable energy systems, it is crucial to comprehend how heat is absorbed or created and its subsequent impact on temperature distributions and rates of transfer of heat. Boundary layer above an uninterrupted flat surface, was described by Sakiadis BC [1]. Sakiadis B.C. [2] also describe boundary-layer equations for axisymmetric, two-dimensional flow. Using convective boundary conditions, Hayat and Obaidat [3] studied the boundary layer flow of a nanofluid across an exponentially stretched sheet. Hayat and coauthors [4] investigated the role of convective

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This paper was recommended for publication in revised form by Editor-in Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey
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heat and mass transport in the Powell-Eyring fluid flow through an exponentially extending sheet PloS one. Khan et al. [5] performed a numerical analysis of a nanofluid flowing past through a stretched sheet that is being heated convectively in three dimensions. Magnetohydrodynamics unsteady flow of heat transfer through a sheet with stretching capacity for radiating fluid in the presence of the Dufour effect was studied by Sivaiah and Reddy [6]. Nandhini, and co-authors [7] evaluated the impact of chemical reaction as well as that of the radiation absorption about Casson fluid across an exponential sheet under slip conditions with ethanol as that solvent.

The issue is made more difficult by chemical processes occurring within the fluid. Fluid movement frequently coexists with chemical reactions in industrial and environmental applications. These reactions add to the complexity in this type of analysis of heat transfer as well as that of the flow by drastically changing the fluid's properties, such as density and viscosity. Paul and Das [8] studied about a sheet that has been stretched exponentially experiences thermal and mass transfer while undergoing chemical reaction. Goud, Reddy, Wakif [9] analysed about an inclined spinning disc with nanofluid is subjected to a numerical investigation of the heat & mass transport characteristics of the MHD flow with chemical reaction and heat absorption. An unstable MHD heat and mass transfer fluid flow is present, together with radiation and heat absorption, along with that of the Soret effect. This is studied on an infinite vertical plate by Goud and Reddy [10]. Veera Krishna [11] studied about MHD free convective Casson nanofluids passing through an endlessly oscillating vertical porous plate undergo chemical reaction, Newtonian heating and heat absorption. A chemical reaction with Soret effects along with the impact of absorption of heat and is present in the unstable MHD Casson oscillatory flow fluid across a vertical inclined porous plate was analysed by Kodi and Mopuri [12]. Jayarami Reddy [13] investigated a radiating fluid flowing through an accelerated inclined porous plate with hall current in a MHD heat & mass transfer flow. Patil and co-authors [14] investigation on thermal radiation along with that of the chemical reaction-induced MHD Williamson nanofluid flow across a permeable stretching sheet. The impact of radiation and viscous dissipation on MHD heat transfer in Casson nanofluid flows across a nonlinear stretching surface with chemical reactions was investigated by Kumar et al. [15].

Another important issue to take into account is viscous dissipation, a phenomenon where mechanical energy is transformed into that of the thermal energy within a fluid which is viscous in nature. The shearing of the fluid layers as it passes over the stretching surface produces heat. It is essential to properly account for viscous dissipation in order to estimate temperature profiles and with accuracy the rates of transfer of heat. Through a porous material with viscous dissipation, along with that of the thermal radiation and there is unstable flow of heat transfer and MHD through a stretching sheet. This study was done by Anuar Ishak [16]. B. Zigta's [17] investigation into impacts of viscosity dissipation, chemical reaction, along with that of the heat radiation on a MHD flow. Under the influence of suction and injection, the dynamics of thermal radiation and heat production and absorption on a viscous MHD micropolar fluid are investigated by Adeyemi et al. [18]. Rahman et al. [19] examined the impact of variations in the thermophysical parameters of the heat transfer fluid on pumping performance, specifically regarding delivery rate, slip factor coefficient, and volumetric efficiency. Dang et al. [20] investigated the numerical study of non-Newtonian free stream flow in three-dimensional magnetohydrodynamics caused by a permeable stretching surface.

Consideration of suspended particles in the moving fluid requires consideration of thermophoresis, which describes how particles move in response to temperature gradients. In applications ranging from nanoparticle deposition in materials manufacturing to aerosol dynamics in environmental research, this phenomenon can have an impact on concentration profiles and overall mass transfer rates. Shehzad et al. [21] studied the impact of Joule heating and thermophoresis on Jeffrey fluid radiative flow with mixed convection. Effects of thermophoresis, viscous dissipation etc. on MHD flow through a radiatively permeable, sloped surface with changing thermal conductivity was analysed by Reddy [22]. Umme et al. [23] examine the impact of thermophoresis and Brownian diffusion on the convective boundary layer flow of micropolar fluids across a stretched wedge-shaped surface. Makinde and Animasaun [24] investigated the effects of thermophoresis and Brownian motion on the magnetohydrodynamic bioconvection of nanofluid, including nonlinear thermal radiation and quartic chemical reaction, along the upper horizontal surface of a paraboloid of revolution. Ganjikunta et al. [25] investigated the effects of activation energy and diffusion thermodynamics on unsteady magnetohydrodynamic Maxwell fluid flow across a porous, vertically stretched sheet, including thermophoresis and Brownian motion.

Research on flow across a stretching sheet up to this point has mostly concentrated on these components' individual effects or small combinations. However, many real-world situations involve the co-existence of thermophoresis, viscous dissipation, chemical processes, heat absorption etc. Therefore, it's crucial to have a thorough understanding of how they all interact. Natural convection across a wavy surface inclined in a porous, saturated medium: effects of thermal radiation and stratification, was researched by Wu and Lei [26]. Srinivasacharya and coauthors [27] studied about heat convective boundary conditions with slip viscous flow across an increasingly extending porous sheet. Researchers looked at the effects of radiation and chemical reaction on the flow of a nanofluid through a nonlinearly porous stretched sheet with a nonuniform heat source during MHD heat transfer was studied by Reddy, Mangamma [28]. Mahmood et al. [29] researched about tri-hybrid nanofluid numerical analysis across that given nonlinear sheet in conditions of heat generation, heat absorption, and slip. The current study intends to look into how these variables interact to affect the flow characteristics near an exponentially stretched sheet. The current study's objective is to offer information on the impacts of heat absorption and chemical reaction on a fluid that is unstable, incompressible, viscous, electrically conducting, Newtonian, chemically reactive, and radiating. This research was motivated by Srinivasacharya and Jagadeeshwar [30], who studied about how flow across an exponentially stretched sheet is affected by thermophoresis and viscous dissipation.

MATHEMATICAL FORMULATION

Take into consideration a stretched sheet in flow of a laminar slip, a viscous incompressible fluid with concentration C_∞ and temperature T_∞. By placing the positive $\bar{x}$-axis parallel and that of $\bar{y}$-axis perpendicular to the sheet, the Cartesian framework is determined. A $U_*(\bar{x}) = U_0 e^{\frac{\bar{x}}{L}}$ assumption is made regarding the sheet's stretching velocity, where $\bar{x}$ denotes distance from the slit. Consider that a fluid with a heat transfer coefficient of h_f also a temperature of T_f is used to either convectively cool or heat the sheet, where $h_f = h\sqrt{\frac{U_0}{2L}}$, the velocity vector is $(\bar{u}_x, \bar{u}_y)$, $\bar{C}$ is the concentration and $\bar{T}$ is the temperature. The flow across the sheet is injected/sucked at a velocity of $V_*(\bar{x}) = V_0 e^{\frac{\bar{x}}{2L}}$; V_0 is strength of suction or injection. On top of that, $N(\bar{x}) = N_0 e^{-\frac{x}{2L}}$ is supposed to be the fluid's slip velocity.

Applying the approximations of boundary layer of that fluid & using Boussinesq approximation; the governing equations of flow of the fluid are given by:

$$\frac{\partial \bar{u}_x}{\partial \bar{x}} + \frac{\partial u_y}{\partial \bar{y}} = 0 \tag{1}$$

$$\bar{u}_x \frac{\partial \bar{u}_x}{\partial \bar{x}} + \bar{u}_y \frac{\partial \bar{u}_x}{\partial \bar{y}} = v\frac{\partial^2 \bar{u}_x}{\partial \bar{y}^2} + g\beta(\bar{T} - T_\infty) + g\beta^*(\bar{C} - C_\infty) \tag{2}$$

$$\bar{u}_x \frac{\partial \bar{T}}{\partial \bar{x}} + \bar{u}_y \frac{\partial \bar{T}}{\partial \bar{y}} = \alpha\frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \frac{\mu}{\rho c_p}\left(\frac{\partial \bar{u}_x}{\partial \bar{y}}\right)^2 + \frac{Q_x}{\rho c_p}(\bar{T} - T_\infty) \tag{3}$$

$$\bar{u}_x \frac{\partial \bar{c}}{\partial \bar{x}} + \bar{u}_y \frac{\partial \bar{c}}{\partial \bar{y}} = D\frac{\partial^2 \bar{c}}{\partial \bar{y}^2} - \frac{\partial}{\partial \bar{y}}[V_T(\bar{C} - C_\infty)] - K_c(\bar{C} - C_\infty) \tag{4}$$

where D mass diffusivity of given medium, α thermal diffusivity, v kinematic viscosity, V_T thermophoretic velocity, c_p specific heat capacity at constant pressure. V_T can be written as:

$$V_T = -\frac{vk_t}{T_r}\frac{\partial \bar{T}}{\partial \bar{y}} \tag{5}$$

where the thermophoretic coefficient k_t and the reference temperature Tr. Boundary conditions are

$$\begin{aligned}&\bar{u}_x = U_* + Nu\frac{\partial \bar{u}_x}{\partial \bar{y}},\ \bar{u}_y = -V_*(\bar{x}), -k\frac{\partial \bar{T}}{\partial \bar{y}} = h_f\left(T_f - \bar{T}\right),\\ &\bar{C} = C_w\ \ at\ \bar{y} = 0\end{aligned} \tag{6}$$

$$\bar{u}_x \to 0,\ T \to T_\infty,\ C \to C_\infty\ \ as\ \ \bar{y} \to \infty \tag{7}$$

steam function $\psi(x,y)$ is given as,

$$u' = \frac{\partial \psi}{\partial y\prime},\ v' = -\frac{\partial \psi}{\partial x\prime} \tag{8}$$

We use some non-dimensional quantities, those are:

$$\begin{gathered}x = \frac{\bar{x}}{L}, y = \bar{y}\sqrt{\frac{U_0}{2vL}}e^{\frac{\bar{x}}{2L}}, \psi = \sqrt{2vLU_0}e^{\frac{\bar{x}}{2L}}F(x,y), Q = \frac{Q_x v}{U_0^2},\\ Gr = \frac{g\beta v(\bar{T}_w - T_\infty)}{U_0^3}, Gm = \frac{g\beta^* v(\bar{C}_w - C_\infty)}{U_0^3}, \gamma = \frac{K_c x}{U_0^2},\\ \bar{T} = T_\infty + \left(T_f - T_\infty\right)T(x,y), \bar{C} = C_\infty + (C_f - C_\infty)C(x,y)\end{gathered}$$

These non-dimensional quantities are used to create the governing equations, which have the following form:

$$F''' + FF'' - 2F'^2 - GrT - GmC = 0 \tag{9}$$

$$\frac{1}{Pr}T'' + FT' + Ec\, e^{2x}F'' - QT = 0 \tag{10}$$

$$\frac{1}{Sc}C'' + FC' - \tau(T'C' + CT') + \gamma C = 0 \tag{11}$$

where $S = V_0\sqrt{\frac{2L}{vU_0}}$ is suction parameter according to $S > 0$ or $S < 0$ respectively, Ec is the Eckert number, Bi Biot number, τ is the Thermophoretic parameter, Q is the heat absorption parameter, Sc Schmidt number, Pr Prandtl number The transformed boundary conditions are as follows:

$$\begin{gathered}F(x,0) + 2\frac{\partial F}{\partial x}(x,0) = S, F'(x,0) = 1 + \lambda F''(x,0)\\ T'(x,0) = -Bi\big(1 - T(x,0)\big), C(x,0) = 1\\ F'(x,y) \to 0, T(x,y) \to 0, C(x,y) \to 0 \quad as\ y \to \infty\end{gathered} \tag{12}$$

Dimensionless Sherwood number $Sh_{\bar{x}}$, skin friction C_f, Nusselt number $Nu_{\bar{x}}$ are given by:

$$\begin{gathered}\sqrt{\frac{L}{2x}}\sqrt{Re_{\bar{x}}}C_f = F''(x.0), \sqrt{\frac{2}{Lx}}\frac{Nu_{\bar{x}}}{\sqrt{Re_{\bar{x}}}} = -T'(x,0),\\ \sqrt{\frac{2}{Lx}}\frac{Sh_{\bar{x}}}{\sqrt{Re_{\bar{x}}}} = -C'(x,0)\end{gathered} \tag{13}$$

Solution of the Problem

The equations (2)-(4) with boundary conditions (6)-(7) are converted to non-dimensional (9)-(11) equations along with respective boundary conditions (12), by using the dimensionless quantities and then solved those equations by bvp4c method in MATLAB. Values of Sherwood number, skin friction as well as Nusselt number were found numerically by this method.

To apply finite difference-based solver bvp4c the dimensionless equations (9)-(11) respectively transformed as:

$$F = y1,\ F' = y1' = y2,\ F'' = y2' = y3;$$
$$T = y4, T' = y4' = y5;\ C = y6, C' = y6' = y7$$
$$y3' = -y1y3 + 2y2^2 + Gry4 + Gmy6 + \frac{1}{K}y2$$
$$y5' = Pr(-y1y5 - Ece^{2x}y3 + Qy4)$$
$$y7' = Sc(-y1y7 + \tau(y5y7 + y6y5))$$

Also initial as well as the boundary conditions (12) are transformed as:

$$y1(0) + 2y2(0) = S;\ y2(0) = 1 + \lambda y3(0);$$
$$y5(0) = -Bi(1 - y4(0));\ y6(0) = 1$$
$$y2(\infty) = 0;\ y4(\infty) = 0;\ y6(\infty) = 0$$

These transformed results are used in MATLAB to perform the numerical computation of the solution.

RESULTS AND DISCUSSION

This paper analyses the fluid flow pattern over an exponentially stretching sheet that is influenced by heat absorption, viscous dissipation, thermophoresis, and chemical reactions in a magnetohydrodynamic flow. The governing equations of the flow model are solved using the bvp4c technique. Analyses have been conducted on the influence of physical parameters on the model solution, including the Grashof number, suction parameter, thermophoretic parameter, Schmidt number, Prandtl number, and Eckert number.

The effect of the thermophoretic parameter τ temperature profile is presented in Figure 1. Increase in the value of τ increases the temperature of the fluid as shown in Figure 1. This is because fluid particles start to move away from cold settings when the thermophoretic parameter increases. Figure 2 shows how the velocity profile changes when the suction parameter S is present. By boosting the value of S, velocity is seen to be increasing. According to Figure 3, the temperature of the fluid falls as the suction parameter S value rises. On the other hand, as seen in Figure 4, concentration rises as suction S increases. Suction effects in fluid flow change the fluid's velocity and pressure distribution close to surfaces or inside flow fields. Suction includes the evacuation of fluid from a particular area. By reducing the thickness of the boundary layer close to the surface, it improves heat transfer while reducing drag and delaying separation.

The fluid velocity decreases with increasing *Pr* which is shown in Figure 5. In physical meaning, the result is possible that the fluids with greater *Pr* have high viscosity, this makes the fluid thicker and so it moves slowly. The fluid temperature increases with increasing *Pr*, which is describe in Figure 6. This is possible because, growing *Pr* reduce the boundary layer thickness. When *Pr* increases, the thickness of fluids boundary layer decreases because *Pr* is the reciprocal of momentum to thermal diffusivity. The decrease in the Prandtl number causes a reduction in momentum

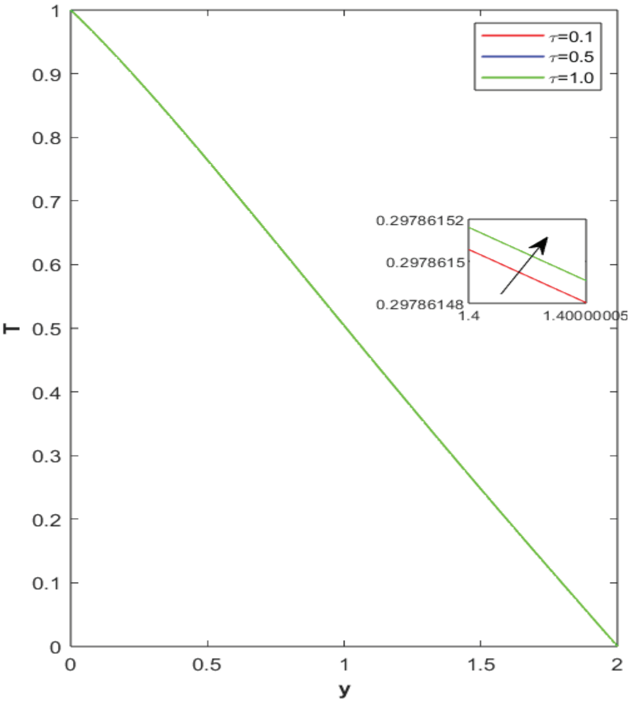

Figure 1. Temperature profile for the values of τ.

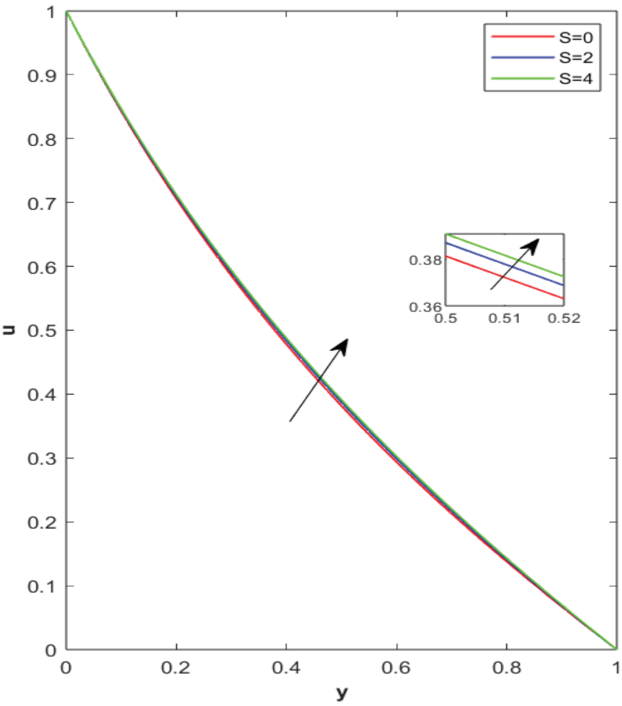

Figure 2. Velocity variation against the values of S.

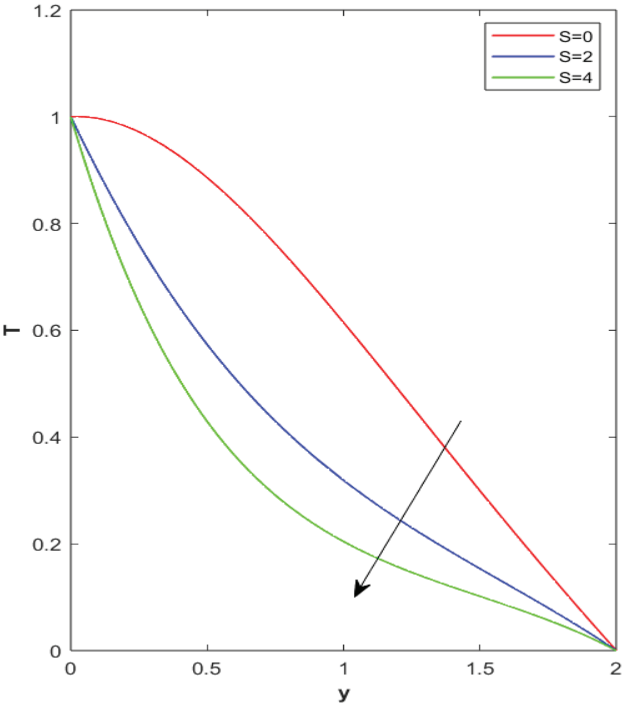

Figure 3. Temperature variation against the values of S.

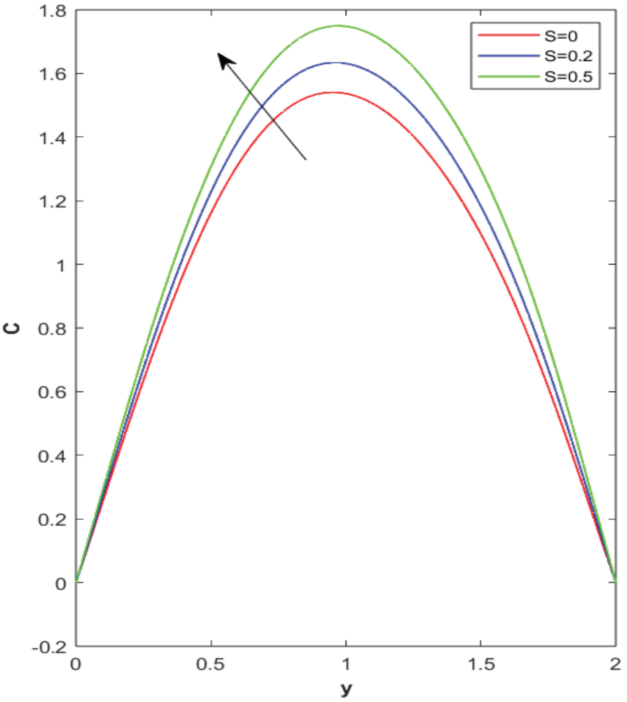

Figure 4. Concentration variation against the values of S.

diffusivity relative to thermal diffusivity. Consequently, the velocity profile becomes steeper as momentum diffuses less effectively compared to heat. Conversely, the increase in thermal diffusivity concerning momentum diffusivity amplifies the rate of thermal diffusion. Thus, the temperature profile becomes smoother and broader due to enhanced heat transfer away from the sheet, resulting in a lower temperature gradient near the surface. The effects of the thermal Grashof number (*Gr*) on u are depicted in Figure 7. In these situations, fluid velocity falls off as *Gr* values rise. The viscous force and thermal buoyancy force are defined by *Gr*. Thus, as *Gr* increases, the forces of heat and concentration get stronger. An increase in the Grashof number amplifies the dominance of buoyancy forces over viscous forces. Consequently, the fluid's momentum near the surface decreases as buoyancy becomes more influential, leading to a reduction in the velocity profile. Figure 8 shows how the value of the fluid's velocity will increase with the value of *Ec*. Figure 9 clearly shows that the temperature rises as the value of *Ec* rises. A decrease in the Eckert number for the velocity profile implies that the kinetic energy per unit mass of the fluid becomes relatively less significant compared to the heat energy per unit mass. This could mean that the influence of heat transfer on the flow dynamics is becoming more pronounced. In the case of temperature, this means that the thermal energy per unit mass becomes more significant, indicating enhanced heat transfer. This might be due to various factors, such as the influence of the magnetic field or the properties of the stretching sheet. With increasing amounts of *Sc*, as shown in Figures 10 and 11, temperature falls as concentration rises. The fact that *Sc* is a ratio of momentum to mass diffusivity enhances the efficiency of mass and momentum transfer in the boundary layer concentration. A decrease in the Schmidt number for the temperature profile suggests that viscous effects become

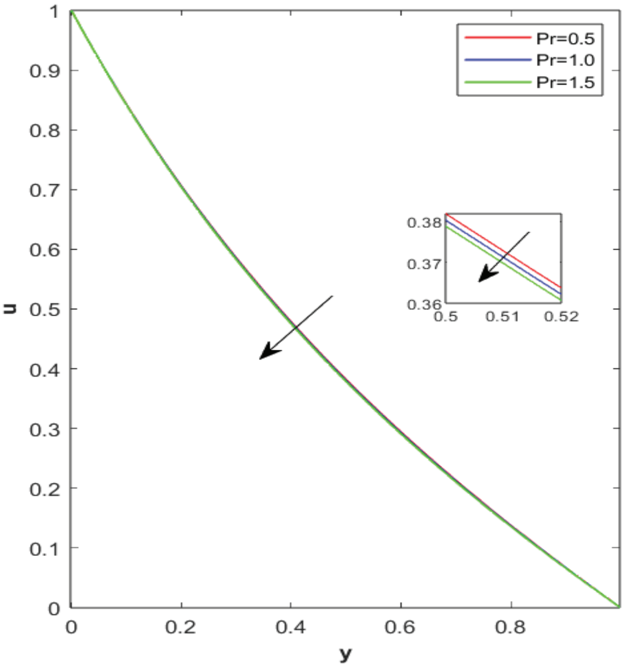

Figure 5. Velocity variation against Pr.

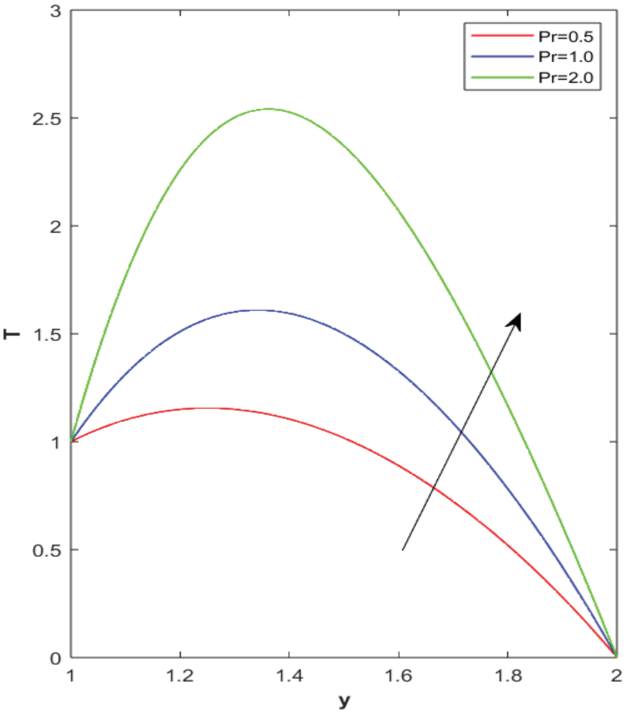

Figure 6. Temperature variation for Pr.

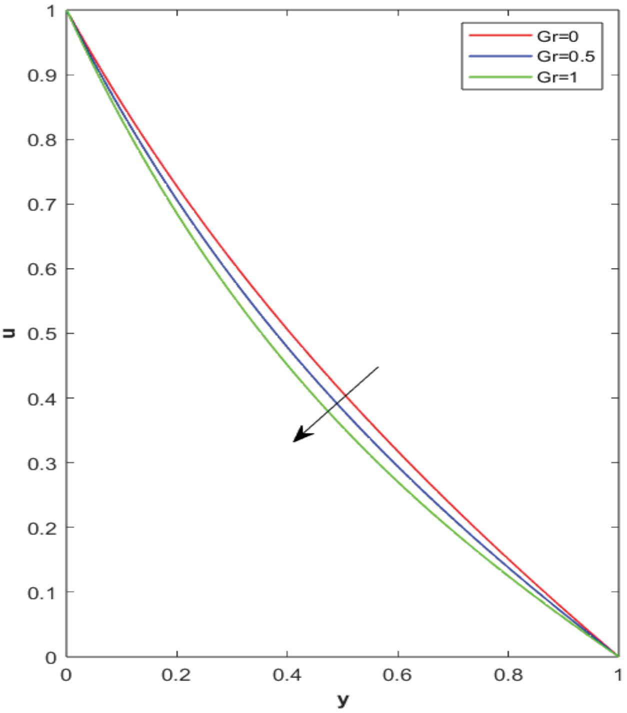

Figure 7. Velocity variation for Gr.

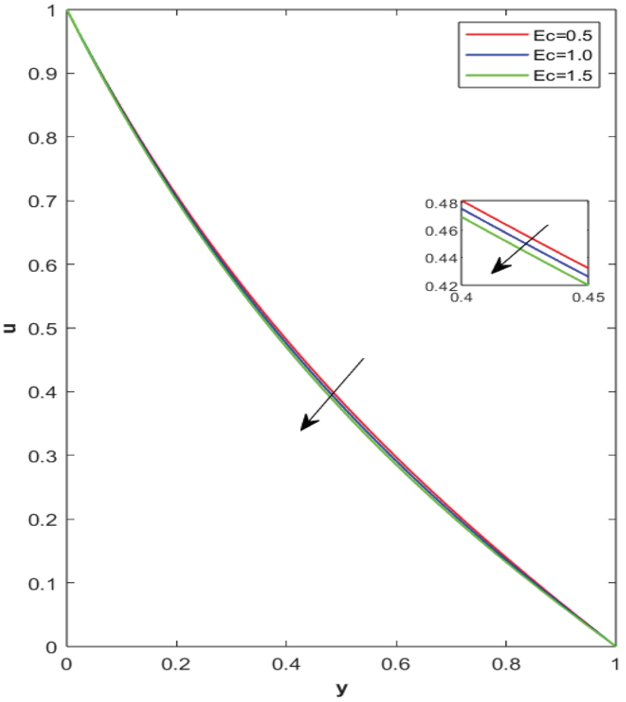

Figure 8. Velocity variation for Ec.

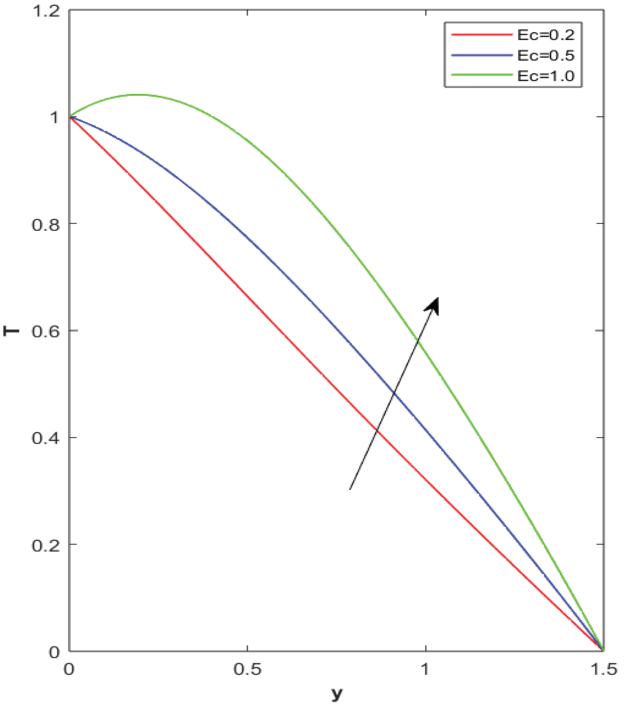

Figure 9. Temperature variation for Ec.

weaker in temperature transport compared to thermal diffusion. An increase in the Schmidt number for the concentration profile means that the relative importance of mass diffusion is increased compared to viscous effects.

Table 1 presents a comparison of our work with previously published research. The values of the Nusselt number are nearly identical to those reported in earlier studies, which validates our findings. This consistency in the results

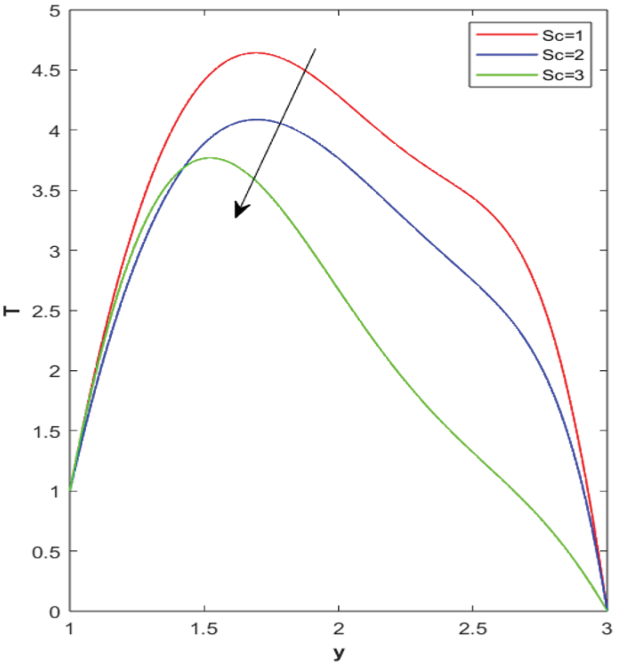

Figure 10. Temperature profile for Sc.

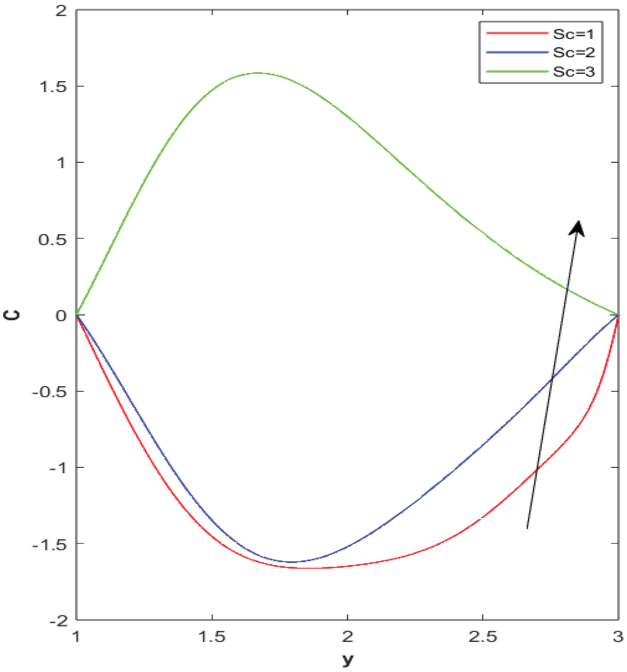

Figure 11. Concentration profile for Sc.

Table 1. Comparison of -*T*′(*x*, 0) value with previously published papers

Sc	*τ*	AhmedA [31]	Present work
0.1		1.05131	1.0513
5.0		0.92841	0.9284
10		0.76340	0.7634
	0.1	0.48266	0.4826
	0.5	0.45182	0.4518
	1.0	0.42311	0.4232

Table 2. Changes of -*T*′(*x*, 0), *F*″(*x*, 0), -*C*′(*x*, 0) for various values of *Pr, S, Ec, τ, Sc*

Pr	*S*	*Ec*	τ	*Sc*	*F*″(*x*, 0)	-*T*′(*x*, 0)	-*C*′(*x*, 0)
0.2					1.5853	0.6197	1.0116
0.5	2	0.5	0.1	2	1.5824	0.5507	1.6556
1					1.5744	0.4392	3.5145
	0				1.5689	0.2376	1.2004
0.5	2				1.5242	0.8298	1.5315
	4				1.4980	1.2499	1.0188
		0.2			1.5392	0.6107	7.5256
		0.5			1.5549	0.4112	7.5330
		1.0			1.5809	0.0687	7.7634
			0		1.5549	0.4113	6.9305
			0.1		1.5548	0.4112	1.2598
			0.5		1.5546	0.4111	1.0391
				1	1.5549	0.4111	1.8905
				2	1.5549	0.4111	2.3400
				3	1.5548	0.4111	3.2356

indicates that our study, considering all the relevant factors, aligns with previous research and confirms the accuracy of our approach.

The value of Skin Friction, Sherwood number, Nusselt Number for various parameter with different values are displayed in Table 2. The value of $C'(x, 0)$ decreases with the increasing value of *Pr, S, Ec,* τ, *Sc*. The value of $F''(x, 0)$ deceases with rising *Pr and S*, but increase with *Ec*. $T'(x, 0)$ will increase with *S* but this value will decrease with increasing *Pr and Ec*.

CONCLUSION

The numerical analysis of the flow over an exponentially stretched sheet while accounting for viscous dissipation, chemical reaction, thermophoresis, and heat absorption is performed using suction as well as that of injection, velocity slip, and thermal convective boundary conditions. The bvp4c method is used to solve the dimensionless governing equations. Following is a list of the key findings:

- The fluid›s velocity increased as the value of a thermophoretic parameter increased.
- Suction/injection parameters boost fluid velocity while lowering temperature.
- Prandtl number raises the fluid's temperature while lowering its speed.
- The fluid's temperature and velocity are both reduced by the thermal Grashof number (Gr)
- The fluid's temperature drops while its concentration rises when the Schmidt number (*Sc*) impact is applied.
- *Ec* decreases the fluid's velocity while its temperature increases.

Heat transport and fluid dynamics appear to be connected to the subject you brought up. A future study in this field could look like this: Take a closer look at the impacts of viscosity dissipation, chemical reactions, thermophoresis, and heat absorption by expanding the study to non-Newtonian fluids, which are more like fluids found in real environments; Determine how the stretching sheet›s porosity and permeability affect mass movement, heat transfer, and flow behaviour; Examine the effects of viscous dissipation, chemical reactions, thermophoresis, and heat absorption by expanding the study to multi-phase flows, such as gas-liquid or liquid-liquid flows; Analyse how heat transmission, mass transport, and flow behaviour are affected by nanoparticles in an exponentially extending sheet. Several engineering domains may find use for these prospective research avenues as they contribute to a deeper comprehension of intricate fluid flow and heat transport phenomena.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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