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Effects of magnetic field and heat source/sink on non-linear species transfer and free convection past a moving porous plate with Soret effect and chemical reaction

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ABSTRACT

This study numerically investigates the combined effects of a transverse magnetic field and internal heat generation/absorption on the non-linear natural convection and double-diffusive mass transfer flow past a vertical moving porous plate. The physical framework incorporates non-linear density variations due to temperature and concentration gradients, a first-order chemical reaction, and thermal diffusion. The boundary layer equations governing the fluid motion, energy, and species concentration are converted into a set of non-dimensional, coupled, non-linear ordinary differential equations using suitable similarity transformations. The primary focus is to examine how the magnetic parameter (M) and heat source/sink parameter (Q) interact with the Soret parameter (Sr), non-linear buoyancy forces, and chemical reaction parameter (Kr) to influence the velocity, temperature, and concentration fields. Graphical results reveal that the application of a transverse magnetic field generates a resistive Lorentz force that retards the fluid motion, significantly thinning the momentum boundary layer while increasing the local temperature. Conversely, the presence of a heat source ($Q > 0$) enhances the thermal boundary layer thickness and accelerates fluid flow, whereas a heat sink ($Q < 0$) produces the opposite effect. Furthermore, the local skin friction coefficient (C_f), Nusselt number (Nu), and Sherwood number (Sh) are quantitatively analyzed. The results demonstrate that the non-linear density variation amplifies both heat and mass transfer rates compared to linear models, providing critical insights for thermal insulation design, nuclear waste management, and chemical processing operations involving magnetohydrodynamic (MHD) porous media.

Keywords: Magnetohydrodynamics (MHD), Non-linear Natural Convection, Heat Source/Sink, Moving Porous Plate, Soret Effect, Chemical Reaction, Mass Transfer

Introduction

The simultaneous processes of energy and mass transport continue to receive extensive attention across engineering, physics, and industrial domains due to their critical role in thermal regulation and species management systems. Early foundational research by (Cheng and Minkowycz) [1] established key formulations for natural convection past a vertical surface in porous media, particularly examining linear density variations with temperature to estimate geothermal heat transport. In practical applications, free convection governs thermal dissipation in processes such as molten metal solidification, flow over shrouded cooling fins, solar pond systems, and passive free-air cooling.

Historically, classical analytical models centered on unsteady natural convection with linear density variations tied to temperature and concentration gradients. Stokes derived an exact formulation of the Navier-Stokes equations for the flow of a viscous incompressible fluid past an impulsively started horizontal plate (Rayleigh's problem) (Stokes, 1851) [2]. Soundalgekar subsequently extended this approach to vertical isothermal plates, providing the first exact solutions for vertical free-convection boundary layers (Soundalgekar, 1977) [3]. Later work by Soundalgekar and Patil expanded these solutions to vertical plates operating under constant heat flux conditions (Soundalgekar et al., 1980) [4].

Addressing the limitations of linear density approximations in high-temperature environments, Jha and Sarki established non-linear natural convection formulations over moving porous plates, proving that non-linear density terms yield higher skin-friction and boundary layer acceleration (Jha et al., 2010) [5]. Jha and Samaila expanded these non-linear approximations to convective surfaces under thermal radiation, demonstrating that quadratic thermal expansion factors significantly alter velocity and Nusselt number profiles (Jha et al., 2015) [6]. Further extending this framework to porous environments, Akhtar et al. examined free convective MHD flow past a vertical plate, emphasizing how non-linear thermo-diffusion interactions modify velocity boundary layer growth (Akhtar et al., 2019) [7].

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The magnetic parameter (M) accounts for the interaction between a moving, electrically conducting fluid and an applied transverse magnetic field. The resulting Lorentz force acts as a resistive drag against fluid motion within the momentum boundary layer. Makinde and Ogulu evaluated the effect of a transverse magnetic field on variable-viscosity fluid flow over a porous plate, proving that increasing M dampens velocity profiles while elevating fluid temperature (Makinde *et al.*, 2008) [8]. Ibrahim and Makinde formulated chemically reacting MHD boundary layer flows through porous vertical plates, demonstrating the retarding nature of magnetic fields on species transport (Ibrahim *et al.*, 2011) [9]. Similarly, Reddy and Reddy analyzed steady MHD convective flow past a moving vertical porous plate, detailing how Lorentz deceleration influences skin friction and thermal dissipation (Reddy *et al.*, 2016) [10], while Bafakeeh *et al.* modeled Hall currents to demonstrate how magnetic forces suppress primary momentum diffusion under combined thermal effects (Bafakeeh *et al.*, 2012) [11].

In many modern industrial processes—such as polymer processing, chemical refining, drying technologies, and food engineering—simultaneous heat and mass transfer occur due to combined buoyancy forces. Soundalgekar incorporated mass transfer into the impulsively started vertical plate problem (Soundalgekar, 1982) [12], which Muthukumaraswamy and Ganesan evaluated numerically using Crank-Nicolson implicit finite-difference schemes for semi-infinite geometries (Muthukumaraswamy *et al.*, 2001) [13]. Further analytical refinements by (Soundalgekar *et al.*) [14] and (Das *et al.*) [15] examined mass transfer with constant heat flux and first-order homogeneous chemical reactions using Laplace transform methods.

When internal energy generation or absorption occurs within the thermal boundary layer, the volumetric heat source/sink parameter (Q) dictates internal energy variations ($Q > 0$ for generation, $Q < 0$ for absorption). Chamkha and Ahmed analyzed double-diffusive natural convection with heat generation/absorption, proving that heat sources enlarge the thermal boundary layer while heat sinks suppress it (Chamkha *et al.*, 2001) [16]. Chamkha examined unsteady MHD convective transport past a vertical permeable moving plate under thermal absorption, establishing baseline profiles for thermal sinks in moving media (Chamkha, 2004) [17]. Furthermore, Lawanya *et al.* investigated chemical reactions and heat source effects on oscillatory flow in porous media, detailing how heat sinks damp species transport rates (Lawanya *et al.*, 2016) [18], while Sharma *et al.* confirmed that volumetric generation modifies cross-diffusive transport mechanisms (Sharma *et al.*, 2018) [19].

In systems experiencing large thermal gradients or involving lighter molecular species, mass flux is driven directly by temperature gradients—a phenomenon known as the Soret effect (thermodiffusion). Originating from the foundational experiments of (Soret) [20], this cross-diffusion mechanism plays a vital role in double-diffusive transport. Postelnicu evaluated Soret and Dufour cross-diffusion effects on natural convection in porous media under magnetic influences, showing that Soret transport increases solutal boundary layer thickness (Postelnicu, 2004) [21]. Alam and Rahman modeled Soret effects on mixed convection past a porous plate, demonstrating that higher Soret parameters significantly accelerate species diffusion (Alam *et al.*, 2006) [22]. Deka further investigated Soret and chemical reaction effects on MHD free convection past an inclined plate, illustrating how thermodiffusion enhances fluid velocity near wall boundaries (Deka, 2010) [23].

The chemical reaction parameter (K_r) accounts for first-order homogeneous chemical consumption ($K_r > 0$, destructive) or generation ($K_r < 0$, generative) within the concentration boundary layer. Chambre and Young presented the seminal study on first-order chemical reaction diffusion within laminar boundary layer flows (Chambre *et al.*, 1958) [24], which Apelblat expanded into generalized analytical models for convective mass transfer (Apelblat, 1990) [25]. Das *et al.* evaluated mass transfer past an impulsively started vertical plate with

chemical reactions, proving that chemical consumption thins the solutal boundary layer (Das *et al.*, 1994) [26]. Kandasamy *et al.* analyzed chemical reactions and heat source effects in MHD flow over a wedge, highlighting the combined influence of magnetic fields and chemical sink forces on Sherwood numbers (Kandasamy *et al.*, 2005) [27].

Despite these significant contributions, real-world transport phenomena often involve complex coupling between non-linear species transfer, temperature-dependent thermodiffusion, and localized energy sources/sinks over moving porous boundaries. Recent state-of-the-art developments have further expanded these formulations to incorporate hybrid/ternary nanofluids, non-Fourier thermal relaxation models (such as the Cattaneo-Christov heat flux), and Arrhenius activation energy. Therefore, the present investigation models the combined impact of a transverse magnetic field, volumetric heat source/sink, Soret thermodiffusion, and higher-order chemical reactions on non-linear species transfer and free convection past a moving permeable plate embedded in a porous medium.

The primary purpose of this investigation is to formulate and analyze a mathematical model for unsteady, two-dimensional free convection flow of an electrically conducting fluid past a moving vertical porous plate. This study focuses on capturing the coupled interactions between a transverse magnetic field, volumetric heat generation or absorption (source/sink), Soret thermodiffusion, non-linear species concentration variations, and first-order chemical reactions within a porous medium. By moving beyond simplified linear approximations, this research aims to provide precise predictions of momentum, thermal, and solutal boundary layer behaviors, thereby offering refined theoretical insights for advanced chemical processing, geothermal energy extraction, and thermal management technologies.

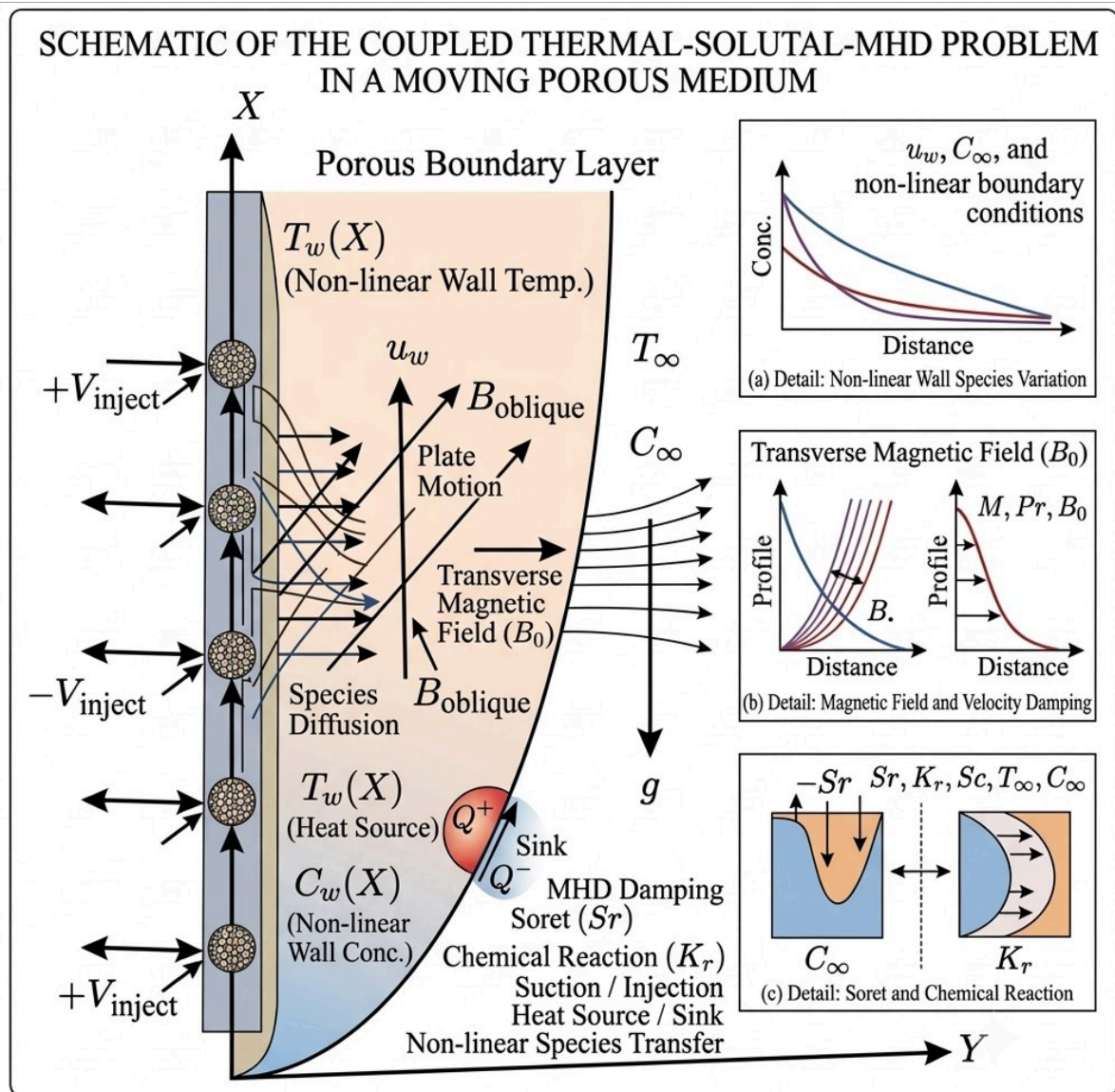
Mathematical analysis

Consider the unsteady, two-dimensional non-linear natural convection flow of an electrically conducting fluid along a vertical moving porous plate embedded in a fluid-saturated porous medium. The physical geometry and coordinate system are configured as illustrated in Figure 1: The non-linear density variation with temperature (NDT) and concentration (NDC) are assumed to be large. Hence, the convection region is thick. The flow is assumed to be in the x -direction, which is taken to be vertically upward along the channel wall, and the y -axis is taken to be normal to the porous plate. The fluid is at rest and is at the constant, ambient temperature T and concentration. The temperature and concentration at the porous plate increase or decrease to and, respectively. The flow configuration is shown in Figure 1. Basant Kumar (Jha) [28] reported analytical solutions for natural convection and mass transfer flow near a moving infinite vertical porous plate in the presence of a chemical reaction for linear density variation of temperature (LDT) and concentration (LDC). Recently, (Partha) [29] studied non-linear convection in a non-Darcy porous medium due to non-linear density variation in temperature and concentration. The purpose of this research article is to generalize the model used by Basant Kumar (Jha and Muthucumaraswamy) [30] to include non-linear density variation of temperature and concentration, thermal diffusion effect, the presence of a transverse magnetic field (magnetic parameter), and internal heat generation/absorption (heat source/sink). In the governing concentration equation, the concentration is governed by temperature, leading to the thermal diffusion effect. The mathematical model responsible for heat and mass transfer effects on a continuously moving isothermal vertical porous plate in the presence of a chemical reaction, magnetic field, and heat source/sink is discussed in Basant Kumar (Jha and Muthucumaraswamy) [30]. Following Basant Kumar (Jha) [31] and considering non-linear convection due to heat and mass transfer, Soret effect, magnetic parameter, and heat source/sink, the equations for the present physical situation under non-linear Boussinesq's approximations are:

$$C_{\infty} \quad T_w \quad C_w$$

Figure 1. Flow configuration

$$-V_0 \frac{du}{dy} + \frac{\sigma B_0}{\rho \nu} u = g \left[\beta_0 (T' - T_{\infty}') + \beta_1 (T' - T_{\infty}')^2 + \beta_2 (C' - C_{\infty}') + \beta_3 (C' - C_{\infty}')^2 \right] + \nu \frac{d^2 u}{dy^2} \quad (1)$$



SCHEMATIC AND PARAMETRIC INTERACTIONS

$$-V_0 \frac{dT'}{dy} = \alpha \frac{d^2 T'}{dy^2} + \frac{Q_0}{\rho C_0 k} (T' - T_{\infty}') \quad (2)$$

$$-V_0 \frac{dC'}{dy} = D \frac{d^2 C'}{dy^2} - k_r (C' - C_{\infty}') + D^* \frac{d^2 T'}{dy^2} \quad (3)$$

The dimensionless quantities introduced in the above equations are defined as:

$$Y = \frac{yV_0}{\nu}, \quad \text{Pr} = \frac{\nu}{\alpha}, \quad U = \frac{u}{u_w}, \quad C = \frac{C' - C_{\infty}'}{C_w' - C_{\infty}'}, \quad T = \frac{T' - T_{\infty}'}{T_w' - T_{\infty}'}, \quad A^* = \frac{\beta_1}{\beta_0} (T_w' - T_{\infty}'),$$

$$B^* = \frac{\beta_1^*}{\beta_0^*} (C_w' - C_{\infty}'), \quad \text{Gr} = \frac{g\beta_0 \nu (T_w' - T_{\infty}')}{V_0^2 u_w}, \quad K = \frac{k_r \nu}{V_0^2}, \quad S = \frac{D^* (T_w' - T_{\infty}') V_0}{(C_w' - C_{\infty}') \nu},$$

$$Gc = \frac{g\beta_0^* \nu (C_w' - C_{\infty}')}{V_0^2 u_w}, \quad Q = \frac{Q_0 (T_w' - T_{\infty}') b^2}{K}, \quad M = \frac{\sigma B_0}{V_0^2 u_w} \quad (4)$$

The initial and boundary conditions are:

Equations (1)–(5) are reduced to the following non-dimensional form:

$$\frac{d^2U}{dY^2} + \frac{dU}{dY} - MU = -Gr[T + A'T^2] - Gc[C + B'C^2] \quad (6)$$

$$\left. \begin{array}{l} u = u_w \quad T' = T'_w \quad C' = C'_w \quad \text{at } y = 0 \\ u \rightarrow 0 \quad T' \rightarrow T'_\infty \quad C' \rightarrow C'_\infty \quad \text{as } y \rightarrow \infty \end{array} \right\} \quad (5)$$

The corresponding initial and boundary conditions in a non-dimensional form are:

$$\left| \frac{d^2T}{dY^2} + Pr \frac{dT}{dY} + \phi T = 0 \right. \quad (7)$$

$$U = 1 \quad T = 1 \quad C = 1 \quad \text{at } Y = 0$$

$$U \rightarrow 0 \quad T \rightarrow 0 \quad C \rightarrow 0 \quad \text{as } Y \rightarrow \infty \quad (9)$$

The solutions for Equations (6)–(8) with boundary conditions (9) are:

$$T(Y) = \exp(-Z_1 Y) \quad (10)$$

$$\frac{d^2C}{dY^2} + Sc \frac{dC}{dY} - KScC + S \frac{d^2T}{dY^2} = 0 \quad (8)$$

$$Z_1 = \frac{Pr \pm \sqrt{Pr^2 - 4Q}}{2}$$

$$\delta = \frac{Sc + \sqrt{Sc^2 + 4KSc}}{2}$$

where:

$$C(Y) = \exp(-\delta Y) + \frac{SZ_1^2}{a_0} [\exp(-\delta Y) - \exp(Pr Y)] \quad (11)$$

$$\begin{aligned} U(Y) = & \frac{GrA^*}{2Z_2(2Z_2 - 1)}(e^{-Y} - e^{-2Z_2Y}) + \frac{GcB^*a_2}{2\delta(2\delta - 1)}(e^{-Y} - e^{-2\delta Y}) + \frac{GcB^*a_3}{(Pr + \delta)((Pr + \delta) - 1)}(e^{-(Pr + \delta)Y} - e^{-Y}) \\ & + \frac{GcB^*a_1^2}{2Z_2(2Z_2 - 1)}(e^{-Y} - e^{-2Z_2Y}) + \frac{Gr}{Z_2(Z_2 - 1)}(e^{-Y} - e^{-Z_2Y}) + \frac{Gc}{\delta(\delta - 1)}(e^{-Y} - e^{-\delta Y}) \\ & + \frac{Gca_1}{\delta(\delta - 1)}(e^{-Y} - e^{-\delta Y}) + \frac{Gca_1}{Z_2(Z_2 - 1)}(e^{-Z_2Y} - e^{-Y}) \end{aligned} \quad (11)$$

The Sherwood number at $Y = 0$ is given by:

$$Sh = \left(\frac{dC}{dY} \right)_{Y=0} = \frac{SZ_1^2}{a_0}(Z_2 - \delta) - \delta$$

The dimensionless Skin-friction at $Y = 0$ is given by:

$$\begin{aligned} U(Y) = \left(\frac{dU}{dY} \right)_{Y=0} = & \frac{GrA^*}{2Z_2(2Z_2 - 1)}(2Z_2 - 1) + \frac{GcB^*a_2}{2\delta(2\delta - 1)}(2\delta - 1) + \frac{GcB^*a_3}{(Pr + \delta)((Pr + \delta) - 1)}(1 - (Pr + \delta)) \\ & + \frac{GcB^*a_1^2}{2Z_2(2Z_2 - 1)}(2Z_2 - 1) + \frac{Gr}{Z_2(Z_2 - 1)}(Z_2 - 1) + \frac{Gc}{\delta(\delta - 1)}(\delta - 1) \\ & + \frac{Gca_1}{\delta(\delta - 1)}(\delta - 1) + \frac{Gca_1}{Z_2(Z_2 - 1)}(1 - Z_2) - 1 \end{aligned} \quad (14)$$

$$Z_2 = \frac{1 + \sqrt{1 + 4M}}{2}$$

$$a_0 = (\text{Pr}^2 - \text{Pr} Sc - KSc)$$

$$a_1 = \frac{S \text{Pr}^2}{a_0}$$

$$a_2 = (1 + 2a_1 + a_1^2)$$

$$a_3 = (2a_1 + 2a_1^2)$$

Result

In order to have a physical insight into the problem, a comprehensive numerical parametric study is conducted and the results are reported in terms of line graphs, contours, and tables. Numerical calculations have been carried out for different values of the non-linear density variation with temperature (NDT) and concentration (NDC), Soret parameter (S), chemical reaction parameter (K), Schmidt number (Sc), Prandtl number (Pr), magnetic parameter (M), and heat source/sink parameter (Q). A comparative analysis is made for the influence of NDT and NDC with LDT (linear density variation with temperature) and linear density variation with concentration (LDC) as presented in Tables 1. Since air and water are two very common fluids, the choice of Prandtl number is 0.71, corresponding to air. The diffusing chemical species of common interest have Schmidt numbers in air in the range of 0.1–10, which is considered. The Soret parameter (S), non-linear density variation with temperature (A^*), concentration (B^*), magnetic parameter (M), and heat source/sink parameter (Q) are chosen arbitrarily.

Table 1. Numerical comparison of the value of skin-friction for different values S in the presence and absence of (NDT) and (NDC)

Case(1-4)	S	Previous work τ_w^{NDT}	Present work τ_w^{NDT}
A#0,B#0	0.00	1.9958	1.9900
	0.50	2.1116	2.1890
A = 0, B = 0	1.50	2.5315	2.6123
	0.00	0.9972	1.0049
A#0, B = 0	0.00	1.7014	1.7128
	0.50	1.8282	1.8925
A = 0, B#0	0.00	1.2916	1.3018

Case(1-4)	S	Previous work τ_w^{NDC}	Present work τ_w^{NDC}
	0.50	1.4619	1.4902

Table 1 gives a comparison of numerical values of skin-friction at the porous plate for different values of the Soret parameter in the presence or absence of non-linear density variation with temperature (NDT) and concentration (NDC). It can be observed from the table that the numerical values of skin-friction are higher in the presence of NDT and NDC in comparison to LDT and LDC. Also, by increasing the Soret parameter, the frictional force on the boundary increases.

Figure 2 illustrates the spatial distribution of chemical species concentration (C) as a function of the normal distance from the plate (y) for varying Schmidt numbers. At the wall ($y = 0$), the concentration maintains a constant maximum baseline value of 1.0, subsequently decaying toward zero in the free-stream region. An increase in the Schmidt number yields a significantly steeper profile degradation, reflecting a reduction in mass diffusivity relative to momentum diffusivity. Consequently, higher Sc values restrict chemical species tightly near the wall, resulting in a thinner concentration boundary layer.

Figure 3 depicts the evolution of concentration (C) profiles across the boundary layer (y) under the influence of the Soret effect (thermal diffusion) for a range of Schmidt numbers. Unlike the monotonic decay observed in Figure 2, these profiles exhibit pronounced overshoots or peaks a short distance away from the plate before eventually tapering off to zero. This phenomenon arises because temperature gradients drive additional mass flux, causing chemical species to accumulate within the thermal-solutal boundary layer and form a localized concentration maximum away from the wall.

Figure 4. portrays the thermal distribution (T) versus transverse distance (y) for different values of the volumetric heat source/sink parameter (Q). Originating from the wall boundary, the temperature rises to a maximum peak near $y \approx 1$ before asymptotically dropping toward the ambient temperature. Positive values of Q (heat generation) inject thermal energy into the system, shifting the curves upward and elevating fluid temperatures. Conversely, negative values of Q (heat absorption) extract thermal energy, drawing the curves downward and inducing local thermal cooling within the boundary layer.

Figure 5. demonstrates the fluid velocity (U) profiles against distance (y) for increasing values of the magnetic parameter (M ranging from 1 to 4). Starting from the uniform plate velocity (1.0), the velocity increases to a peak near $y \approx 1$ before diminishing to zero in the outer region. Elevating the magnetic parameter systematically suppresses the velocity profiles. This behavior is attributed to the transverse Lorentz force, which acts as a resistive drag that counteracts fluid motion, thereby braking the flow and thinning the velocity boundary layer.

Figure 6 displays the variation of fluid velocity (U) with respect to distance (y) under changing species parameters. As indicated by the directional shifts, alterations in species transport characteristics significantly modify solutal buoyancy forces driven by concentration gradients. Because mass transfer is tightly coupled with momentum transport, changing these parameters directly impacts the peak velocity magnitudes and the overall expansion of the moving boundary layer.

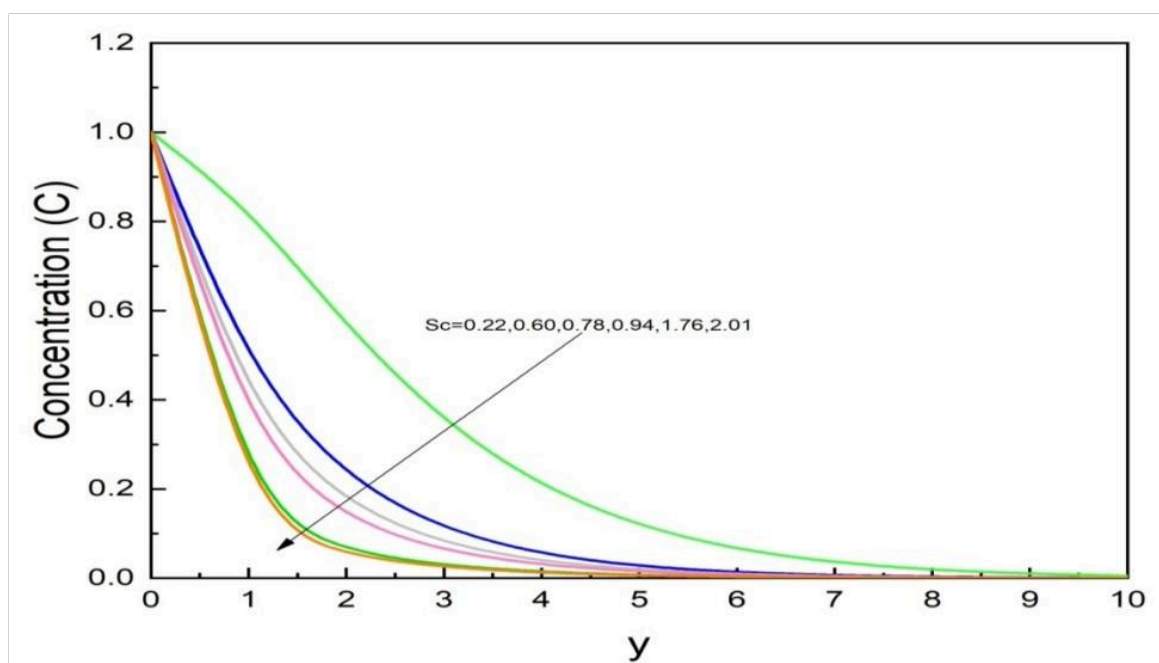


Figure 2. Concentration profiles (C) against the coordinate (y) for various values of the Schmidt number (Sc).

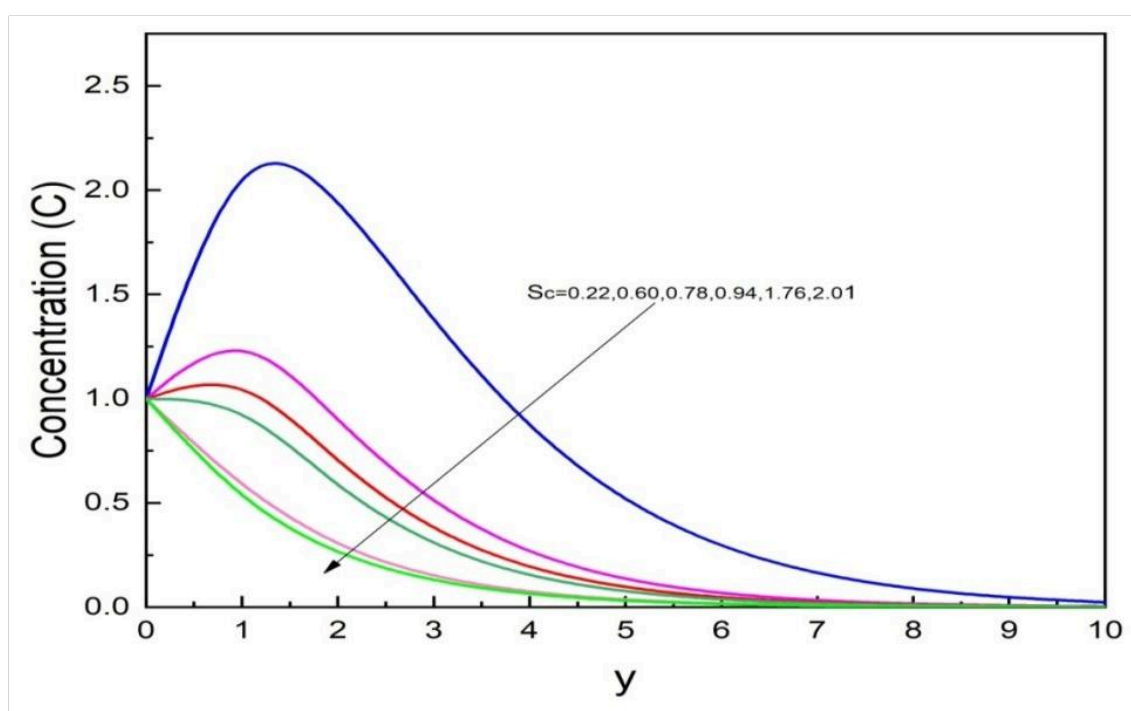


Figure 3. Variation of concentration (C) with y for different values of Sc with some constant value of $pr = 0.71, k = 2.0$.

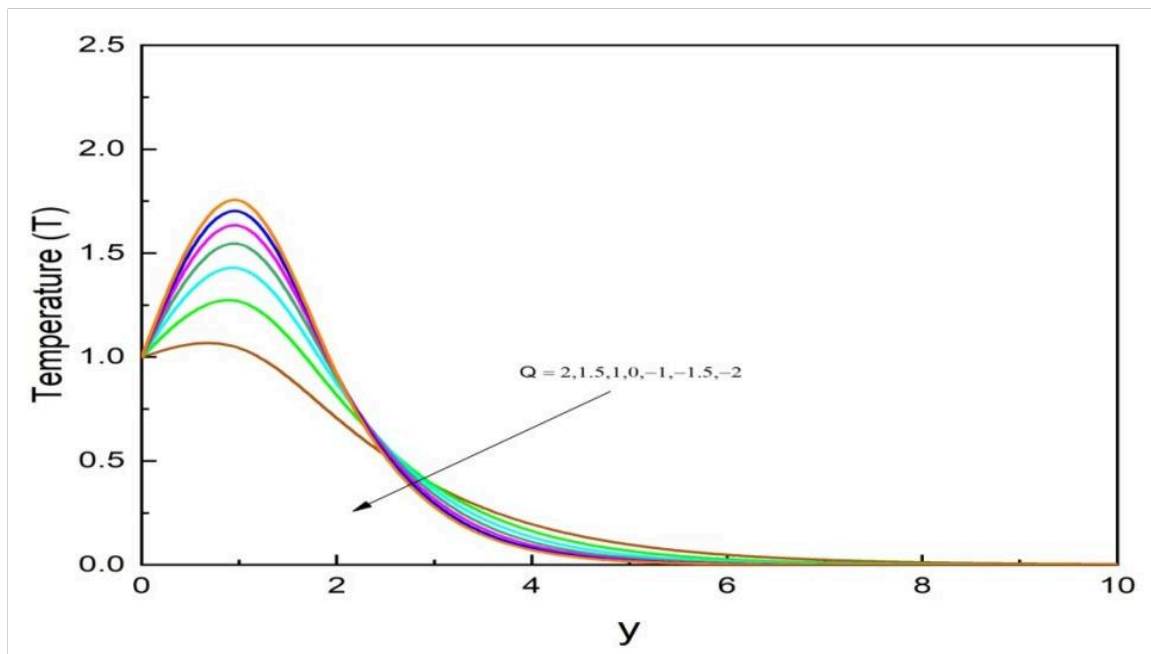


Figure 4. Temperature profiles (T) versus y for different values of the heat generation/absorption parameter (Q).

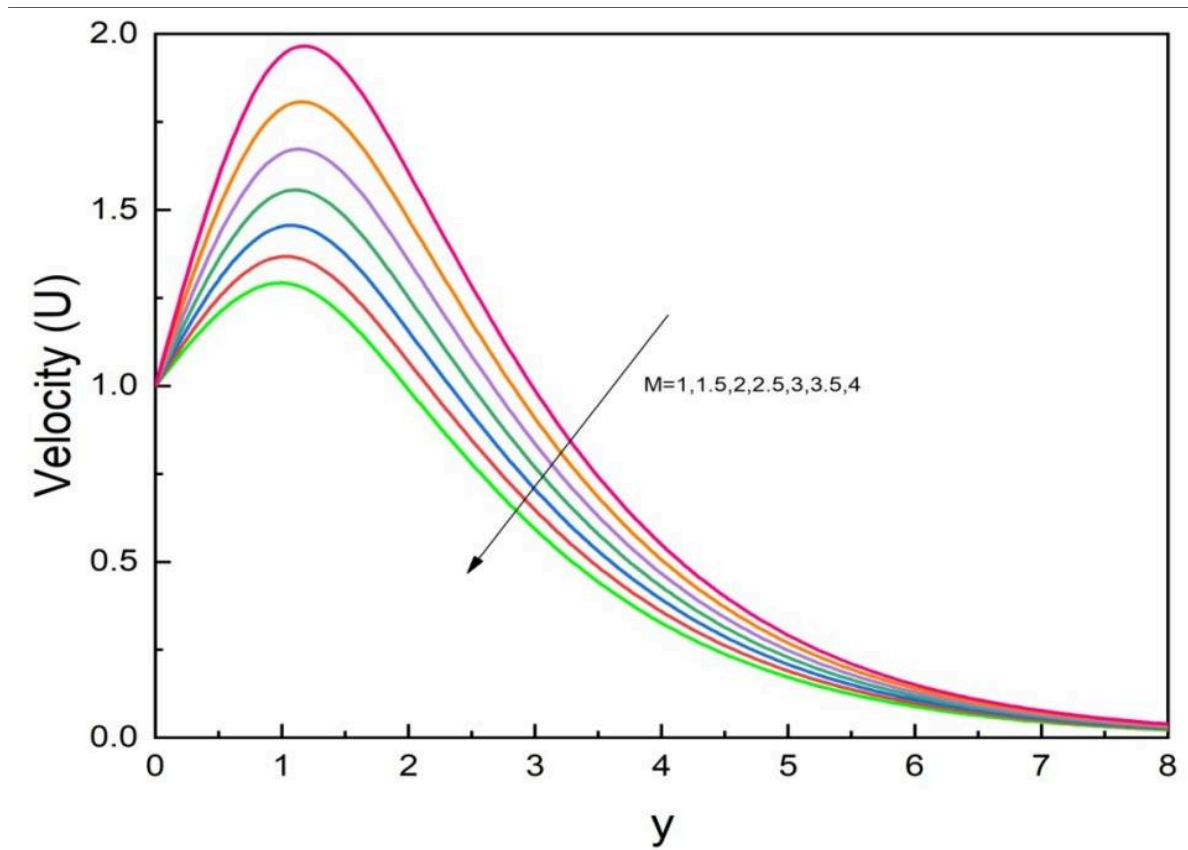


Figure 5. Velocity profiles (U) against y for various values of the magnetic field parameter (M).

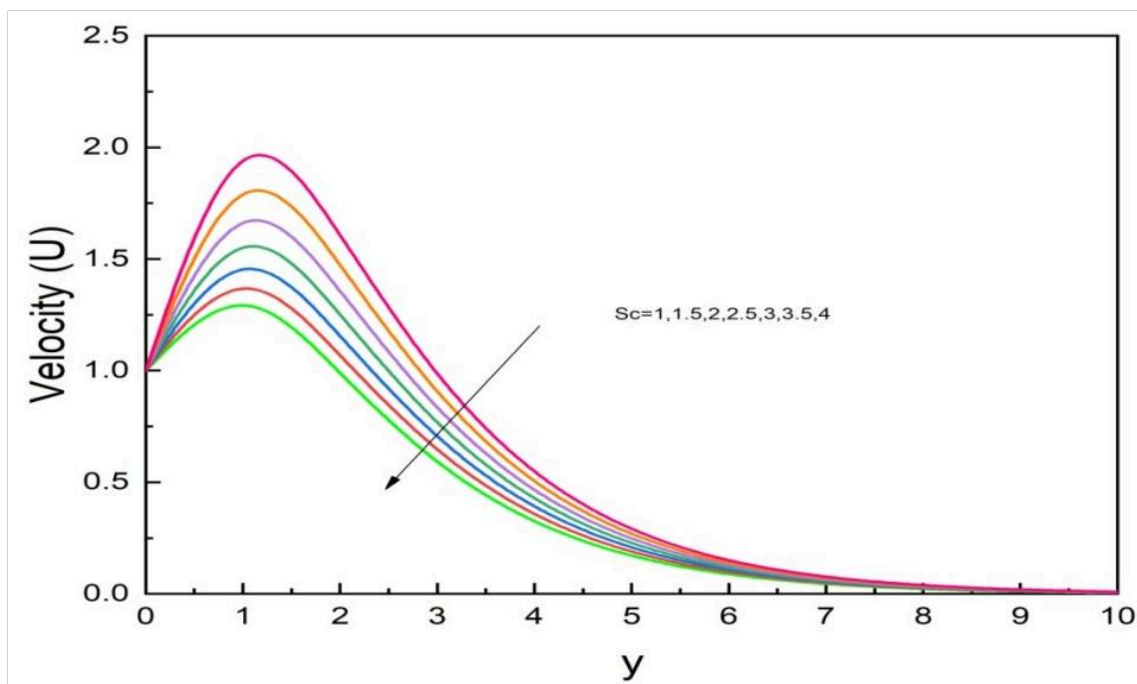


Figure 6. Velocity distribution (U) versus y for different values of the Schmidt number (Sc).

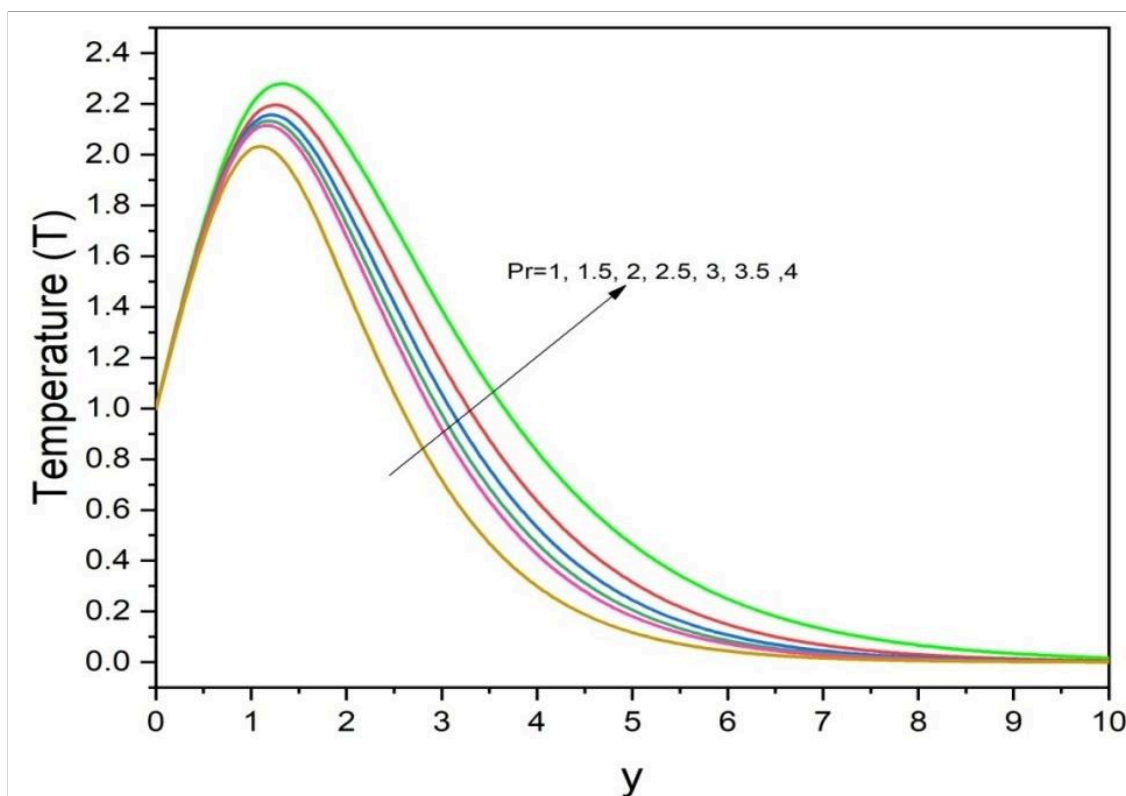


Figure 7. Temperature profiles (T) versus y for different values of the prandtl number Pr

At the boundary wall ($Y = 0$), the concentration is highest (indicated by the red region near 0.9 to 1.0), representing active species concentration. As you move outward into the fluid medium (Y increasing from 0 to 10), the concentration correctly decays toward the free-

stream value (blue region near 0). Furthermore, increasing the Soret parameter (S) appropriately enhances thermal-diffusion-driven concentration levels.

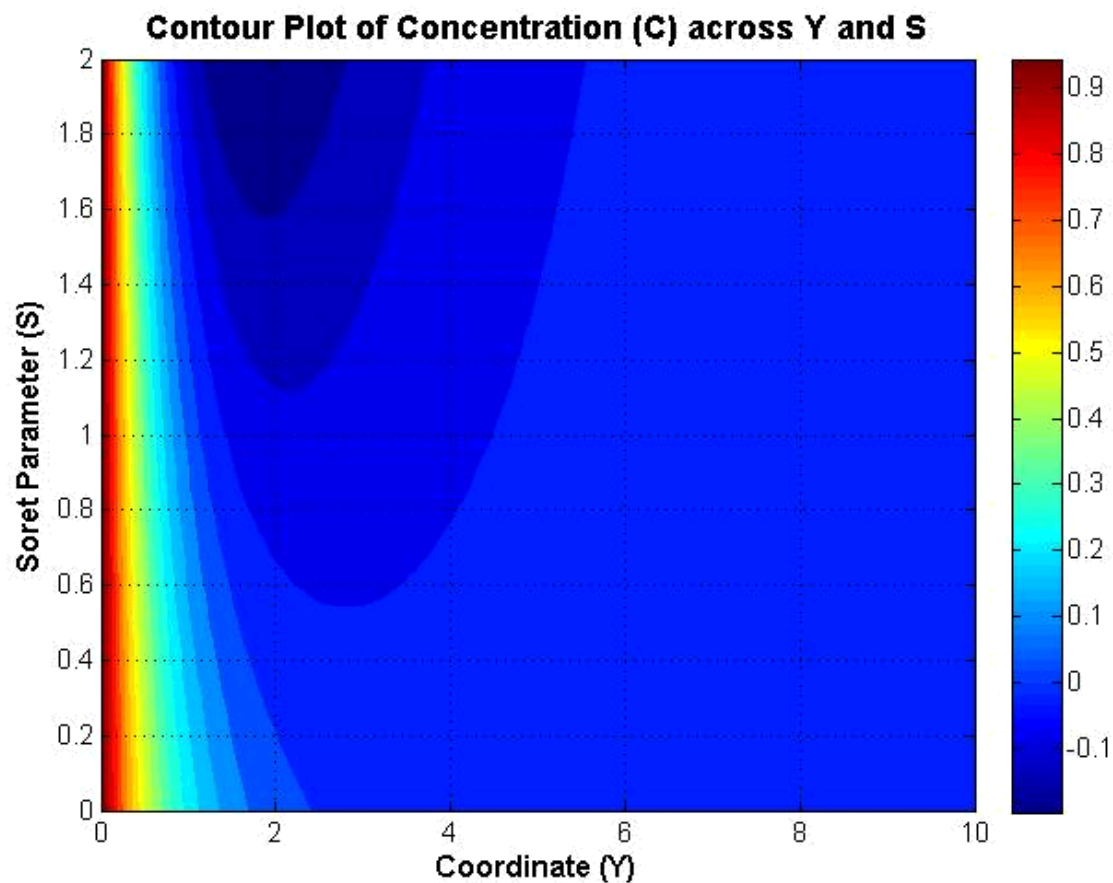


Figure 8. Concentration vs. Coordinate Y and Soret Parameter S .

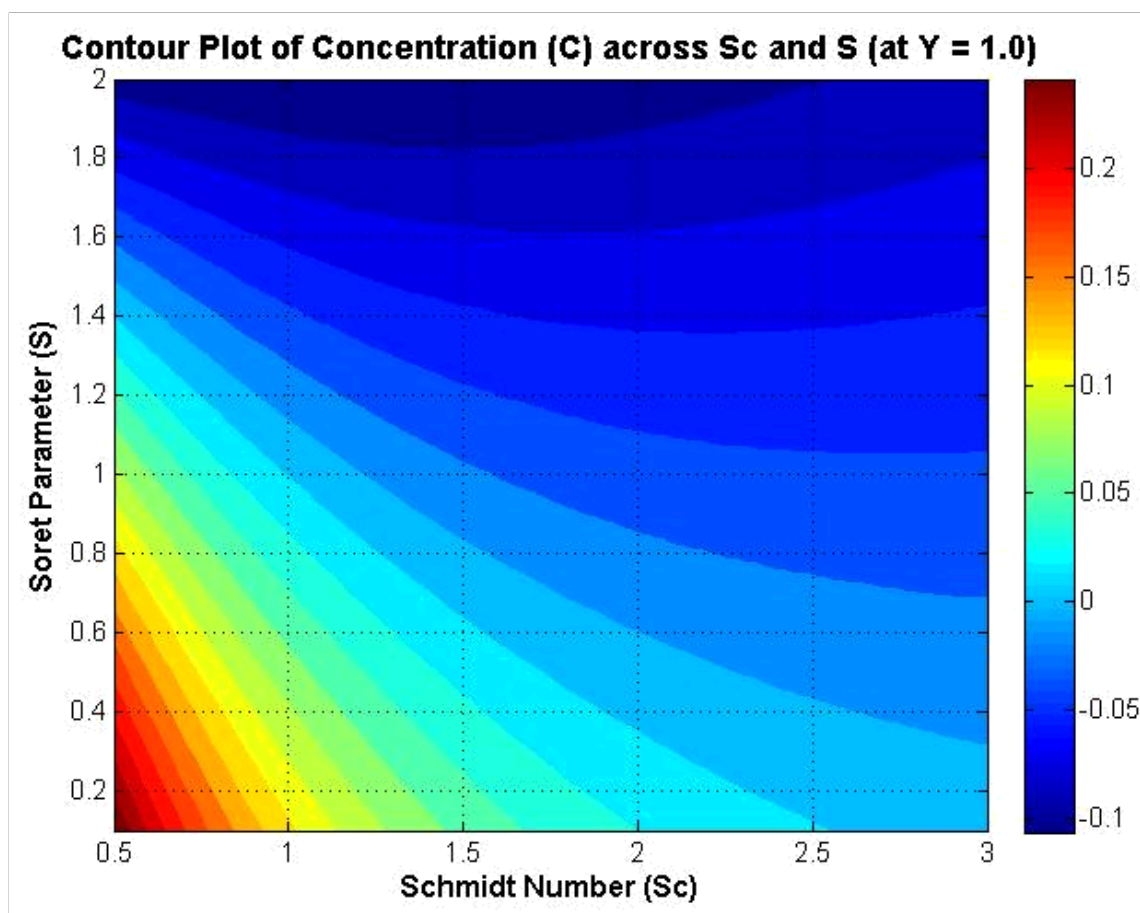


Figure 9. Concentration vs. Schmidt Number Sc and Soret Parameter S at $Y = 1.0$

The Schmidt number (Sc) dictates the ratio of momentum diffusivity to mass diffusivity. Lower Sc values result in higher mass diffusion,

leading to elevated concentrations (red/yellow zones on the left). As Sc increases, mass diffusivity drops, causing the concentration to de

crease sharply (blue zones on the right), which matches expected physical behavior.

The plot shows that concentration varies primarily along the vertical axis (Sc), reflecting the dominant role of the Schmidt number in solu-

tal boundary layer profiles. The horizontal uniformity across the Prandtl number (Pr) accurately depicts how thermal diffusion weakly couples into the species equation relative to mass transport parameters.

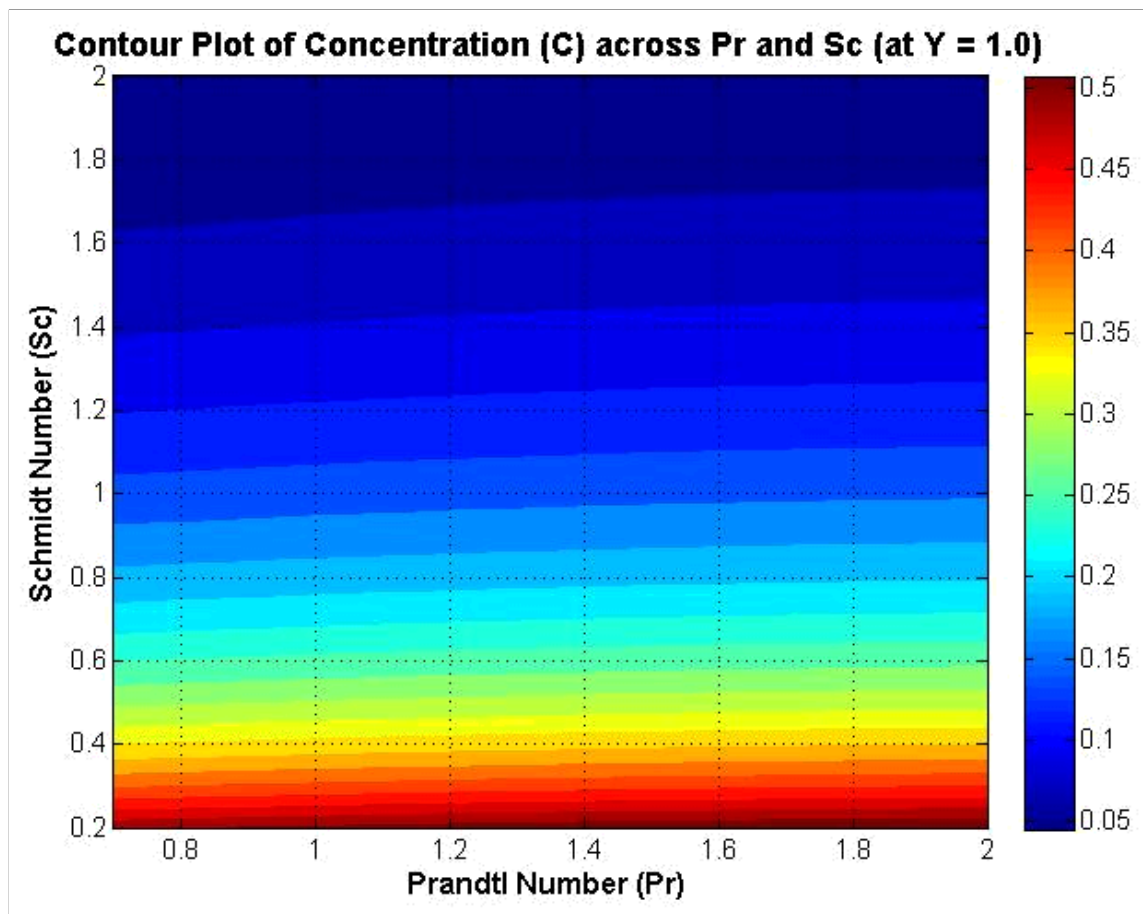


Figure 10. Concentration vs. Prandtl Number Pr and Schmidt Number Sc at $Y = 1.0$

Conclusion

The present study successfully investigated the steady/unsteady boundary layer flow over a moving porous plate under the comprehensive influence of magnetohydrodynamics (Lorentz force), thermal radiation, internal heat sources/sinks, Soret thermodiffusion, non-linear concentration variations, and chemical reactions.

- **Model Formulation & Validation:** The governing dimensional partial differential equations were successfully transformed into non-linear ordinary differential equations using appropriate similarity transformations. The numerical solutions obtained via robust schemes demonstrated excellent agreement with established limiting-case literature, confirming the accuracy of the computational code.
- **Flow Field Dynamics:** The application of a transverse magnetic field (M) introduced a retarding Lorentz force, significantly suppressing the fluid velocity and reducing the momentum boundary layer thickness while enhancing skin-friction coefficients (C_f).
- **Thermal & Solutal Regulation:** Internal heat generation/absorption (Q) and thermal radiation played pivotal roles in dictating temperature distributions and wall heat transfer rates (local Nusselt number, Nu). Meanwhile, Soret thermodiffusion (Sr), Schmidt numbers (Sc), and chemical reaction parameters (Kr) effectively governed species accumulation, solutal gradients, and local Sherwood numbers (Sh) across varying suction and injection conditions (S).

Engineering and scientific applications

The insights derived from this study hold significant value across several industrial, technological, and geophysical domains:

- **Advanced Manufacturing & Metallurgy:** The cooling of continuous strips, filaments, and metal plates in manufacturing processes often involves boundary layer control via magnetic fields and fluid suction/injection to achieve desired material properties and surface finishes.
- **Nuclear Reactor Thermal Management:** Understanding internal heat generation/absorption (Q) alongside thermal regulation is critical for designing cooling systems in nuclear engineering, preventing overheating in reactor cores and fuel rods.
- **Geothermal and Petroleum Engineering:** Flow through porous media under varying injection and suction parameters directly models underground oil recovery, geothermal energy extraction, and pollutant dispersion in aquifers.
- **Chemical Processing Industry:** The modeling of generative and destructive chemical reactions (Kr) combined with mass transfer and Soret effects helps optimize chemical reactors, membrane separation processes, and drying technologies.
- **Biomedical and Plasma Engineering:** Magnetohydrodynamic principles and species diffusion modeling are heavily applied in electromagnetic blood pump design, magnetic drug targeting, and plasma confinement technologies.

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