© DEC 2025 | IRE Journals | Volume 9 Issue 6 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I6-1712600

Free Convection Heat and Mass Transfer in a Slip Flow Regime with Thermo-Diffusion Effects.

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Abstract- This research examines free convection heat and mass transfer in a slip flow regime incorporating thermo-diffusion (Soret) effects. The governing equations for momentum, energy, and concentration were first constructed in dimensional form and then converted into their respective non-dimensional system with suitable similarity variables. The coupled non-linear differential equations were solved using the regular perturbation technique to obtain analytical solutions, resulting in expressions for the velocity, temperature, and concentration fields. The findings indicate that the diffusion-thermo parameter improves both the temperature and velocity of the fluid, indicating an augmentation in thermal energy transfer attributed to the Soret effect. The slip parameter and suction/injection (substation) parameter were shown to considerably affect the increase in the velocity profile, enhancing fluid motion over the surface. In contrast, an increase in the Schmidt number and Prandtl number demonstrated a reduction in fluid velocity due to enhanced resistance to momentum and mass diffusion. The work illustrates how thermo-diffusion and slips circumstances alter free convective transport characteristics, offering valuable insights for micro-flows, energy systems, and engineering processes related to heat and mass diffusion.

Keywords: Free Convection, Diffusion-Thermos, Slip Flow, Prandtl Number, Schmidt Number

I. INTRODUCTION

The natural convection of a viscous incompressible fluid in a vertical channel is a significant challenge pertinent to several engineering applications across various scientific and technological domains, including geophysics, aeronautics, nuclear power reactors, and soil sciences. In these flows, the velocity and temperature distributions are interdependent, since the flow is generated by buoyancy forces resulting from the temperature gradient between the surface and the fluid. The examination of heat transfer is a fundamental aspect of natural convection flow and is included under boundary layer theory difficulties. A substantial amount of research has concentrated on heat and fluid dynamics at micro and nano scales due to their relevance in micro-electro-mechanical systems and nano-electro-mechanical systems, particularly incorporating velocity and temperature slip boundary conditions at the wall, as conventional no-slip conditions produce implausible outcomes for this type of flow. In light of these applications, Jha and Ajibade [1] examined free convection heat and mass transfer flow in a vertical channel constituted by two plates using the Laplace transform approach. Their findings indicated that the transient solution at extended time aligns with the independently calculated steady-state solution. Abid et al. [2] investigated unstable boundary conditions. Numerous transport phenomena in nature are propelled by density disparities resulting from temperature gradients, chemical composition gradients, and material composition, as examined by Siva et al. [3], who analyzed the solution of free convective unsteady fluid flow influenced by thermal diffusion and chemical reactions adjacent to a vertical porous plate with a heat source in the slip flow regime. Joseph et al. [4] investigated the influence of heat and mass transfer on free convective Couette flow of a dissipating fluid through a porous material, including chemical reactions and slip conditions. Ajibade and Ojeagbase [5] examined the impact of temperaturedependent viscosity and thermal conductivity on natural convection flow inside a vertical channel. The governing equations for temperature, velocity, and concentration fields were solved analytically by the differential transformation technique. The findings were corroborated with those obtained from both analytical and numerical approaches, revealing high concordance. The findings of fluid flow inside the channel indicate that rising fluid viscosity and temperature correspond with a reduction in fluid velocity. Additionally, Souayeh et al. [6] examined the heat transmission properties of fractionalized hydromagnetic fluid with a chemical reaction in permeable media. The governing fluid flow equations, together with boundary conditions, have been converted into a system of coupled ordinary differential equations by reduced similarity transformations and solved using Fourier sine and Laplace transforms. The influence of physical characteristics was analyzed. Saeed et al. [7] examined the heat and mass transfer of free convection flow across a vertical plate influenced by chemical reactions and wall slip effects. Closed-form solutions for fluid velocity, temperature, and concentration are obtained by the use of the Laplace transform. Umavathi and Shekar [8] examined the combined influence of variable and thermal conductivity on the free convection flow of a viscous fluid in a vertical channel using the differential transformation approach. Ajibade and Ojeagbase [9] examined steady natural convection heat and mass movement in a vertical porous channel, including viscosity and thermal conductivity. The fluctuations in viscosity and thermal conductivity are seen as linear functions of temperature. The governing equations are converted into a system of linked nonlinear ordinary differential equations. The findings produced were compared with the exact solution under relaxed flow circumstances, and the results from the differential transformation approach demonstrated good concordance with the analytically derived exact solution. Sehra et al. [10] investigated convective heat and mass transport, together with magnetohydrodynamic flow across a vertical plate, including chemical reactions, arbitrary shear stress, and exponential heating. Alim et al. [11] examined the impact of heat production on magnetohydrodynamic natural convection flow over a vertically undulating surface with varied thermal conductivity. Rout et al. [12] investigated the magnetohydrodynamic heat and mass transfer of chemically reactive fluid flow across a moving vertical plate, including a heat source and convective surface boundary conditions. Uwanta and Omokhuale [13] examined the impact of varying thermal conductivity on heat and mass transmission in Jeffery fluid. Thermochemical reactions involving fluids and masses are prevalent in chemical engineering processes that use moving plates. According to Joshna et al. [14], these methods have several commercial uses, including polymer synthesis, ceramic or glassware manufacture, and food preparation. Mass and heat transfer, in conjunction with chemical reactions, have lately garnered considerable interest and research due to their importance in many industrial processes. Heat and mass coupling transpires in several processes, such as drying, surface evaporation of water, energy transfer in a humid cooling tower, and operation in a desert cooler. This kind of flow might be used in several different sectors. In the energy sector, there exists a technique for generating electricity that use a flowing conductive fluid to directly harvest electrical energy. Usman et al. [15]. Research by Chamkha [16] examined the Magnetohydrodynamic (MHD) flow of a computer model depicting a uniformly extended vertical permeable surface. The research also examined the effects of heat production and absorption, along with chemical interactions. Muthucumaraswamy and Ganesan [17] investigated the impact of chemical reactions on the chaotic flow next to a semi-infinite vertical plate experiencing sudden heating. Ibrahim et al. [18] examined the impact of chemical reactions and radiation absorption on unsteady magnetohydrodynamic (MHD) free convective flow. Observers were able to witness the flow by subjecting a semi-infinite, vertically permeable moving plate to a heat source and suction. Agarwalla et al. [19] examined the impact of chemical reactions on multi-phase heat transfer (MHFT) within the framework of porous media, an inclined plate, thermal radiation, a heat source, and a variable plate velocity integrated into a porous medium.

Diffusion-Thermo and Thermal-Diffusion phenomena have garnered significant attention from scholars across several disciplines, including geosciences, engineering, and commerce. Hydrology, petrology, gas-particle trajectories, foam combustion, and turbine blades include these domains. The "Dufour effect" refers to the movement of masses induced by concentration gradients, while the "Soret effect" pertains to the transfer of heat resulting from temperature gradients. Usman et al. [20] and Babu et al. examined the influence of a chemical reaction and a magnetic field on unstable natural convection flow inside a vertical porous channel. [21] elucidated the influence of the Soret and Dufour effects on mass and heat transport in chemically reacting magnetohydrodynamic flow over a wavy channel. Research by Uwanta and Usman [22] examined the impact of the Soret and Dufour effects on the flow of free convective heat and mass transfer in a channel characterized by continuous suction and viscous dissipation. Sharma and Bhaskar [23] investigated the influence of thermal radiation and chemical processes on three-dimensional magnetohydrodynamic (MHD) incompressible and viscous flows, including the Dufour and Soret effects. Gbadeyan et al. [24] examined the effects of Dufour and Soret phenomena on chemically reacting magnetohydrodynamic flow inside a wavy channel, focusing on the implications of Dufour on mass and heat transmission. The work by Yale et al. [25] examined an infinite vertical plate in relation to the Soret effect on magnetohydrodynamic flow, focusing on heat and mass transfer in a viscous, incompressible, electrically conducting fluid. Choudhury et al. [26] investigate the Soret effect on transient maximum hydrodynamic pressure convective flow using a semi-infinite vertical porous plate, a chemical process, and a heat sink. Conversely, Venkateswarlu Malapati et al. investigate the impacts of Soret effects and chemical reactions on radiative magnetohydrodynamic flow from an endlessly vertical porous plate. [27]. Unsteady Magnetohydrodynamic Flow of a Viscoelastic Micropolar Fluid Adjacent to an Infinite Vertical Plate with a Thermal Source: An Investigation of Chemical Reaction and Soret Effects Kuppala and colleagues [28]. An infinite isothermal vertical plate was examined for the effects of chemical processes and heat radiation on unsteady magnetohydrodynamic parabolic flow. Muthucumaraswamy and colleagues [29]. Utpal et al. [30] investigated the Soret and Dufour effects by constraining the flow of a viscoelastic fluid between a long vertically undulating wall and a parallel flat wall. Through the ingestion of chemical entities.

1.1 Research Novelty

This work enhances the current knowledge of fluid flow and heat transfer by analytically investigating free convection heat and mass transfer in a slip flow regime that includes thermo-diffusion (Soret/Dufour) effects, a combination seldom explored concurrently in the literature. This study incorporates velocity slip and convective boundary conditions, in contrast to traditional no-slip boundary assumptions, hence enhancing the realism of the analysis for micro- and nano-scale fluid systems where slip effects prevail. The conversion of governing equations into non-dimensional form, followed by a regular perturbation method, produces closed-form solutions for the velocity, temperature, and concentration fields, allowing direct evaluation of parameter sensitivity. The work delineates distinct correlations indicating that diffusion-thermo augments thermal transport and velocity, while Prandtl and Schmidt numbers inhibit flow and mass diffusion, providing novel insights into flow regulation in thermally driven systems. The interaction of slip, thermo-diffusion, and convection inside a vertical channel establishes a new paradigm for enhancing heat-mass transfer in engineering applications.

1.2 Applications in Industry and Engineering

This research's results have significant applicability in sectors where heat and mass transmission under microscale slip conditions is essential. This include microfluidic devices, heat exchangers, chemical reactors, and cooling systems for electronic components, where the regulation of thermal and species movement is crucial for efficiency. Thermo-diffusion influences the theoretical framework for the design of energy systems, solar collectors, and petroleum refining apparatus when temperature-induced mass separation transpires. The findings are relevant to biomedical flows, polymer processing, food drying, and gas separation membranes, where slip flow and diffusion effects are significant. The concept is pertinent to environmental systems, including pollution dispersion in vertical channels and energy storage materials where natural convection induces fluid motion. The established framework facilitates enhanced design of thermal devices, optimization of mass diffusion processes, and advancement of next-generation high-efficiency transport technologies.

II. MATHEMATICAL ANALYSIS

Take into account the free-convective and mass transfer flows of an incompressible viscous fluid in a vertical channel created by two infinitely tall parallel plates. Temperature and concentration gradients work together to generate a convection current. Based on these assumptions, the flow must be along the x'-axis, which runs vertically along the channel walls, and the y'-axis, which is normal to the plates spaced h distance apart. Fluid conditions include resting temperature T0 and starting concentration C0 at time t'0. When t' > 0, the concentration and temperature on the wall y' = 0 go up to Tw and Cw, respectively, while on the wall y'=h, they stay at T0 and C0, respectively. The fluid's viscosity holds the velocity of the fluid on both walls constant, u'=0. According to the rules, concentration controls the temperature.

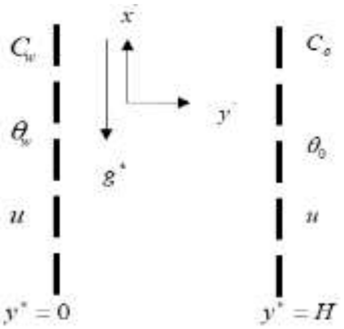

Figure. 1 Flow configuration and coordinate system

$$\frac{\partial u^*}{\partial t^*} - w_0^*(1+\varepsilon e^{-n^* t^*})\frac{\partial u^*}{\partial y^*} = v\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta(T^* - T_0^*) + g\beta^*(C^* - C_0^*) \tag{1}$$

$$\frac{\partial T^*}{\partial t^*} - w_0^*(1+\varepsilon e^{-n^* t^*})\frac{\partial T^*}{\partial y^*} = \frac{\alpha}{v}\frac{\partial^2 T^*}{\partial y^{*2}} + \frac{DmkT}{Cp}\frac{\partial^2 C^*}{\partial z^{*2}} \tag{2}$$

$$\frac{\partial C^*}{\partial t^*} - w_0^*(1+\varepsilon e^{-n^* t^*})\frac{\partial C^*}{\partial y^*} = Dm\frac{\partial^2 C^*}{\partial y^{*2}} \tag{3}$$

The initial and boundary condition for present problem are:

$$\left\{\begin{array}{llll} t^* \le 0 : u^* = 0, & \theta^* \to \theta_0^* & C^* \to C_0^* & \\ t^* > 0 : u^* = \gamma^* \dfrac{\partial u^*}{\partial y'}, & \theta^* = 1 + \varepsilon e^{-n^* t^*}, & C^* = 1 + \varepsilon e^{-n^* t^*} & y^* = 0 \\ u^* = 0, \quad \theta^* = 0, & C^* = 0, & y^* = H & \end{array}\right\} \tag{4}$$

The non-dimensional parameters and quantities are given as:

$$z = \frac{z^*}{H^*},\ t = \frac{t^* v^*}{H^2},\ u = \frac{u^*}{u_0},\ \Pr = \frac{v}{\alpha}.\ w_0 = \frac{w_0^*}{H},$$
$$Sc = \frac{v}{D},\ \theta = \frac{\theta^* - \theta_0}{\theta_w - \theta_0^*},\ C = \frac{C^* - C_0}{C_w - C_0^*},\quad \gamma = \frac{\gamma^*}{H} \tag{5}$$
$$N = \frac{\beta^*(C_w - C_0)}{(\theta_w - \theta_0)},\ Du = \frac{Dm(C_w - C_0)}{\alpha(\theta_w - \theta_0)},\ \varepsilon = \frac{R\theta_0}{E}$$

Using equation (5) in equation (1) to (3), subject to equation (4) we have the dimensionless momentum, energy and concentration governing equations as:

$$\frac{\partial u}{\partial t} - w_0(1+\varepsilon e^{-nt})\frac{\partial u}{\partial y} = \frac{\partial^2 u}{\partial y^2} + \theta + NC \tag{6}$$

$$\Pr\left[\frac{\partial \theta}{\partial t} - w_0(1+\varepsilon e^{-nt})\frac{\partial \theta}{\partial y}\right] = \frac{\partial^2 \theta}{\partial y^2} + Du\frac{\partial^2 C}{\partial y^2} \tag{7}$$

$$Sc\left[\frac{\partial C}{\partial t} - w_0(1+\varepsilon e^{-nt})\frac{\partial C}{\partial y}\right] = \frac{\partial^2 C}{\partial y^2} \tag{8}$$

$$\left.\begin{array}{llll} U = L\dfrac{\partial u}{\partial y}, & \theta = 1 + \varepsilon e^{-nt}, & C = 1 + \varepsilon e^{-nt}, & y = 0 \\ U = 0, & \theta = 0, & C = 0, & y = 1 \end{array}\right\} \tag{9}$$

2.1 Solution of the Problem

In order to reduce the above system of partial differential equations to a system of ordinary differential equations in dimensionless form we may represent the velocity, temperature and concentration as:

$$\left.\begin{aligned} U &= U_0(z)+\varepsilon e^{-nt}U_1(z) \\ \theta &= \theta_0(z)+\varepsilon e^{-nt}\theta_1(z) \\ C &= C_0(z)+\varepsilon e^{-nt}C_1(z) \end{aligned}\right\} \tag{10}$$

Using equation (5) in equations (1) to (3), and neglecting the coefficient of , we obtain the following solution for velocity, temperature and concentration as:

$$\begin{aligned} U(z,t) = {} & A_9 + A_{10}e^{m_{10}z} + L_7 + L_8e^{m_2z} + L_9e^{m_6z} + \varepsilon e^{-nt}(A_{11}e^{m_{11}z} + A_{12}e^{-m_{12}z} + L_{10}e^{m_{10}z} + L_{11}e^{m_2z} \\ & + L_{12}e^{m_6z} + L_{13}e^{-m_4z} + L_{14}e^{-m_8z} + L_{15}e^{m_3z} + L_{16}e^{m_7z}) \end{aligned} \tag{11}$$

$$\begin{aligned} \theta(z,t) = {} & A_5 + A_6e^{m_6z} + L_2e^{m_2z} + \varepsilon e^{-nt}(A_7e^{m_7z} + A_8e^{-m_8z} + L_3e^{m_6z} + L_4e^{m_2z} \\ & + L_5e^{m_3z} + L_6e^{-m_4z}) \end{aligned} \tag{12}$$

$$C(z,t) = A_1 + A_2e^{m_2z} + \varepsilon e^{-nt}(A_3e^{m_3z} + A_4e^{-m_4z} + L_1e^{m_2z}) \tag{13}$$

The expression for the skin-friction ( ) at the both plates is given by:

$$\begin{aligned} \tau_0 = \left[\frac{du}{dz}\right]_{z=0} & = m_{10}A_{10} + m_2L_8 + m_6L_9 + \varepsilon e^{-nt}\big[m_{11}A_{11} - m_{12}A_{12} + m_{10}L_{10} + \\ & m_2L_{11} + m_6L_{12} - m_4L_{13} - m_8L_{14} + m_3L_{15} + m_7L_{16}\big] \end{aligned} \tag{14}$$

$$\begin{aligned} \tau_1 = \left[\frac{du}{dz}\right]_{z=1} & = m_{10}Ae^{m_{10}} + m_2L_8e^{m_2} + m_6L_9e^{m_6} + \varepsilon e^{-nt}\begin{bmatrix} m_{11}A_{11}e^{m_{11}} - m_{12}A_{12}e^{-m_{12}} \\ +m_{10}L_{10}e^{m_{10}} + \end{bmatrix} \\ & m_2L_{11}e^{m_2} + m_6L_{12}e^{m_6} - m_4L_{13}e^{-m_4} - m_8L_{14}e^{-m_8} + m_3L_{15}e^{m_3} + m_7L_{16}e^{m_7}\big] \end{aligned} \tag{15}$$

The expression for the Nusselt number ( ) at the both plates is given by:

$$Nu_0 = \left[\frac{d\theta}{dz}\right]_{z=0} = m_6A_6 + m_2L_2 + \varepsilon e^{-nt}\left[m_7A_7 - m_8A_8 + m_6L_3 + m_2L_4 + m_3L_5 - m_4L_6\right] \tag{16}$$

$$\begin{aligned} Nu_1 = \left[\frac{d\theta}{dz}\right]_{z=1} & = m_6A_6e^{m_6} + m_2L_2e^{m_2} \\ & + \varepsilon e^{-nt}\begin{bmatrix} m_7A_7e^{m_7} - m_8A_8e^{-m_8} + m_6L_3e^{m_6} + m_2L_4e^{m_2} + m_3L_5e^{m_3} \\ -m_4L_6e^{-m_4} \end{bmatrix} \end{aligned} \tag{17}$$

The expression for the Nusselt number ( ) at the both plates is given by:

$$Sh_0=\left[\frac{dc}{dz}\right]_{z=0}=m_2A_2e^{m_6}+\varepsilon e^{-nt}\left[m_3A_3-m_4A_4+m_2L_1\right] \tag{18}$$

$$Sh_1=\left[\frac{\partial C}{\partial z}\right]_{y=1}=m_2A_2e^{m_2}+\varepsilon e^{-nt}\left[m_3A_3e^{m_3}-m_4A_4e^{-m_4}+m_2L_1e^{m_2}\right] \tag{19}$$

The constant

$A_1, A_2, A_3, A_4, A_5, A_6, A_7, A_8, A_9, A_{10}, A_{11}, A_{12}$
$L_1, L_2, L_3, L_4, L_5, L_6, L_7, L_8, L_9, L_{10}, L_{11}, L_{12}, L_{13}, L_{14}, L_{15}, L_{16}$
$m_1, m_2, m_3, m_4, m_5, m_6, m_7, m_8, m_9, m_{10}, m_{11}, m_{12}.$
are defined in Appendix

III. RESULT AND DISCUSSION

The problem of free convection slip flow with diffusion-thermo effects in a vertical channel has been analysed, and analytical solutions for the velocity, temperature, and concentration fields have been derived in the previous section. The graphical representations of velocity, temperature, concentration, skin friction coefficient, Nusselt number, and Sherwood number are assessed for various chosen values of the governing non-dimensional parameters to analyse their impact on flow and transport characteristics. Figure 2 illustrates Dufour's effect on dimensionless fluid velocity and temperature adjacent to the left wall of the channel. It was observed that a modest increase in Dufour number results in a resistance force that enhances fluid flow, thereby augmenting the momentum profile. Figure 3 illustrated the effect of diffusion-thermos on the energy profile. An elevation in Du results in a substantial augmentation of the temperature profile. Illustration 4. The analysis of Prandtl number behavior on dimensionless velocity revealed that a high Prandtl number indicates that momentum diffusivity prevails over thermal diffusivity. In these fluids, thermal diffusion occurs slowly, leading to a thin thermal boundary layer and pronounced temperature gradients near the surface. The elevated viscosity linked to substantial Prandtl numbers impedes fluid motion, resulting in diminished momentum transfer from the wall. Illustration 5. The effect of Pr on temperature parallels that of velocity. Illustration. Figure 6 illustrates the effect of Sc on velocity profiles, while Figure 7 demonstrates its impact on concentration profiles. It is noted that the concentration and velocity of the fluid diminish as the Schmidt number (Sc) increases. Figures 8 and 9 illustrate the impact of the Navier slip parameter L and the sustentation parameter N on fluid velocity. It was observed that when N increases, the fluid velocity also increases, as seen in Figure 9. The data indicate that as the slip parameter L increases, the fluid flow velocity at the lower surface of the plate also increases due to the plate's slipperiness.

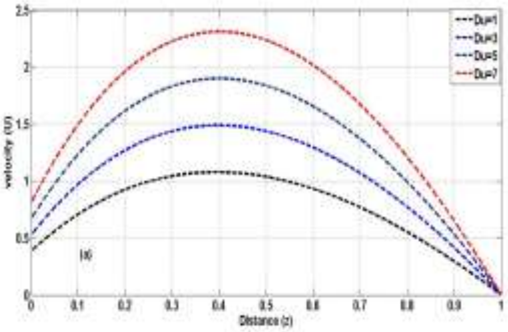

Figure 2. Velocity profile for different values of Du

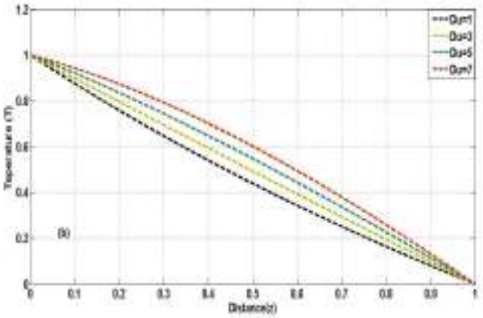

Figure 3. Temperature profile for different values of Du

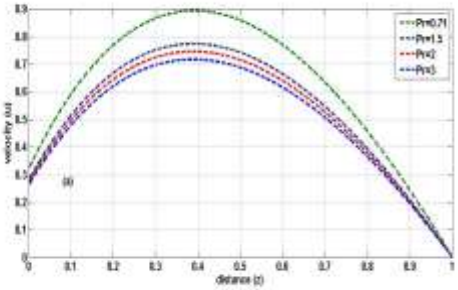

Figure 4. Velocity profile for different values of Pr

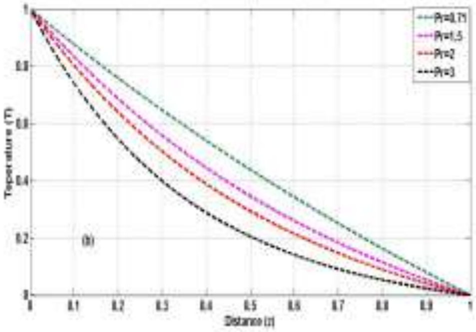

Figure .5 Temperature profile for different values of Pr.

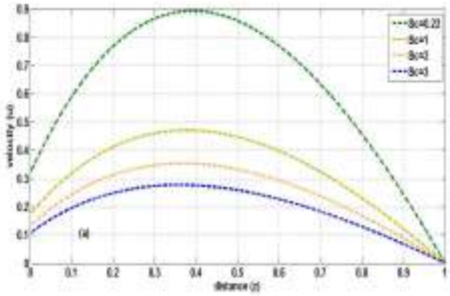

Figure 6. Velocity profile for different values of Sc

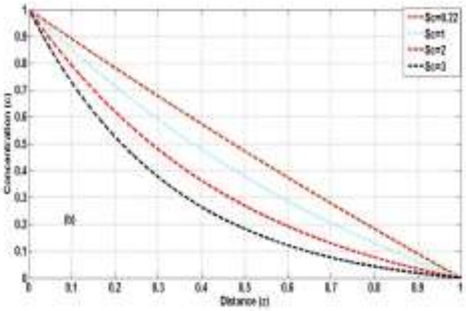

Figure 7. Concentration profile for different values of Sc

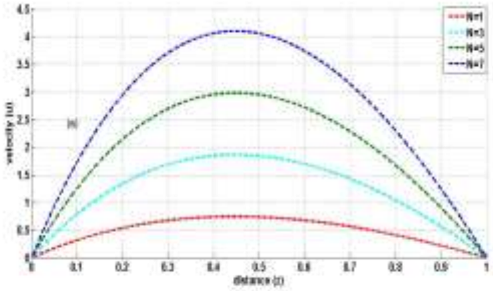

Figure 8. Concentration profile for different values of Sc

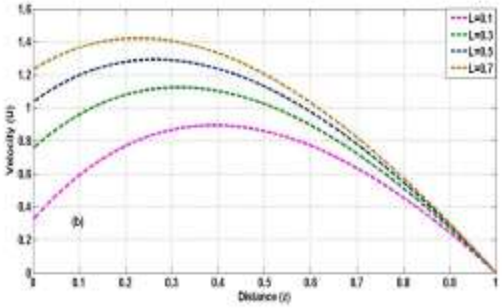

Figure 9 Velocity profiles for different value of L.

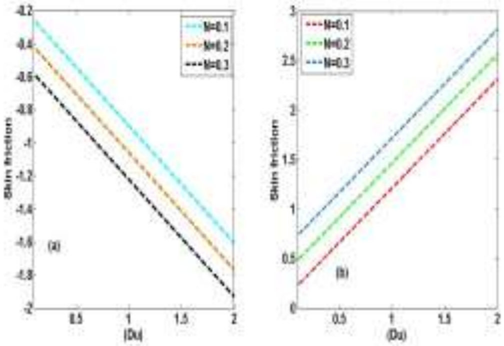

Figure .10. Variation of skin friction with N and Du at y= 0 and y= 1.

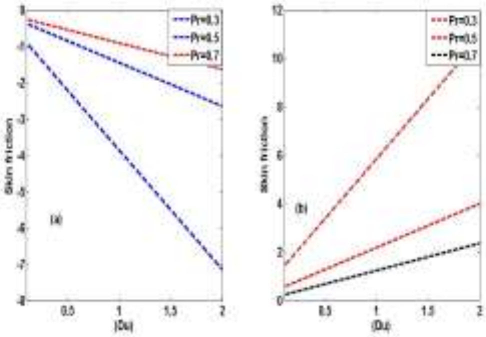

Figure.11. Variation of skin friction with Pr and Du at z= 0 and z= 1.

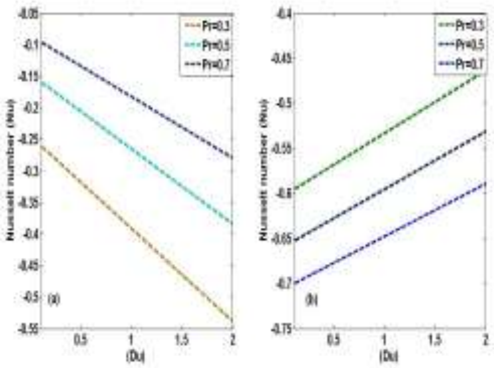

Figure. 12 Variation of Nusselt number with N and Du at z= 0 and z= 1.

The impact of N on skin friction at the lower and upper plates is examined in Figures 10a and 10b, respectively. Figure 10a illustrates that an increase in the sustentation parameter results in a reduction in skin friction at plate z=1; conversely, Figure 10b indicates an increase in skin friction with ascending values of N. Figures 11a and 11b illustrate the fluctuation of the Prandtl number (Pr) and the Du on skin friction at the plate (z=0 and z=1), respectively. It is seen in Figure 11a. The increased skin friction seen at the bottom plate (z=0), as shown in Figure 11b. It is observed that skin friction diminishes at the top plate (z=1) with an increase in Pr. The heat transfer rate, in terms of Nusselt number, depends on the Dean number for different Prandtl number values at both the bottom and upper channels of the plate, respectively. Figure 12a illustrates that a rise in the Prandtl number (Pr) results in a drop in the Nusselt number at the upper plate (z=1), while the opposite trend is seen in Figure 11b.

IV. CONCLUSION

This study analyzes the issue of free convection slip flow with diffusion-thermo effects in a vertical channel. The governing equations for momentum, energy, and concentration were established, non-dimensionalized, and solved analytically to examine the influence of many physical factors on flow behavior. The following conclusions are derived from the findings obtained:The diffusion-thermo (Dufour) parameter D promotes thermal energy transfer, therefore elevating both the temperature and velocity profiles inside the channel.The Prandtl number significantly affects the flow field by diminishing fluid velocity and temperature, signifying that fluids with a high Prandtl number display low thermal diffusivity and more resistance to motion.The Schmidt number (Sc) is shown to diminish both the velocity and concentration profiles, indicating enhanced resistance to mass diffusivity in fluids with higher Sc values.The Prandtl number is noted to elevate both the skin friction coefficient and Nusselt number at the lower plate, while decreasing skin friction at the higher plate, hence demonstrating its dual impact on surface shear and thermal transfer properties. The work offers valuable insights into how slip conditions and diffusion-thermo processes alter free convective heat and mass transfer in vertical channels. The results pertain to microfluidics, energy systems, and engineering applications where heat and mass diffusion are predominant factors.

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