

Detailed approaches to heat and mass transfer by exponentially accelerating a fluid over an inclined plate subjected to temperature variation and uniform mass diffusion

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Abstract

The impact of heat and mass transfer on magneto hydro dynamic flow across an inclined plate with a Hall effect is examined in this research. We have tried to explain the Hall effect and how an inclination angle affects the flow field when the temperature is varying and mass diffusion is uniform. One finds the energy, momentum, and concentration equations as coupled second-order partial differential equations (PDEs). The model's non-dimensionality and the fact that it is governed by many dimensionless parameters are proven. A solution to the resulting system of dimensionless PDE can be found by applying the Laplace transform. Numbers such as the Prandtl number (PrN), the magnetic parameter (M), the Hall parameter (m), the rotation parameter (Ω), and the angle of inclination (α) on the velocity, temperature, and concentration profiles, as well as graphical and qualitative explanations of the relevant parameters, are presented alongside the numerical results for these variables.

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1. Introduction

Magneto hydrodynamic flows (MHDF), when paired with the effects of heat and mass transfer (HMT), have important applications in many fields. In order to understand geophysical fluid dynamics, one must examine the revolving motion of electrically conducting fluids when a magnetic field is present. The generation of sunspots, the solar cycle, and the structure of rotating magnetic stars are all affected by MHDF, which also have an impact on solar physics. Because hydro magnetic flows and heat transfer have numerous applications in petroleum and agricultural engineering, research into them has become increasingly important. These applications include better oil recovery in the petroleum industry as well as agricultural procedures where MHDF contribute to growing crop development. Moreover, Magneto hydrodynamic (MHD) heat transfer has been demonstrated helpful for a range of engineering environments. The concepts of MHD heat transfer are the core of MHD generators, which produce electricity. MHD heat transfer principles are also useful in ionized-geothermal energy systems, nuclear reactor thermal dynamics, and plasma propulsion systems in astronautics. MHDF with Hall current are important in engineering applications. The Hall effect can be utilized by MHD pumps, MHD bearings, and other equipment to regulate and control MHDF. Numerous more applications make advantage of the Hall effect principle, including Hall effect joysticks that operate hydraulic valves and hypersonic flows. Further applications include Hall current accelerators, plasma actuators, brushless direct current motors, nuclear energy reactors, and calculations using magnetic fields.

The combined impacts of rotation and Hall current on MHD were studied by Muthucumaraswamy et al. [1] using an exponentially accelerated vertical plate that had experienced HMT. After applying the Laplace transform method to solve the dominant flowing model, they found that primary and secondary velocities increased with reducing magnitude of magnetic field. Rajput and his coworker [2] investigated the impacts of Hall currents on MHDF over a revolving inclined plate incorporating mass diffusion and heat transfer. Primary and secondary velocities had similar effects on heat energy absorption and the inclined angle of the plate, according to their findings. Jothi and Selvaraj [5] investigated the effectiveness of the DuFour effect on unsteady MHDF over a porous media by means of an exponentially accelerated bent vertical plate that was subjected to changing temperature and mass diffusion. The Magneto hydrodynamic Casson fluid flow with a leaned plate was solved by Kranthi Kumar et al. [7] using perturbation techniques in the existence of aligned magnetic effects and Hall. It was seen that the fluid velocity decreased with increasing angle of inclination.

Rajput and Gaurav Kumar [3] considered Hall currents when they investigated the effect of radiation and rotation on MHDF over an inclined plate with varying mass diffusion and wall temperature. They discovered that the velocity in the region of borderline layer decreased as the radiation parameter values increased. The DuFour effect on MHD-free convective heat and mass transfer flow across an inclined plate immersed in a porous medium was studied by Islam and Begum [6] using a closed analytical technique. Among other things, they exposed the point that the velocity profile drops as the Hartmann numbers, heat source, and radiation elements obtain greater. Meanwhile, the velocity profile grows in proportion to the increases in the DuFour, Schmidt, Grashof, dimensionless time, and Prandtl numbers. Vijayaragavan et al. [8] studied the effects of HMT on a MHD Casson fluid flow with an inclined plate by applying the Laplace transformation method. It was discovered that the axial velocity dropped off when the DuFour number was raised. They also found that as the number of DuFour grows, the species concentration decreases. With viscous dissipation and Hall currents included, Gollapalli Shankar et al. [4] investigated the impact of HMT on unsteady MHDF across an inclined plate in a permeable moderately. Radiation and tilted magnetic fields impacts on free convection MHDF were investigated by Rajput and N.K. Gupta [9] using rotational and Hall current models. Raising the radiation parameter in the boundary layer region causes the velocity to increase, they found. Additionally, they found that radiation and rotational factors both raise the drag at the plate surface. In their study, Usman et al. [10] examined the heat and mass transfer for the Magneto hydrodynamic Casson nano-fluid flow when thermal radiation was present.

Taking into account a constant mass distribution and temperature changes, this work aims to examine the MHDF properties of an exponentially accelerated inclined plate along with rotating system and a Hall current. By using exponential and complementary error functions, the authors hope to derive analytical solutions to the dimensionless governing equations. The data are shown visually through the use of MATLAB graphs that show concentration, temperature, and fluid velocity profiles.

2. Mathematical Formulation

We take a look at a viscous, incompressible fluid that conducts electricity as it flows over an endless plate that fills $z'=0$ plane. While the x' -axis follows the path of the moving plate, the y' -axis lies perpendicular to both the x' and z' axes. Both the fluid and the plate originally spin at the same rate, Ω' , around the z' -axis that is orthogonal to the inclined plate. The plate temperature and concentration close to it are denoted as T_∞ and c'_∞ , respectively. The other corner of the plate temperature increases to T_w and the magnitude of concentration close to it stays constant at c'_w while the plate is exponentially enhanced with a velocity $u' = \frac{u_0}{A} \exp(a't')$ in its plane along the x' -axis at time $t' > 0$. In this case, the plate does not conduct electricity. Along with that, a constant magnetic field is run parallel to the z' -axis. The flow field also exhibits uniform pressure. Consider the components of the velocity vector F as u', v' and w' . All the way through the flow, the $\nabla \cdot F = 0$ (continuity equation) produces $w' = 0$. Assuming the flow away from the plate remains unchanged, the quantities of flow in this situation are solely dictated by w' and t' .

These assumptions lead to the following equations that regulate the unsteady flow:

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial z'^2} + 2\Omega' v' - \frac{\sigma \mu_e^2 B_0^2}{\rho(1+m^2)} (u' + mv') + g\beta(T - T_\infty) \cos \alpha + g\beta^*(c' - c'_\infty) \cos \alpha \quad (1)$$

$$\frac{\partial v'}{\partial t'} = \nu \frac{\partial^2 v'}{\partial z'^2} - 2\Omega' u' + \frac{\sigma \mu_e^2 B_0^2}{\rho(1+m^2)} (mu' - v') \quad (2)$$

$$\rho c_p \frac{\partial T}{\partial t'} = K \frac{\partial^2 T}{\partial z'^2} \quad (3)$$

$$\frac{\partial c'}{\partial t'} = D \frac{\partial^2 c'}{\partial z'^2} \quad (4)$$

where v' denotes the transverse velocity and u' the axial velocity.

The most appropriate beginning and end points are

$$u' = 0, v' = 0, T = T_\infty, c' = c'_\infty \text{ at } t' \leq 0 \text{ for all } z'$$

$$u' = \frac{u_0}{A} e^{a' t'}, v' = 0, T = T_w, c' = c'_w$$

for all $t' > 0$ at $z' = 0$

$$c' \rightarrow c'_\infty, v' \rightarrow 0, u' \rightarrow 0, T \rightarrow T_\infty \text{ as } z' \rightarrow \infty$$

where the constant is $A = \left(\frac{u_0^2}{\nu}\right)^{\frac{1}{3}}$.

After providing the subsequent non-dimensional quantities,

$$u = \frac{u'}{(u_0 \nu)^{\frac{1}{3}}}, v = \frac{v'}{(u_0 \nu)^{\frac{1}{3}}}, z = z' \left(\frac{u_0}{\nu^2}\right)^{\frac{1}{3}}, t = \left(\frac{u_0^2}{\nu}\right)^{\frac{1}{3}} t', \Omega = \Omega' \left(\frac{\nu}{u_0^2}\right)^{\frac{1}{3}},$$

$$M^2 = \frac{\sigma \mu_e^2 B_0^2 v^{\frac{1}{3}}}{2 \rho u_0^{\frac{2}{3}}}, a = \left(\frac{\nu}{u_0^2}\right)^{\frac{1}{3}} a', Gc = \frac{g \beta^* (c'_w - c'_\infty)}{u_0}, Gr = \frac{g \beta (T_w - T_\infty)}{u_0},$$

$$C = \frac{c' - c'_\infty}{c'_w - c'_\infty}, \theta = \frac{T - T_\infty}{T_w - T_\infty}, Pr = \frac{\mu c_p}{K}, Sc = \frac{\nu}{D}$$

The governing equations in the non-dimensional form that follows are derived from equations (1), (2), (3), and (4).

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial z^2} + 2 \Omega v - \frac{2M^2}{1+m^2} (u + mv) + Gr \theta \cos \alpha + Gc C \cos \alpha \quad (5)$$

$$\frac{\partial v}{\partial t} = \frac{\partial^2 v}{\partial z^2} - 2 \Omega u + \frac{2M^2}{1+m^2} (mu - v) \quad (6)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial z^2} \quad (7)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C}{\partial z^2} \quad (8)$$

with initial and boundary conditions

$$\theta = 0, u = 0, v = 0, C = 0 \text{ for all } z \text{ at } t \leq 0 \quad (9)$$

$$C = 1, u = e^{at}, v = 0, \theta = t \text{ at } t > 0, z = 0 \quad (10)$$

$$\theta \rightarrow 0, u \rightarrow 0, v \rightarrow 0, C \rightarrow 0 \text{ as } z \rightarrow \infty \quad (11)$$

Equations (5)-(6), as well as boundary condition Equations (9-11), were combined and presented.

$$\frac{\partial q}{\partial t} = \frac{\partial^2 q}{\partial z^2} - 2q \left[\frac{M^2}{1+m^2} + i \left(\Omega - \frac{M^2 m}{1+m^2} \right) \right] + Gr \theta \cos \alpha + Gc C \cos \alpha \quad (12)$$

$$\frac{\partial \theta}{\partial t} = \frac{1}{Pr} \frac{\partial^2 \theta}{\partial z^2} \quad (13)$$

$$\frac{\partial C}{\partial t} = \frac{1}{Sc} \frac{\partial^2 C}{\partial z^2} \quad (14)$$

with boundary conditions

$$\theta = 0, q = 0, C = 0 \text{ for all } z, \text{ at } t \leq 0 \quad (15)$$

$$\theta = t, q = e^{at}, C = 1 \text{ at } z = 0, \text{ for all } t > 0 \quad (16)$$

$$\theta \rightarrow 0, q \rightarrow 0, C \rightarrow 0 \text{ as } z \rightarrow \infty \quad (17)$$

where $q = u + iv$.

3. Problem Solution

With the initial and boundary conditions given by Equations (15)–(17), the dimensionless governing equations (12)–(14) are solved using the Laplace-Transform method. We express our findings using exponential and complementary error functions.

$$\begin{aligned}
 C &= \operatorname{erfc}(\eta\sqrt{Sc}) \\
 \theta &= t \left[(1 + 2\eta^2 \operatorname{Pr}) \operatorname{erfc}(\eta\sqrt{Pr}) - \frac{2\eta\sqrt{Pr}}{\sqrt{\pi}} \exp(-\eta^2 \operatorname{Pr}) \right] \\
 q &= \frac{e^{at}}{2} \left[\exp(2\eta\sqrt{(a+b)t}) \operatorname{erfc}(\eta + \sqrt{(a+b)t}) + \right. \\
 &\quad \left. - \exp(-2\eta\sqrt{(a+b)t}) \operatorname{erfc}(\eta - \sqrt{(a+b)t}) \right] \\
 &\quad - \frac{1}{2} \left[\frac{c_1}{b_1^2} + \frac{c_2}{b_2} \right] \left[\exp(-2\eta\sqrt{bt}) \operatorname{erfc}(\eta - \sqrt{bt}) + \right. \\
 &\quad \left. \exp(2\eta\sqrt{bt}) \operatorname{erfc}(\eta + \sqrt{bt}) \right] \\
 &\quad + \left[\frac{c_1}{b_1^2} \right] \left[\frac{e^{b_1 t}}{2} \right] \left[\exp(-2\eta\sqrt{(b_1+b)t}) \operatorname{erfc}(\eta - \sqrt{(b_1+b)t}) \right. \\
 &\quad \left. + \exp(2\eta\sqrt{(b_1+b)t}) \operatorname{erfc}(\eta + \sqrt{(b_1+b)t}) \right] \\
 &\quad \left[\frac{c_2}{b_2} \right] \left[\frac{e^{b_2 t}}{2} \right] \left[\exp(-2\eta\sqrt{(b_2+b)t}) \operatorname{erfc}(\eta - \sqrt{(b_2+b)t}) \right. \\
 &\quad \left. + \exp(2\eta\sqrt{(b_2+b)t}) \operatorname{erfc}(\eta + \sqrt{(b_2+b)t}) \right] \\
 &\quad + - \frac{c_1}{b_1} \left[\frac{t}{2} \left[\exp(-2\eta\sqrt{bt}) \operatorname{erfc}(\eta - \sqrt{bt}) + \right. \right. \\
 &\quad \left. \left. \exp(2\eta\sqrt{bt}) \operatorname{erfc}(\eta + \sqrt{bt}) \right] - \frac{\eta\sqrt{t}}{2b} \left[\exp(-2\eta\sqrt{bt}) \operatorname{erfc}(\eta - \sqrt{bt}) + \right. \right. \\
 &\quad \left. \left. \exp(2\eta\sqrt{bt}) \operatorname{erfc}(\eta + \sqrt{bt}) \right] \right] \\
 &\quad - \left[\frac{c_1}{b_1^2} \right] \left[\frac{e^{b_1 t}}{2} \right] \left[\exp(-2\eta\sqrt{b_1 Pr t}) \operatorname{erfc}(\eta\sqrt{Pr} - \sqrt{b_1 t}) \right. \\
 &\quad \left. + \exp(2\eta\sqrt{b_1 Pr t}) \operatorname{erfc}(\eta\sqrt{Pr} + \sqrt{b_1 t}) \right] \\
 &\quad + \left[\frac{c_2}{b_2} \right] [\operatorname{erfc}(\eta\sqrt{Sc})] + \left[\frac{c_1}{b_1^2} \right] [\operatorname{erfc}(\eta\sqrt{Pr})] \\
 &\quad + \frac{c_1}{b_1} t \left[(1 + 2\eta^2 \operatorname{Pr}) \operatorname{erfc}(\eta\sqrt{Pr}) - \frac{2\eta\sqrt{Pr}}{\sqrt{\pi}} \exp(-\eta^2 \operatorname{Pr}) \right] \\
 &\quad - \frac{c_2}{b_2} \left[\frac{e^{b_2 t}}{2} \right] \left[\exp(-2\eta\sqrt{Sc b_2 t}) \operatorname{erfc}(\eta\sqrt{Sc} - \sqrt{b_2 t}) + \right. \\
 &\quad \left. \exp(2\eta\sqrt{Sc b_2 t}) \operatorname{erfc}(\eta\sqrt{Sc} + \sqrt{b_2 t}) \right]
 \end{aligned}$$

where $b = 2 \left[\frac{M^2}{1+m^2} + i \left(\Omega - \frac{M^2 m}{1+m^2} \right) \right]$, $b_1 = \frac{b}{Pr-1}$, $c_1 = \frac{Gr \cos \alpha}{Pr-1}$, $b_2 = \frac{b}{Sc-1}$, $c_2 = \frac{Gc \cos \alpha}{Sc-1}$, $\eta = z/2\sqrt{t}$

For a clearer picture of the flow field, this work divided q into both imaginary and real parts to get v and u , such as transverse and axial components.

4. Interpretation of Results

Numerical computations were conducted using a range of physical parameters, such as Sc , GrN (Thermal Grashof number), M , GcN (Mass Grashof number), m , Pr , in order to gain a deeper understanding of the issue. The water-related Prandtl number, 7.0, was chosen. The impact of the Schmidt number (Sc) on the concentration field is seen in Figure 1. While maintaining constants for $M = m = 0.5$, $a = 2.0$, $t = 0.2$, and $Gr = Gc = 5.0$, the values of Sc selected were 0.16, 0.6, and 2.01. The concentration of the fluid medium is observed to decrease with increasing Sc . Figure 2 shows how the PrN affects the temperature field. Raising the PrN causes a decrease in temperature.

For various parameters, the axial and transverse velocity profiles were examined.

As Gr , m , and M increase, the axial velocity decreases, as shown in Figures 3, 5, and 6. Figure 4 shows an interesting pattern where the velocity starts to drop after initially increasing for rotation parameters within the range of $0 \leq \Omega < 1.5$. Additionally, Figures 7 and 8 demonstrate how the axial velocity rises as Gc and α values rise. The transverse velocity decreases as M , Ω , Gc , and α increase, as seen in Figures 9, 10, 13, and 14. As m and Gr rise, the transverse velocity also increases, as seen in Figures 11 and 12.

These results provide valuable insights into the behaviour of the velocity and concentration fields under different parameter variations.

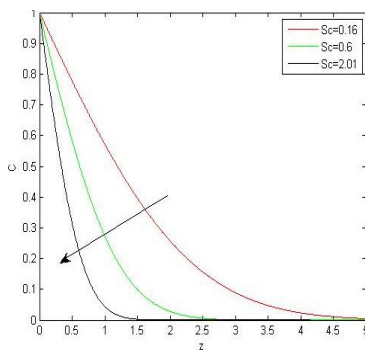


Figure 1
Profiles of Concentration for various Sc values

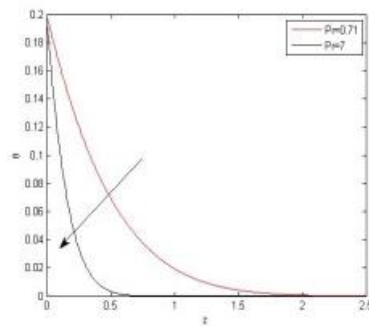


Figure 2
Profiles of temperature for various Pr values

5. Graphical Representation

The axial and transverse velocity of the graphical representation for different parameters is depicted as follows:

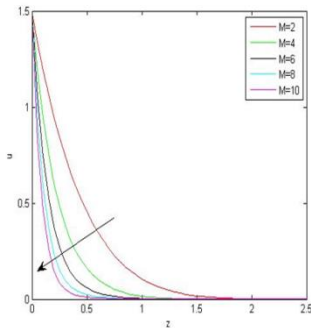


Figure 3
Magnetic field M of u verses z

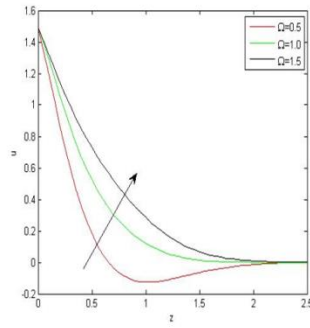


Figure 4
Rotation parameter of u verses z

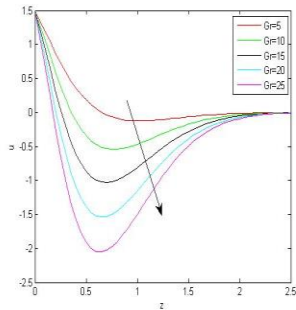


Figure 5
Hall parameter m of u verses z

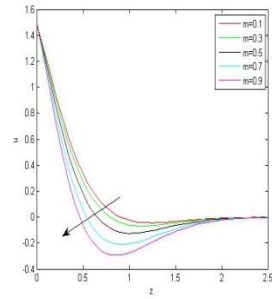


Figure 6
Thermal Grashof Gr of u verses z

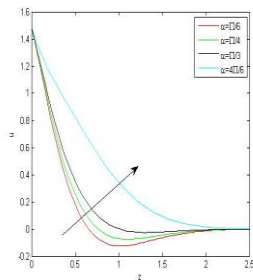


Figure 7
Mass Grashof G_c of u verses z

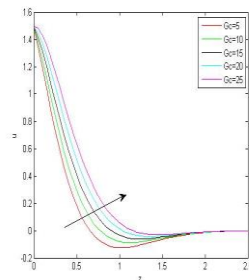


Figure 8
Inclination angle α of u verses z

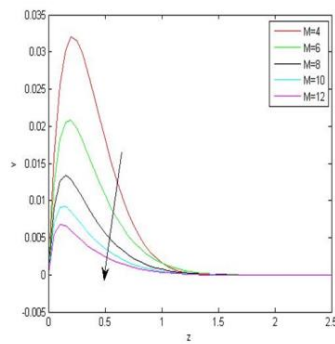


Figure 9
Magnetic field M of v versus z

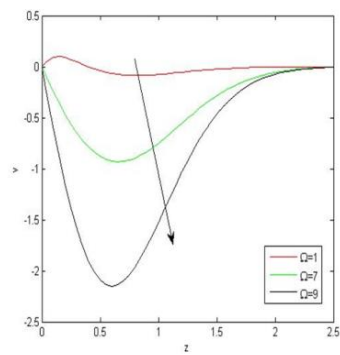


Figure 10
Rotation Parameter Ω of v versus z

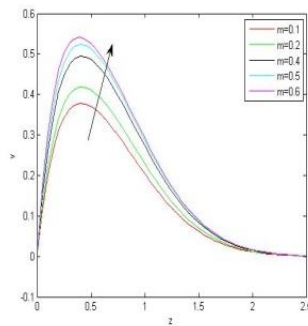


Figure 11
Hall Parameter m of v versus z

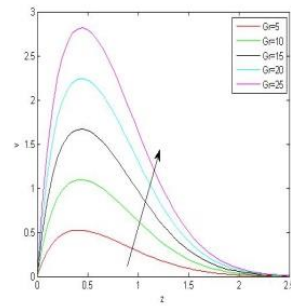


Figure 12
Thermal Grashof Gr of v versus z

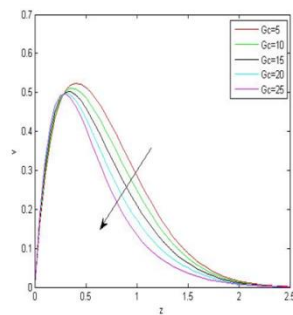


Figure 13
Mass Grashof G_c of v versus z

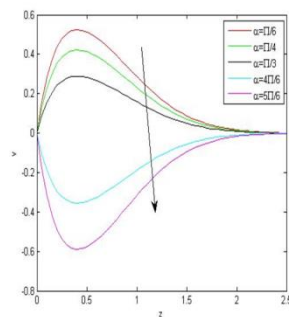


Figure 14
Inclination angle α of v versus z

6. Conclusion

The goal of this work was to examine how the MHDF over an inclined plate accelerated exponentially, while maintaining varying temperature and mass diffusion, which was affected by Hall current and rotation. The results that followed were reached after the flow was analyzed.

As the Prandtl number (PrN) rises, the plate's temperature falls. This indicates that higher Prandtl numbers result in lower temperatures in the flow. The concentration near the plate increases as the Schmidt number decreases. This implies that lower Schmidt numbers lead to higher concentrations in the flow.

Axial and transverse velocity effects depend on several parameters, such as the rotation parameter, GrN, GcN, angle of inclination, and m . This suggests that these parameters play a significant role in determining the velocities in the flow. The axial and transverse velocities decrease as the magnetic field parameter increases. This indicates that higher magnetic field parameters result in lower velocities in both the axial and transverse directions. The results offer a significant understanding of the MHD flow's behaviour and demonstrate how different parameters affect the system's temperature, concentration, and velocities.

Nomenclature

- $a, A, a' \rightarrow$ Constants
 $B_0 \rightarrow$ Magnetic field implementation(T)
 $C \rightarrow$ Concentration without dimensions
 $c' \rightarrow$ Concentration of species in the fluid (mol/m³)
 $c_p \rightarrow$ Constant pressure's specific heat (J/Kg.K)
 $c'_w \rightarrow$ Plate concentration
 $c'_\infty \rightarrow$ The fluid's concentration far from the plate
 $D \rightarrow$ Coefficient of mass diffusion
 $erfc \rightarrow$ complementary function for errors
 $Gc \rightarrow$ Mass Grashof number
 $Gr \rightarrow$ Thermal Grashof number
 $g \rightarrow$ gravitational acceleration (m/s²)
 $K \rightarrow$ Thermal conductivity (W/m.K)
 $M \rightarrow$ Hartmann number
 $m \rightarrow$ Hall parameter
 $Pr \rightarrow$ Prandtl number
 $Sc \rightarrow$ Schmidt number
 $T \rightarrow$ The fluid's temperature close to the plate(K)
 $T_w \rightarrow$ Plate temperature (K)
 $T_\infty \rightarrow$ fluid's temperature at a distance from the plate (K)
 $t \rightarrow$ Time without dimensions.

t' → Time (s)
 u_0 → Plate's velocity
 $(u' v' w')$ → Velocity Field's Components F (m/s)
 $(u v w)$ → Dimensionless Velocity Elements
 $(x' y' z')$ → Coordinates in Cartesian Form
 z → Dimensionless coordinate perpendicular to the plate
 μ_e → Permeability of Magnetism(H/m)
 ν → Kinematic Viscosity (m^2/s)
 Ω' → Angular Velocity Component (rad/s)
 Ω → Dimensionless Angular Velocity
 ρ → Density of Fluids (kg/m^3)
 σ → Conductivity of Electricity(Siemens/m)
 θ → temperature without dimensions
 η → Parameter of similarity
 β → thermal expansion coefficient in volume
 β^* → Concentration-dependent volumetric coefficient of expansion
 α → The inclination angle

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