



# Dynamical Behaviour of Wall Concentration and Superhydrophobicity Effects on a Combined Reactive Flow in a Slit Microchannel

Emmanuel Omokhuale<sup>1\*</sup>, Godwin Ojemeru<sup>2</sup>, Benard Alechenu<sup>3</sup>, Haruna Ishaya Germache<sup>4</sup>, Jeremiah Aaron Dazi<sup>5</sup>

<sup>1</sup>Department of Mathematical Sciences, Faculty of Sciences, Federal University Gusau, P. M. B. 1001, Zamfara State.

<sup>2,4,5</sup>Department of Mathematics, College of Science, Federal University of Agriculture, Zuru, P. M. B. 28, Kebbi State, Nigeria.

<sup>3</sup>Department of Mathematics and Statistics, Faculty of Science, Federal University of Kashere, P. M. B. 0182, Gombe State.

\*Corresponding Author's email: [emmanuelomokhuale@gmail.com](mailto:emmanuelomokhuale@gmail.com)

Received on: August, 2025

Revised and Accepted on: September, 2025

Published on: October, 2025

## ABSTRACT

This work shows how Arrhenius-controlled heat and mass transfer flow influenced by uniform wall concentration over a superhydrophobic microchannel is affected by mixed convection with a constant pressure gradient. While the other parallel plate has a no-slip surface (NSS), one of the plates is purposefully altered to have a superhydrophobic surface (SHS). A semi-analytical approach is used for the nonlinear ordinary differential equations. A graphic illustration of the behaviors of the main parameters governing the flow behavior in terms of mass diffusion, temperature, and velocity trends is provided. It was observed that the presence of mixed convection parameter boosts the fluid velocity. Additionally, the symmetric wall concentration effect significantly affects the development of flow reversal. Finally, these findings will find applications in manufacturing processes like hot rolling, drawing of wire, continuous casting, production of glass fiber, and fabrication of paper, cracking in petrochemical engineering, chemical synthesis, anti-wetting micro-technology, etc.

**Keywords:** Mixed (Combined) flow, Mass flow, wall concentration, reactive fluid, Magnetohydrodynamics (MHD), Superhydrophobic Microchannel.

## 1.0 INTRODUCTION

Heat transfer in flows with equal relative contributions from induced and natural convection is common in engineering situations. These fluxes are referred to as mixed convection flows. Mixed convection occurs when buoyant and viscous forces significantly influence a forced flow process. Thermal-hydraulic applications encompass nuclear reactors, polymer processing, float glass manufacturing, recoverable systems, electronics cooling, lubrication innovations, drying methods, flow and heat transfer in solar ponds, and lake dynamics. (Mandal *et al.*, 2020; Ullah *et al.*, 2024). Understanding the two limiting regimes is often required for studying a mixed convection flow. Mixed convection can be utilized for the dispersion of chemical contaminants in various processes within the chemical industry, as well as for the transportation of heated or cooled fluids, among other applications, as reported by Lavine (1988). Mixed convection is interrelated with the Richardson number,  $Ri$ , which originates from the Grashof number and Reynolds number. Many studies have agreed that altering  $Ri$  can modify the types of convection in various cases, including home ventilation, fire prevention, solar collectors, drying technologies, and chemical processing, as indicated by Saedodin *et al.* (2013). Much emphasis has been placed on the investigation of mixed convective flow along a rigid plate lately because it is essential for a variety of applications,

including the electronic cooling devices by fans, the cooling of nuclear reactors during an unexpected failure, the placement of heating systems in minimal-velocity environments, solar cells, and others. (Aydin and Kaya, 2013). Over the years, several authors have carried out studies in this field. In this context, Ahmad *et al.* (2023) evaluated the effects of a pressure gradient that was exponentially increasing or decreasing on the transient mixed convection flow of viscous reactive fluids in a vertical tube between two concentric tubes. The nonlinear partial differential equation governing the flow formation is solved using the implicit finite difference form, where all time differentials were calculated using the forward difference formula. Hamza *et al.* (2019) studied the impact of thermal diffusion and radial magnetic field on a chemically reactive fluid through an upstanding porous annulus. Hindebu *et al.* (2022) analyzed the hydrodynamic and heat transfer problems of unsteady mixed convection flow of nanofluid in a micro-channel filled with porous material. Ajibade and Umar (2021) scrutinized the effects of viscous dissipation on a steady mixed convection Couette flow of heat-generating/absorbing fluid. Jafar *et al.* (2022) reported that the buoyant force has a substantial impact on the flow field for vertical or inclined surfaces. Jamaludin *et al.* (2020) examined the influence of heat emission/absorption in MHD mixed convection stagnation point in a hybrid nanofluid. They reported that the heat transfer of the conventional

alumina/water nanofluid is greater than that of the copper–alumina water nanofluid with the increment in the heat source and sink parameter. Malvandi *et al.* (2015) presented a theoretical analysis of MHD mixed convection of alumina/water nanofluid inside a vertical annular pipe. Hayat *et al.* (2016) investigated mixed convection flow of viscoelastic nanofluid by a cylinder with variable thermal conductivity and heat source/sink. Hamza and Abdulsalam (2022) investigated the Influence of chemical kinetic exponent on transient mixed convective hydromagnetic flow in a vertical channel with convective boundary conditions.

Magneto-hydrodynamics (MHD) is one of the important areas of development in modern scientific research and engineering problems, which can also be considered as a fluid mechanics sub-discipline dealing with the mutual interaction between an externally imposed magnetic field and the flows of fluids that conduct electricity (Obalulu *et al.* 2021). MHD is a core field of fluid mechanics that investigates the magnetic characteristics of electrically conducting fluids. The magnetic field is required to confine the warmed plasma in the fusion phase, which produces solar energy. The use of a magnetic field to regulate melt flow may impact the solidification process. In the biological realm, the MHD phenomenon plays a critical part in applications such as cancer treatment therapy and targeted magnetic drug delivery (Reddy and Goud 2025). In transverse channel flows of incompressible liquids, the Lorentz force, rather than pump pressure, is used to accelerate the channel liquid more deeply or faster. Chemical energy technology, which includes the utilization of MHD pumps to transfer electrically conductive fluids, is currently employed in some nuclear power plants. Apart from these purposes, when the fluid is electrically conductive, an applied magnetic field can drastically boost natural convection movement (Jha *et al.* 2015). Several authors have published quality works to exemplify this phenomenon. To this end, Narender *et al.* (2021) studied the viscous dissipation and heat impacts on the MHD combined convection stagnation point flow of Maxwell nanofluid traveling across a stretching surface. Similarity transformations are used to convert governing partial differential equations into ordinary differential equations. Onwubuya and Ojemer (2023) presented a comparative analysis of the MHD flow of a viscous and incompressible fluid traveling through a slit microchannel coated with superhydrophobic slip and temperature jump effects using the homotopy perturbation method. The function of magnetized natural convective slip flow of a chemically reacting fluid affected by convective heating was reported by Hamza *et al.* (2021). Taid and Ahmed (2022) deliberated on the actions of thermal diffusion, viscous dissipation, and chemical reaction on steady two-dimensional MHD natural flow across an inclined porous plate coated with porous media using the

perturbation series scheme. Using the Laplace transformation procedure, Osman *et al.* (2022) described the impact of buoyancy-induced magnetized flow across an infinite inclined plate. A thorough response to the MHD impact on a heat transfer evaluation of electroosmotic flow in a rotating microfluidic channel was described by Siva *et al.* (2021). Amar *et al.* (2023) looked at the effects of thermal radiation and viscous dissipation on the MHD heat transfer flow of Casson fluid along a shifting wedge with a convective boundary condition when internal heat production and intake are present. Other references that provide further insights into this concept can be found in the works of Ojemer and Hamza (2022), Hamza *et al.* (2023), Hassan *et al.* (2020), Gambo and Gambo (2020), and Parthban and Pasad (2023).

There are several transport processes in industry and in nature where buoyancy force arises from both thermal and mass diffusion, which are caused by the temperature gradients and the concentration differences of dissimilar chemical species. Hence, these kinds of flows are driven by temperature gradients and concentration differences (Kaita *et al.* 2024). The problems of steady and unsteady flows having combined heat mass transfer by free convection with and without chemical reaction have been studied extensively by different researchers. Areas of possible engineering applications include Nuclear power plants, missiles, gas turbines, and space vehicles, to mention a few. To be more specific, Omokhuale and Ojemer (2025) recently analyzed the magnetized heat and mass transfer flow of a viscous reactive fluid affected by symmetric wall concentration using a semi-analytical method. Earlier on, Hamza *et al.* (2024) presented the analytical solutions of viscous Casson fluid with heat absorption affected by uniform wall temperature and concentration conditions using the differential transform method. Saeed *et al.* (2019) discussed Heat and Mass transfer of free convection flow over a vertical plate with chemical reaction under the wall slip effect. Solutions for the fluid velocity, temperature, and concentration are achieved in closed forms by applying the Laplace transform. Rout *et al.* (2013) established the MHD heat and mass transfer of chemical reaction fluid flow over a moving vertical plate in the presence of a heat source with convective surface boundary conditions. Sehra, *et al.* (2021) studied convection heat mass transfer and MHD flow over a vertical plate with chemical reaction, arbitrary shear stress, and exponential heating. Sani and Kaita (2023) studied steady-state free convection with heat and mass transfer in the presence of variable thermal conductivity. Dagana and Amos (2020) investigated MHD free convection heat and mass transfer flow in a porous medium with Dufour and chemical reaction effects. Ajibade and Ojeagbase (2020) investigated steady natural convection heat and mass transfer flow through

a vertical porous channel with viscosity and thermal conductivity. The variability in viscosity and thermal conductivity is considered as a linear function of temperature. Makinde (2010) investigated the effect of magnetized heat and mass transfer flow along a stretching upward channel with Convective heating at the boundary. None of these works considered the impact of mixed convection in the presence of symmetric wall concentration and superhydrophobicity via microchannels.

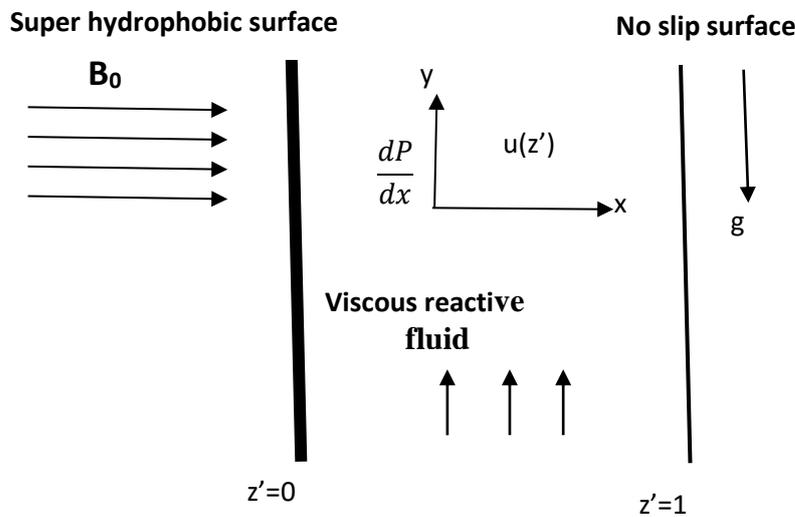
By addressing these research limitations, this work attempts to incorporate and investigate the influence of mixed convection parameters to fill a gap in the existing literature and provide valuable insights for the development and maximization of advanced flow situations. The work of Omokhuale and Ojemer (2025) is used as the benchmark work. Additionally, some chemical and engineering processes, such as polymer production, manufacturing of ceramics or glassware, and food processing, are made realistically possible when heat and mass transfer occur simultaneously. Finally, the outcome of this paper will not only be essential for improving fluid flow in microchannels but will also serve as a guide for the design of advanced thermal and mass management systems for

microfluidic devices and high-performance applications.

**2.0 MATHEMATICAL FORMULATION**

Imagine a steady mixed flow of an incompressible fluid passing through two vertical parallel plates affected by Arrhenius kinetics and symmetric wall concentration conditions. As shown in Figure 1, the wall at  $y_0 = 0$  is instigated by the extremely difficult-to-wet known as the SHO effect, while the NSS is kept at  $y_0 = L$ . A transversely applied magnetic field of intensity  $B_0$  is said to be introduced within two upstanding microchannel plates. All the fluid properties are assumed to be constants. The flow variables are functions of space  $z$  only. In view of the present formulation, the following assumptions are further made:

- i. The fluid is laminar and incompressible.
- ii. The flow is fully developed and obeys the Bousinesq approximation.
- iii. It is assumed that the fluid is influenced by Arrhenius kinetics.
- iv. The fluid is assumed to be affected by symmetric wall concentration
- v. The fluid is influenced by a constant pressure gradient.



**Figure 1: Sketch of the flow**

Following Omokhuale and Ojemer (2025) and Hamza et al. (2024c), the present problem in dimensional form can be written as:

$$V \frac{d^2 u'}{dz'^2} - \frac{\sigma B_0^2 u'}{\rho} + g\beta_0(T' - T_0) + g\beta_1(\xi' - \xi_0) = \frac{dP}{dx} \tag{1}$$

$$\frac{k}{\rho c_p} \frac{d^2 T'}{dz'^2} + \frac{QC_0 A}{\rho c_p} e^{\left(\frac{-E}{RT'}\right)} = 0 \tag{2}$$

$$D \frac{d^2 \xi'}{dz'^2} = 0 \tag{3}$$

Subject to the boundary conditions:

$$\left. \begin{aligned} u(z') &= \gamma' \frac{du'}{dz'} \\ T(z') &= T_h + \Gamma' \frac{dT'}{dz'} \\ \xi' &= \xi_w \end{aligned} \right\} \text{at } z' = 0$$

$$\left. \begin{aligned} u(z') &= 0 \\ T(z') &= T_o \\ \xi' &= -\xi_w \end{aligned} \right\} \text{at } z' = L$$
(4)

Introducing the dimensionless quantities as:

$$u = \frac{u'}{U}, z = \frac{z'}{h}, \theta = \frac{T' - T_o}{T_w - T_o}, x = \frac{x'v}{Uh^2}, M^2 = \frac{\sigma\beta_o^2 h^2}{\rho v}, (Z, \gamma, \Gamma) = (Z', \gamma', \Gamma')/h$$

$$\xi = \frac{\xi' - \xi_o}{\xi_w - \xi_o}, N = \frac{g\beta^*(T_w - T_o)H^2}{vU}, \varepsilon = \frac{RT_o}{E}, \lambda = \frac{QC_o^* AEH^2}{RT_o^2}, Gr = \frac{g\beta(T_1' - T_o)b^3}{v^2} Re = \frac{U_o b}{v}, A = \frac{1}{\rho} \frac{dP}{dx}$$
(5)

Substituting eqn(5) into eqns (1-4), the basic equations of the temperature and velocity become:

$$\frac{d^2 U}{dz^2} - Ha^2 U + \frac{Gr}{Re} (\theta + N\xi) = A$$
(6)

$$\frac{d^2 \Gamma}{dz^2} + \lambda e^{\frac{\theta}{1+\varepsilon\theta}} = 0$$
(7)

$$\frac{d^2 \xi}{dz^2} = 0$$
(8)

The boundary conditions are:

$$\xi(z) = R_w, \quad \theta(z) = 1 + \Gamma \frac{d\theta}{dz}, \quad u(z) = \gamma \frac{du}{dz} \quad \text{at } z = 0$$
(9)

$$\xi(z) = -R_w, \quad \theta(z) = 0, \quad u(z) = 0 \quad \text{at } z = 1$$

Where  $\frac{Gr}{Re} = Gre$  is mixed convection parameter, A is the constant pressure gradient, Ha is the magnetic parameter, N is the sustention parameter,  $\lambda$  is the viscous heating parameter,  $\varepsilon$  is the activation energy,  $R_w$  is the wall concentration parameter,  $\Gamma$  is the temperature jump parameter, and  $\gamma$  is the velocity slip parameter.

### 3.0 Solution Procedure

The coupled nonlinear governing equations are solved using the regular perturbation method, such that the solutions of the temperature and velocity are assumed as;

$$U = u_0 + \lambda(u_1) \tag{10}$$

$$\theta = \theta_0 + \lambda(\theta_1) \tag{11}$$

$$\xi = \xi_0 + \lambda(\xi_1) \tag{12}$$

Inserting eqns (8) and (9) into eqns (5) to (7), and taking the coefficients of  $\lambda^0$  and  $\lambda$ , we derive the following system of ordinary differential equations with their corresponding boundary conditions as:

$$\lambda^0: \frac{d^2 u_0}{dz^2} - Ha^2 u_0 = -Gre(\theta_0 + N\xi_0) + A \tag{13}$$

$$\lambda: \frac{d^2 u_1}{dz^2} - Ha^2 u_1 = -Gre(\theta_1 + N\xi_1) \tag{14}$$

$$\lambda^0: \frac{d^2 \theta_0}{dz^2} = 0 \tag{15}$$

$$\lambda: \frac{d^2 \theta_1}{dy^2} + 1 + \theta_0 + \left(\frac{1}{2} - \varepsilon\right)\theta_0^2 = 0 \tag{16}$$

$$\lambda^0: \frac{d^2 \xi_0}{dz^2} = 0 \tag{17}$$

$$\lambda: \frac{d^2 \xi_1}{dz^2} = 0 \tag{18}$$

$$\left. \begin{aligned} \lambda^0: \theta_0 &= 1 + \Gamma \frac{d\theta_0}{dz} \\ \lambda: \theta_1 &= \Gamma \frac{d\theta_1}{dz} \\ \lambda^0: u_0 &= \gamma \frac{du_0}{dz} \\ \lambda: u_1 &= \gamma \frac{du_1}{dz} \\ \lambda^0: \xi_0 &= R_w \\ \lambda: \xi_1 &= 0 \end{aligned} \right\} \text{at } z = 0$$
(19)

and

$$\left. \begin{array}{l} \lambda^0: \theta_0 = 0 \\ \lambda: \theta_1 = 0 \\ \lambda^0: u_0 = 0 \\ \lambda: u_1 = 0 \\ \lambda^0: \xi_0 = -R_w \\ \lambda: \xi_1 = 0 \end{array} \right\} \text{at } z = 1 \tag{20}$$

The solutions of temperature and velocity is derived as:

$$\xi_0 = X_1 z + X_2 \tag{21}$$

$$\xi_1 = 0 \tag{22}$$

$$\theta_0 = X_5 z + X_6 \tag{23}$$

$$\theta_1 = -\frac{z^2}{2} - X_5 \frac{z^6}{3} - X_6 \frac{z^2}{2} - d_1 \left( X_5^2 \frac{z^4}{12} + X_5 X_6 \frac{z^3}{3} + X_6^2 \frac{z^2}{2} + X_7 z + X_8 \right) \tag{24}$$

$$u_0 = X_9 \cosh(Haz) + X_{10} \sinh(Haz) + X_{11} z + X_{12} \tag{25}$$

$$u_1 = X_{13} \cosh(Haz) + X_{14} \sinh(Haz) + X_{15} z^5 + X_{16} z^4 + X_{17} z^3 + X_{18} z^2 + X_{19} z + X_{20} \tag{26}$$

Where the heat transfer rate and shearing stress is derived as:

$$\frac{d\xi}{dz} \Big|_{z=0} = X_1 \tag{27}$$

$$\frac{d\xi}{dz} \Big|_{z=1} = X_1 \tag{28}$$

$$\frac{d\theta}{dz} \Big|_{z=0} = X_5 + \lambda X_7 \tag{29}$$

$$\frac{d\theta}{dz} \Big|_{z=1} = X_5 + \lambda \left[ -2X_5 - 2X_6 - d_1 \left( \frac{X_5^2}{3} + X_5 X_6 + X_6^2 + X_7 \right) \right] \tag{30}$$

$$\frac{dU}{dz} \Big|_{z=0} = M X_{10} + X_{11} + \lambda [H a X_{14} + X_{19}] \tag{31}$$

$$\frac{dU}{dz} \Big|_{z=1} = H a X_9 \sinh(Ha) + H a X_{10} \cosh(Ha) + X_{11} + \lambda [H a X_{13} \sinh(Ha) + H a X_{14} \cosh(Ha) + 5X_{15} + 4X_{16} + 3X_{17} + 2X_{18} + X_{19}] \tag{32}$$

Where all the constants are defined in the appendix

#### 4.0 RESULTS AND DISCUSSION

The analysis of mixed convection of a chemically reactive fluid with symmetric wall concentration effect is studied over a microchannel coated with SHS and temperature jump conditions. A semi-analytical method is employed to treat the resultant steady ordinary differential equations. Some graphs have been plotted using MATLAB software to demonstrate the consequences of key parameters. The default values chosen for this analysis are ( $\gamma = \Gamma = 1, N = 5, R_w = 0.1, Ha = 0.5, \lambda = 0.001, Gre = 50, A = 1$ ).

Figure 2 depicts the influence of  $R_w$  on the concentration gradient. The graphic shows that increasing  $R_w$  enhances the fluid concentration near the left wall while decreasing it near the right wall. This is due to the symmetrical character of the wall concentration parameter. However, there is a point of intersection in the middle of the microchannel where the flow is unaffected by the parameter being considered. This conclusion is extremely valuable in the creation and control of reverse flow. Figure 3 explains how  $R_w$  affects the velocity profile. It is inferred that the impact of temperature on fluid flow caused the reversal to start faster at the top plate before rising considerably nearer the bottom plate. Figure 4 depicts the influence of  $Gre$ , which clearly increases fluid velocity in the microchannel at a constant pressure

gradient. Figure 5 depicts the fluid motion pattern as a function of magnetic parameter  $M$ . The flow pattern clearly shows a reduction for all investigated  $M$  values. The primary reason of this behavior is the presence of a magnetic effect, which operates to generate a resistive force (the Lorentz force) that limits velocity. Figure 6 depicts the fluctuation of the velocity gradient vs displacement  $z$ , and the findings are consistent with earlier research. This image shows that when particles move away from the SHS, their velocity temporarily increases before diminishing as they approach the center. Furthermore, in the absence of SHS and NSS, the fluid's velocity grows slowly before steadily moving till it reaches the microchannel's midpoint. Overall, in the presence of velocity slip and temperature jump, maximum velocity is achieved. Figure 7 shows how the chemically reactive parameter  $\lambda$  varies over the temperature gradient. Increasing the value of  $\lambda$  leads to significant temperature improvement. Similarly,  $\lambda$  increases fluid velocity in the microchannel, as seen in Figure 8. Furthermore, it is seen that the fluid wall effect decreases when velocity slip increases at the SHO walls. As a result, the gas flows quickly toward the wall. An increase in temperature causes a drop in fluid viscosity and an increase in fluid velocity as  $\lambda$  increases. Figures 9a and b show the effect of  $R_w$  against  $\gamma$  on the skin friction coefficient. Because of the symmetric wall circumstances, increasing  $R_w$  values

boosts the frictional force at microchannel plates. Figures 10a and b show the frictional force pattern as Gre varies. The graph shows an accelerated trend across both microchannel plates. Figures 11a and 11b show how Ha acts on both upstanding walls to cause skin friction. Figure 11a shows that near the wall ( $y=0$ ), the shearing stress is significantly strengthened; however, when  $y=1$ , the opposite effect occurs, as shown in Figure 11b.

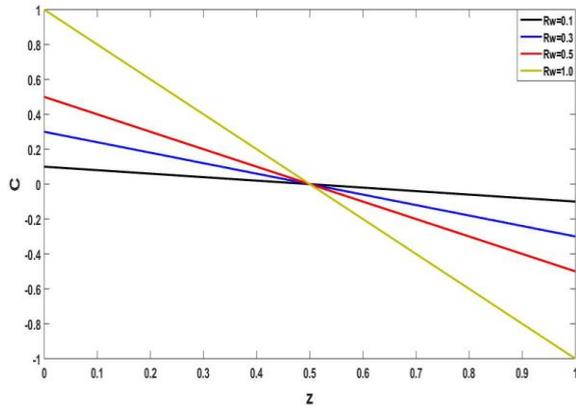


Figure 2: Output of  $R_w$  on Concentration distribution

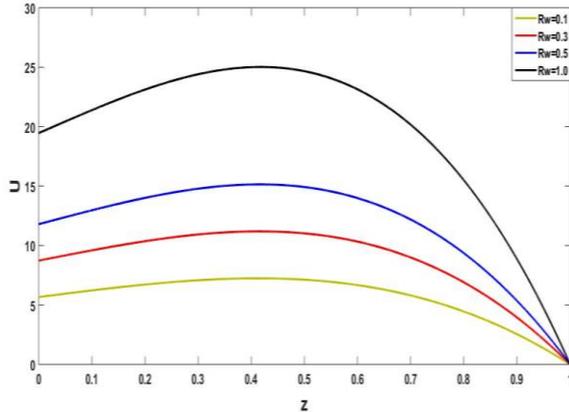


Figure 3: Output of  $R_w$  on Velocity distribution

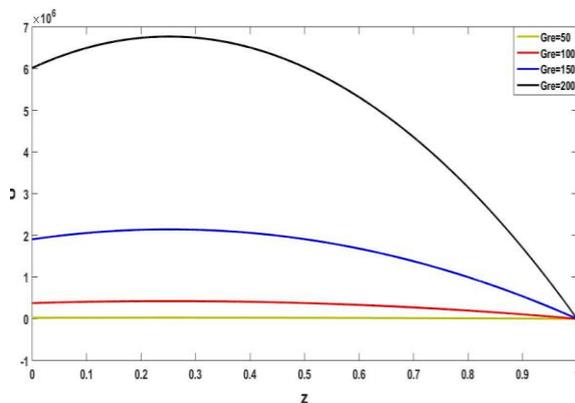


Figure 4: Output of  $Gre$  on Velocity distribution

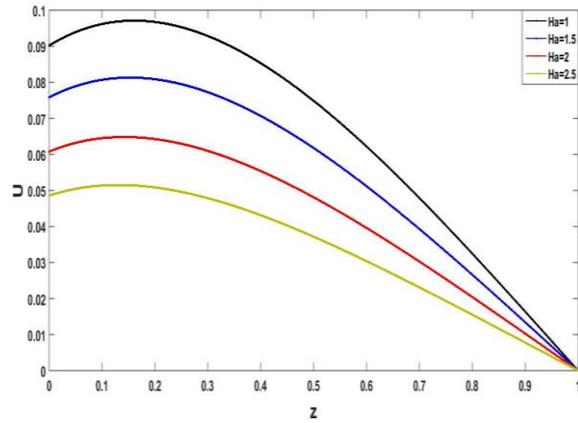


Figure 5: Output of  $Ha$  on velocity distribution

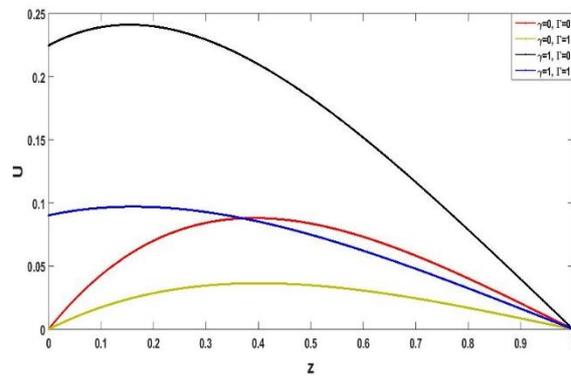


Figure 6: Output of displacement  $z$  on velocity distribution

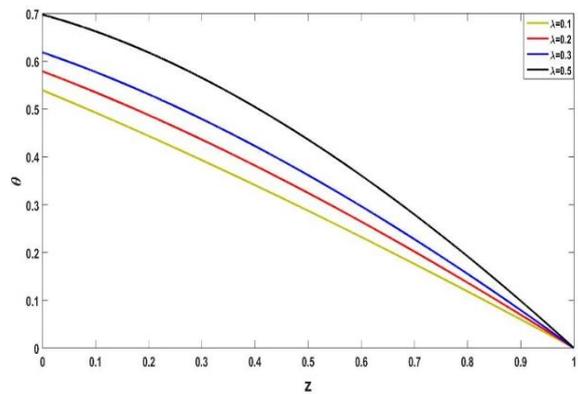


Figure 7: Output of  $\lambda$  on temperature distribution

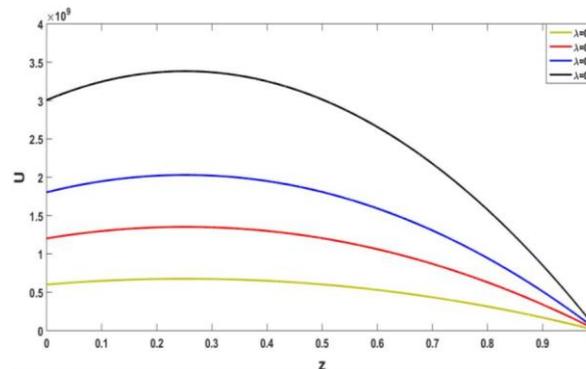


Figure 8: Output of  $\lambda$  on velocity distribution

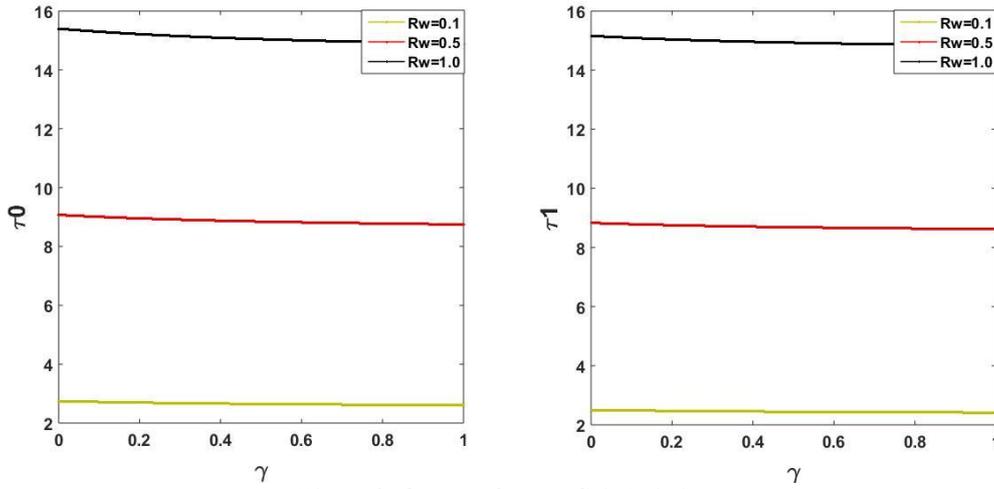


Figure 9: Output of  $R_w$  on Skin Friction

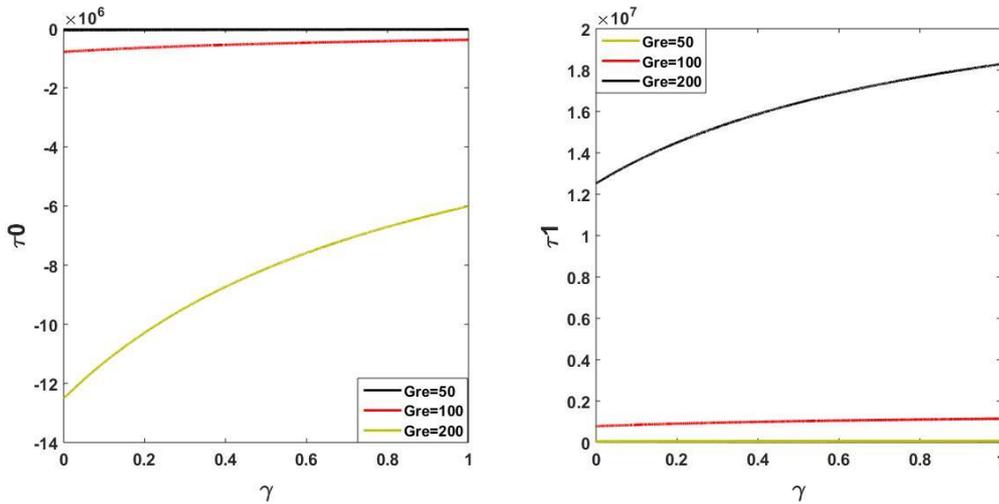


Figure 10: Output of  $Gre$  on Skin Friction

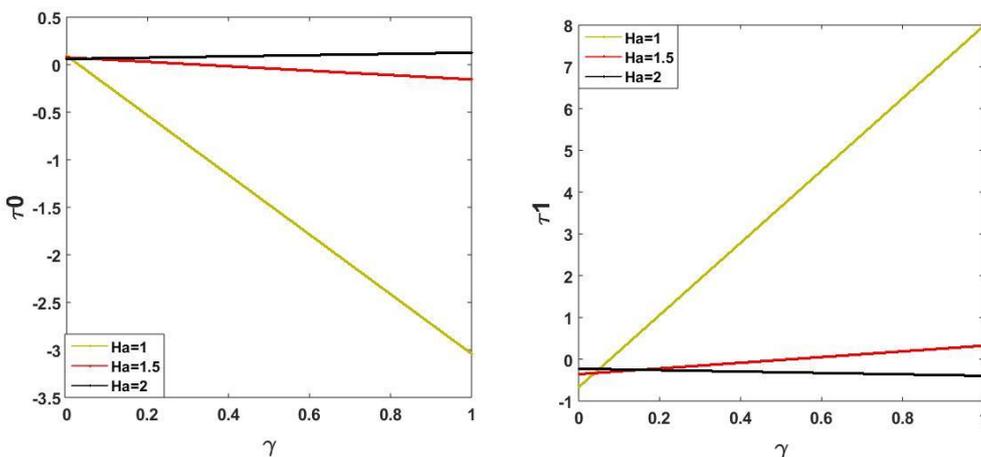


Figure 11: Output of  $Ha$  on Skin Friction

#### 4.1 Validation of Results

Setting  $Gre = 1$  and  $A = 0$ , the work of Omokhuale and Ojmeri (2025) is successfully retrieved, establishing a good concurrence between the present study and their work.

**Table 1:** Demonstrates the numerical comparison of Omokhuale and Ojmeri (2025) work with the present study for velocity gradient for  $\gamma = \Gamma = 1$ ,  $M = 1$ , when  $Gre = 1$  and  $A = 0$ .

Y	Omokhuale and Ojemeru (2025) $\gamma = \Gamma = 1,$ $\lambda = 0.001, \xi_w = 0.1$		Present work $\gamma = \Gamma = 1,$ $\lambda = 0.001, \xi_w = 0.1$ $Gre = 1, A = 0$		Present work $\gamma = \Gamma = 1,$ $\lambda = 0.001, \xi_w = 0.1$ $Gre = 50, A = 1$	
	$\theta(z)$	U(z)	$\theta(z)$	U(z)	$\theta(z)$	U(z)
0.1	0.4500	0.0843	0.4500	0.0843	0.4500	2.5584e+06
0.2	0.4000	0.0856	0.4000	0.0856	0.4000	2.6539e+06
0.3	0.3500	0.0831	0.3500	0.0831	0.3500	2.6555e+06
0.4	0.3000	0.0772	0.3000	0.0772	0.3000	2.5629e+06
0.5	0.2500	0.0686	0.2500	0.0686	0.2500	2.3760e+06

### 5.0 CONCLUSION

The combined convection flow with constant pressure gradient is examined in the presence of symmetric wall concentration and exothermic chemical reaction with heat and mass transfer flow in a superhydrophobic microchannel. A semi-analytical (regular perturbation) approach is used to treat the novel ordinary differential equations dictating the flow in terms of velocity, temperature, and mass diffusion gradients. The impact of the major parameters involved in the fluid is demonstrated with the aid of line graphs. For the limiting case ( $Gre = 1, A = 0$ ), these results are compared with previous work, and a very good concurrence exists. Some interesting findings from this paper are outlined below:

- (i) The mixed convection parameter is seen to boost the velocity of the fluid under constant pressure effect.
- (ii) The velocity and concentration of the fluid are strongly influenced by the action of the symmetric wall concentration. Flow reversal is observed as the symmetric wall concentration increases.
- (iii) The effect of  $\lambda$  is envisaged to improve the fluid's temperature and velocity gradients.
- (iv) The fluid's velocity and temperature are at their peak by elevating the velocity slip and temperature jump parameters, respectively.
- (v) It was concluded that higher values of  $R_w$  parameter improve the skin friction at both plates of the microchannel.
- (vi) The function of the mixed convection parameter is to elevate the skin friction at both plates.
- (vi) The shearing stress is stronger at the surface ( $y = 0$ ) for mounting level M, whereas a counter attribute occurs at ( $y = 1$ ).
- (vii) In the future, the effects of diffusion thermo and thermal diffusion would be studied on this model.

### References

Ahmad S. K., Sani A. A., Muhammad I., and Usman H. (2023). Impacts of Exponentially Growing/Decaying Pressure Gradient on Mixed Convection Flow of Viscous Reactive Fluid in a Vertical Tube: A Numerical Approach, *Saudi Journal of Engineering and Technology*, 8(7), pp. 181-188.

Ajibade, A. O. and Ojeagbase, P. O. (2020). Steady Natural Convection Heat and Mass Transfer Flow through a Vertical Porous Channel with Variable Viscosity and Thermal Conductivity, *Engineering Reports*, <https://doi.org/10.1002/eng2.12268> 2(11):12268.

Ajibade, A. O., Umar, A. M. Effects of viscous dissipation on a steady mixed convection Couette flow of heat generating/absorbing fluid. *Science Forum (J Pure Applied Sci)*. 21, 67-76 (2021). <http://dx.doi.org/10.5455/sf.93898>

Amar N., Kishan N. and Goud B. S. (2023). Viscous Dissipation and Radiation Effects on MHD Heat Transfer Flow of Casson Fluid Through a Moving Wedge with Convective Boundary Condition in the Existence of Internal Heat Generation/Absorption, *Journal of Nanofluids*, 12, pp. 643-651,

Aydin, O. and Kaya, A. (2013). MHD mixed convection of a viscous dissipating fluid about a vertical slender cylinder. *Desalination and water treatment*, 51(16-18), 3576-3583.

Dagana, J. and Amos, E. (2020). MHD Free Convection Heat and Mass Transfer Flow in a Porous Medium with Dufour and Chemical Reaction Effects, *Int. J. Inno. Scientific & Eng. Tech. Res.*, 8(2):1-12.

Gambo J. and Gambo D. (2020). On the effect of heat generation/absorption on magneto-hydrodynamic free convective flow in a vertical annulus: An Adomian decomposition method. *Heat transfer, Wiley*. 50(1), 1-15. DOI: 10.1002/hti.21978.

Hamza M. M., Ojemeru G. and Abdulsalam S (2019). Mixed Convection Flow of Viscous Reactive Fluids with Thermal Diffusion and Radial Magnetic Field in a Vertical Porous Annulus. *Computational Mathematics and Modeling*, 30(3).

Hamza, M. M. and Shuaibu, A. (2022). Influence of chemical kinetic exponent on transient mixed convective hydromagnetic flow in a vertical



- channel with convective boundary condition. *International Journal of Thermofluids*, 16, 100220.
- Hamza, M. M., Bello S. R., Ibrahim Y., Bello A. and Tasiu R. A. (2024). Casson fluid flow with heat sink affected by symmetric wall temperature and concentration conditions, *Journal of Engineering Technology*, 15(2). <https://doi.org/10.54554/jet.2024.15.2.002>
- Hamza, M. M., Ojemer, G. and Ahmad, S. K. (2023). Insights into an analytical simulation of a natural convection flow controlled by Arrhenius kinetics in a micro-channel, *Heliyon* 9(2023) e17628, pp. 1-13.
- Hamza, M. M., Shehu M. Z. and Tambuwal, B. H. (2021). Steady state MHD free convection slip flow of an exothermic fluid in a convectively heated vertical channel, *Saudi Journal Engineering Technology*. DOI: 10.36348/sjet.2021.vo6i10.006.
- Hasan, N. Z. Mohammed, Y. Nasreen, S. N. (2020). Effects of thermal radiation, heat generation and induced Magnetic field on Hydromagnetic free convective flow of couple stress fluid in an isoflux-isothermal vertical channel, *Journal of Applied Mathematics*, vol.2020, Article ID 4539531.
- Hayat, T., Waqas, M., Shehzad, S. A., and Alsaedi, A. (2016). Mixed convection flow of viscoelastic nanofluid by a cylinder with variable thermal conductivity and heat source/sink. *International Journal of Numerical Methods for Heat & Fluid Flow*, 26(1), 214-234.
- Hindebu, B., Makinde, O. D., Guta, L. Unsteady mixed convection flow of variable viscosity nanofluid in a micro-channel filled with a porous medium. *Indian J Phys*, 96, 1749-1766 (2022)
- Jafar, A. B., Shafie, S., Ullah, I., Safdar, R., Jamshed, W., Pasha, A. A., Eid, M. R. (2022). Mixed convection flow of an electrically conducting viscoelastic fluid past a vertical nonlinearly stretching sheet. *Scientific Reports*, 12(1), 14679. <https://doi.org/10.1038/s41598-022-18761-0>
- Jamaludin A., Naganthran K., Nazar R., Pop I. (2020). Thermal radiation and MHD effect in the mixed convection flow of Fe<sub>3</sub>O<sub>4</sub> water Ferrofluid towards a nonlinear moving surface, *Processes*, 8, (95), <https://doi.org/10.3390/pr8010095>
- Jha, B. K., Aina, T., and Ajiya, A. T. (2015). Role of Suction/Injection on MHD Natural Convection Flow in a Vertical Microchannel, *International Journal Energy and Technology*, 7(2), pp. 30–39.
- Kaita, I. H., Zayyanu, S. Y., Mas'ud, L., Hamsiu, A., Abdullahi, U. and Auwal, D. M. (2024). Heat and mass transfer flow in a channel filled with porous medium in the presence of variable thermal conductivity, 8(2), pp. 225 – 234.
- Lavine, A. S. (1988). Analysis of fully developed opposing mixed convection between inclined parallel plates. *Wärme-und Stoffübertragung*, 23(4), 249-257.
- Makinde, O. D. (2010). On MHD Heat and Mass Transfer over a Moving Vertical Plate with a Convective Surface Boundary Condition, *The Canadian Journal of Chemical Engineering*, 88(6):983-990. <https://doi.org/10.1002/cjce.20369>
- Malvandi, A., Safaei, M. R., Kaffash, M. H., & Ganji, D. D. (2015). MHD mixed convection in a vertical annulus filled with Al<sub>2</sub>O<sub>3</sub>–water nanofluid considering nanoparticle migration. *Journal of Magnetism and Magnetic Materials*, 382, 296-306.
- Mandal B, Bhattacharyya, K, Banerjee, A, kumarverma A. & Gautam, A. k. (2020). MHD mixed convection on an inclined stretching plate in Darcy porous medium with sores effect and variable surface conditions, *Nonlinear Engineering*, 9, 457-469. <https://doi.org/10.1515/nleng-2020-0029>
- Narender G., Govardhanb K. and Sarmaa G. S. (2021). Viscous dissipation and thermal radiation effects on the flow of Maxwell nanofluid over a stretching surface, *Int. J. Nonlinear Anal. Appl.* 12(2), 2008-6822. <http://dx.doi.org/10.22075/ijnaa.2020.18958.2045>.
- Obalalu A. M., Ajala O. A., Adeosun A. T., Aindele A. O., Oladapo O. A. and Olajide O. A. (2021). Significance of variable electrical conductivity on non-Newtonian fluid flow between two vertical plates in the coexistence of Arrhenius energy and exothermic chemical reaction, *Partial Differential Equations Applications and Mathematics*, 4, 100184, pp. 1-9
- Ojemer, G. and Hamza, M. M. (2022). Heat transfer analysis of Arrhenius-controlled free convective hydromagnetic flow with heat generation/absorption effect in a micro-channel, *Alexandria Eng. J.*, 61, pp. 12797-12811.
- Omokhuale E. and Ojemer G. (2025). Arrhenius-controlled fluid flow over a superhydrophobic microchannel with symmetric wall concentration, *Journal of Basic Physical Research*, 14(1), pp. 77 – 90. <https://journals.unizik.edu.ng/jbpr/>
- Onwubuya I. O. and Ojemer G. (2023). Evaluation of mixed convection-radiation flow of a viscous fluid restricted to a vertical porous channel: A comparative Study, *Caliphate Journal Science and Technology*, 5(3), pp. 1-9.
- Osman H. I, Omar N. F. M., Vieru D. and Ismail Z. (2022). A study of MHD free convection flow past an infinite inclined plate, *Journal of Advances in Research of fluid Mechanics and Thermal Sciences*, 92 (1), pp. 18-27.
- Parthiban S. and Prasad V. R. (2023). Thermal radiation and Hall current effects in a MHD non-Darcy flow in a differentially heated square enclosure Lattice-Boltzmann simulation. *Journal of porous media*, Begell house, 26(5), pp37-56. DOI: 10.1615/JPorMedia.2022044054.
- Rout, B. R., Parida, S. K. and Panda, S. (2013). MHD Heat and Mass Transfer of Chemical Reaction Fluid Flow over a Moving Vertical Plate in Presence of Heat Source with Convective Surface Boundary Condition, *International Journal of Chemical*

IJS GS FUGUSAU VOL. 11(3)	WEBSITE: <a href="https://fugus-ijsgs.com.ng">https://fugus-ijsgs.com.ng</a>
<p>Engineering, 1:1-10.  <a href="https://doi.org/10.1155/2013/296834">https://doi.org/10.1155/2013/296834</a>            Saedodin, S., Biglari, M., Esfe, M. H. &amp; Noroozi, M. J. (2013). Mixed convection heat transfer performance in a ventilated inclined cavity containing heated blocks: Effect of dispersing Al<sub>2</sub>O<sub>3</sub> in water and aspect ratio of the block, <i>J. Comput. Theor. Nanosci.</i> 10, 2663–2675.            Saeed, U. J., Sami, H., Inayat, S. A. and Ilyas, K. (2019). Heat and Mass Transfer of Free Convection Flow over a Vertical Plate with Chemical Reaction under Wall Slip Effect, <i>Arabian Journal for Science and Engineering</i>, 44:9869-9887.  <a href="https://doi.org/10.1007/s13369-019-03863-1">https://doi.org/10.1007/s13369-019-03863-1</a>            Sani, M. and Kaita, I. H. (2023). Steady State Free Convection with Heat and Mass Transfer in the Presence of Variable Thermal Conductivity, <i>Journal of Energy and Environment</i>, 5(3):105-118.  <a href="https://doi.org/10.5281/zenodo.10003527">https://doi.org/10.5281/zenodo.10003527</a>            Sehra, S., Sami, H., Inayat, S. A. S., Saeed, U. J., Ilyas, K. and Nisar, K. S. (2021). Convection Heat Mass</p>	<p>Transfer and MHD Flow over a Vertical Plate with Chemical Reaction, Arbitrary Shear Stress and Exponential Heating, <i>Scientific Reports</i>, 11:4265.  <a href="https://doi.org/10.1038/s41598-021-81615-8">https://doi.org/10.1038/s41598-021-81615-8</a>.            Siva, T., Jaangili, S. and Kumbhakar, B. (2021). Heat transfer analysis of MHD and electroosmotic flow of non-Newtonian fluid in a rotating microfluidic channel: an exact solution, <i>Applications of Mathematics and Mechanics</i>, 42, pp. 1047-1062.            Taid, B. K. and Ahmed, N. B. (2022). MHD free convection flow across an inclined porous plate in the presence of heat source, sores effect and chemical reaction affected by viscous dissipation ohmic heating, <i>Bio-interface Research in Applied Chemistry</i>, 12(5), pp. 6280-6296.            Ullah P., Arif M., Nadeem S., and Alzabut J. (2024). Numerical computations of MHD mixed convection flow of Bingham fluid in a porous square chamber with a wavy cylinder, <i>International Journal of Thermofluids</i>, 24,100938.</p>

**Appendix**

$$\begin{aligned}
 X_2 = R_w, X_1 = -2R_w, X_5 = -X_6, X_6 = \frac{1}{1 + \Gamma}, X_7 = \frac{\left(\frac{1}{2} + \frac{X_5}{6} + \frac{X_6}{2} + d_1 \frac{X_5^2}{12} + d_1 \frac{X_5 X_6}{3} + d_1 \frac{X_6^2}{2}\right)}{1 + \Gamma}, \\
 X_8 = \Gamma X_7, X_9 = \gamma[MX_{10} + X_{12}] - X_{11}, X_{10} = \frac{-\gamma X_{11} \cosh(M) + X_{12} \cosh(M)}{\gamma M \cosh(M) + \sinh(M)}, \\
 X_{12} = \frac{Gre(X_5 + A)}{M^2}, X_{13} = \frac{Gre(X_6 + 2X_{11})}{M^2}, X_{13} = \gamma[MX_{14} + X_{19}] - X_{20}, \\
 X_{14} = \frac{Gre(-d_7 - d_6)}{\gamma M \cosh(M) + \sinh(M)}, J_{12} = \frac{-Gred_2}{M^2}, X_{16} = \frac{-Gred_3}{M^2}, X_{17} = \frac{Gre(d_2 + 20X_{15})}{M^2}, \\
 J_{15} = \frac{Gre(d_5 + 12X_{16})}{M^2}, X_{19} = \frac{Gre(d_6 + 6X_{17})}{M^2}, X_{20} = \frac{Gre(d_5 + 2X_{18})}{M^2}, d_1 = \frac{1}{2} - \varepsilon, \\
 d_2 = X_8 + X_9 + X_{10}, d_3 = \frac{X_1^2 d_1}{12}, d_4 = \frac{X_5}{6} + \frac{X_5 X_6 d_1}{3} \\
 d_5 = -X_8, d_6 = X_{15} + X_{16} + X_{17} + X_{18} + X_{19} + X_{20}, d_7 = (\gamma X_{19} - X_{20}) \cosh(M)
 \end{aligned}$$

**Nomenclature**

- $B_0$ =constant magnetic flux density [kg/s<sup>2</sup>.m<sup>2</sup>]
- $g$ =gravitational force [m/s<sup>2</sup>]
- $h$ = channel size [m]
- $C_p C_v$ =specific heats at constant pressure and constant volume [Jkg<sup>-1</sup>K<sup>-1</sup>]
- $M$ = magnetic field [-]
- $N$ = Sustention parameter [-]
- $Gre$  = Mixed convection parameter [-]
- $A$ = Constant pressure gradient [-]
- $R_w$  = Symmetric wall concentration [-]
- $e$ = activation energy
- $Nu$ =dimensionless heat transfer rate [-]
- $T$ =dimensionless temperature of the fluid [K]
- $T_0$ =reference temperature [K]
- $u$ =dimensionless velocity of the fluid [ms<sup>-1</sup>]
- $y$ = dimensionless distance between plates
- $U_0$ =reference velocity [ms<sup>-1</sup>]

**Greek letters**

- $\gamma$  = velocity slip parameter (-)



- $\Gamma$  = temperature jump parameter (-)
- $\lambda$  =chemical reacting parameter (-)
- $\beta$  =thermal expansion coefficient [K-1]
- $\mu$  =variable fluid viscosity [kgm-1s-1]
- k=thermal conductivity [m.kg/s3.K]
- $\alpha$  =thermal diffusivity [m2s-1]
- $\sigma$  =conductivity of the electric fluid [s3m2/kg]
- $\rho$  = fluid density[kgm-3]
- $v$  =viscosity of the fluid [m2s-1]