



Analysis Of Arrhenius Activation Energy In An Electrically Conducting Fluid Flow With Chemical Reaction And Viscous Dissipation

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Abstract: This study takes into account the effects of Arrhenius activation energy on the fluid, the viscous dissipation of the fluid, and the chemical reactions in the fluid as it investigates recent advancements in electrically conducting reactive fluid flow on an extended porous surface. By applying a uniform magnetic field that is orthogonal to the fluid flow, the related nonlinear partial differential equations are generated and analysed. After including similarity variables into the flow, the resulting equations are transformed to dimensionless form and numerically solved using the finite difference method. Upon solving the equations using computer-generated methods, graphs and tables will be presented for analyzing the elements influencing the flow. This study attempts to illustrate that the Arrhenius energy activation parameter influences the concentration profiles by enhancing them, despite the fact that the rate of the fitted fluid displays contradictory characteristics. In addition, the impact of the Schmidt number, the Nusselt number, and the Sorret parameter on the flow will be investigated, and the velocity and temperature profiles will be graphically shown.

Key words: Newtonian fluid, Magnetohydrodynamic (MHD) flow, the Arrhenius equation, the Energy Activation parameter, the reaction rate parameter, Viscous dissipation, chemical reactions, Sorret effect.

I. INTRODUCTION

Numerous industrial processes now in use depend on chemical reactions, and scientists are always working to improve them in order to enhance energy yields and reduce reagent use. Because of the many potential industrial and technological applications of the study of reactive fluids, a great lot of research has been devoted to the subject. The significance of solar energy cannot be emphasised, and a tremendous deal of research and development is now being conducted in this field. Due to the inefficiency of solar cells and the absence of a correct execution balance in their designs, solar energy has a limited lifetime. Due to their potential to lower the number of reagents required in industrial settings and boost the yields of several technological processes, chemical reactions play an essential role in contemporary civilization. Solar energy is favoured as a renewable energy source, however solar technologies have disadvantages, such as limited cell lifetimes. Understanding the activation energy of the sources is crucial for resolving challenges associated with energy instability. According to N. Vijay et al., the Arrhenius activation energy of the fluid and the chemical reactions in MHD flows have several relevant applications in areas as varied as the food industry, engineering, and lubricants (2020). The study of conductive fluids is known as Magnetohydrodynamics.

The activation energy is the amount of energy necessary to break chemical bonds and begin a reaction. The energy released by chemical reactions alters the flow of a fluid. The Arrhenius equation explains the link between a fluid's temperature and the effect of the energy produced during a chemical reaction. Zeeshan et al. (2018) investigated the impact of activation energy on nanofluid Couette flows. Irfan et al. (2019) explored the combined global effects of Arrhenius energy and chemical energy in a 3D Carreau nano fluid by invoking Buongiorno's theory. It was found that a higher activation energy parameter led to a greater concentration. Hayat et al. observed via an examination of the Arrhenius activation energy in peristalsis of Jeffrey's fluid that the velocity of Hall and Darcy parameters increases (2009). There was a noted negative link between temperature and the parameter measuring radiation.

The viscosity of an MHD fluid is not constant for a given flow, since it relies on a variety of factors, such as the pressure and shear of the fluid's flow and its temperature. Variable viscosity MHD fluids include paints, paste, greases, lubricating oil, coal tars, etc. These fluids are referred regarded as "non-Newtonian fluids" since they defy the traditional thermodynamic principle.

Dharmaiah et al. (2018) studied the flow of magnetohydrodynamic fluids through a porous, flat, semi-infinite plate with an applied heat source. They found that the fluid concentration drops as the Schmidt number increases. The fluid velocity was also found to be considerably impacted by the heat absorption parameter.

MHD flows and their potential industrial applications are the subject of a boom in research. As this is seen as the obvious next step on the field to the technological revolution, it has garnered the interest of several scholars. Applications exist in a variety of fields, including astrophysics, plasma physics, and aerodynamics.

The viscosity of MHD fluid flows across a porous material impedes energy extraction from thermally defined zones via solid filtering. Sandya et al. have extensively studied magnetohydrodynamic fluid flows of porous and inclined plates under the influence of chemical reactions and radiation (2019). Dhanalakshmi et al. (2019) studied the effect of porous media on convective MHD fluid flows (2019). D. Ravi Kumar et al. have performed extensive chemical research on the influence of chemicals in a slip flow regime on the effects of an unstable convective MHD flow (2019). It was observed in these studies that when the value of the chemical reaction parameter is raised, velocity, concentration, and viscosity are observed to drop dramatically.

Vedavathi et al. examined the effects of chemical reactions and radiations on nanofluids on a semi-infinite porous surface with flat boundaries (2017). Charan K. et al. examined micropolar fluid over a stretched sheet in a porous medium under the influence of radiation and chemical reaction (2018). In addition to a magnetic hydrodynamic free convective heat transfer flow, Chandra Sekhar. et al. (2018) studied the movement of a second-grade fluid over a defined stretched sheet under various conditions.

There is still opportunity for research into the details of the Arrhenius energy of activation in an electrically conducting fluid with chemical reactions and viscous dissipation, notwithstanding these advancements. This is particularly true in light of the vast array of industrial applications spanning several sectors and technology. This study's major objective is to examine activation energy in a chemical reaction and viscous dissipation in an MHD fluid flow. This study also includes the ideas of viscosity and joule heating of the fluid flow.

II. FORMULAION OF GOVERNING EQUATIONS FOR THE FLOW

In this study, an incompressible two-dimensional unsteady mixed convective reactive flow is considered. The flow is induced by an elongated plate that is vertically elongated and placed in a medium that is saturated and porous, with a magnetic force applied to the elongated plate, as shown in figure 1. We shall consider the origin to be the fixed point while the plate is elongated along the x-axis as well as the y-axis, as shown:

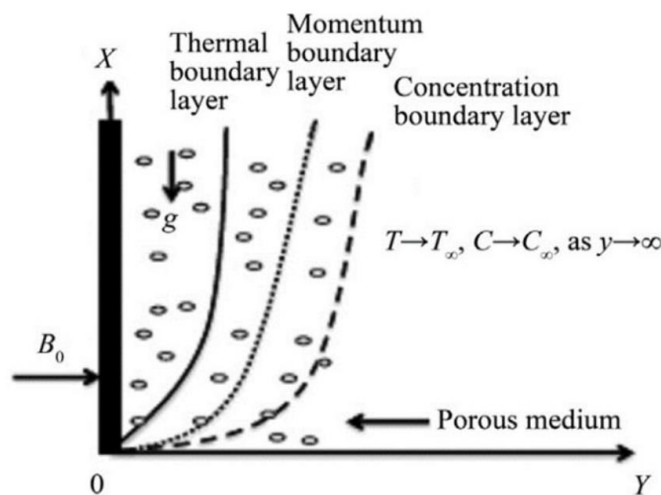


Figure 1: Geometrical flow formulation

The induced magnetic fields in this study as a result of the application of the uniform magnetic field on the elongated plate will be ignore by assuming low Reynold’s number.

The equations governing the flow are the continuity, momentum, energy, and concentration equations. The Maxwell’s equations as well as the Ohm’s law equations also affect the flow and as such will be considered.

For the considered 2-dimensional, unsteady, and incompressible flow, the momentum, energy, and concentration equations are as shown below:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{1}$$

$$\frac{\partial u}{\partial t} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\mu u}{\rho k} + \frac{\mu}{\rho} \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\sigma}{\rho} B_0^2 u^2 + g_x [\beta_T (T - T_\infty) + \beta_c (C - C_\infty)] \tag{2}$$

$$\frac{\partial v}{\partial t} + \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = \frac{k}{\rho c_p} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + \frac{\mu}{\rho c} \left(2 \left[\left(\frac{\partial u}{\partial x} \right)^2 + \left(\frac{\partial u}{\partial y} \right)^2 \right] + \left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} \right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \right)^2 \right) + \frac{1}{\rho c_p} \sigma B_y^2 u^2 + \frac{1}{\rho c_p} \alpha_v \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \tag{3}$$

$$\frac{\partial v}{\partial t} + \left(u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \frac{k}{\rho c_p} \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right] + \frac{\mu}{\rho c} \phi + \frac{1}{\rho c_p} \sigma B_y^2 u^2 + \frac{1}{\rho c_p} \alpha_v \left(\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} \right) \tag{4}$$

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D_{ij} \left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} \right) + D_T \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) - k_r^2 (C - C_\infty) \left(\frac{T}{T_\infty} \right)^m e^{-E_a/RT} \tag{5}$$

Subject to the boundary conditions,

$$u = u_0(x) , \quad v = 0 \quad u \rightarrow 0 \quad C^* = C_\infty \quad C^* \rightarrow C_\infty$$

$$T^* = T_\infty \quad T^* \rightarrow T_\infty \quad \text{as } y \rightarrow \infty$$

N. Vijaya et. al (2021), defined the following dimensionless parameters and variables which were used to non-dimensionalize the equations:

$$\theta = \frac{T^* - T_\infty}{T_w - T_\infty}, \quad \omega = \frac{k_r^2}{a}, \quad \delta = \frac{(T_w - T_\infty)}{T_\infty}, \quad a = \frac{U}{L}, \quad S_r = \frac{D_t(T_w - T_\infty)}{uL(C_w - C_\infty)}, \quad M = \frac{\sigma B_0^2 L}{\rho u}, \quad C = \frac{C^* - C_\infty}{C_w - C_\infty}, \quad Sc = \frac{v}{D}, \quad Gr = \frac{g\beta(T^* - T_\infty)v}{U^3}, \quad G_c = \frac{g\beta(C - C_\infty)v}{U^3},$$

Where Gr is the Grashof number while G_c is the modified Grashof number, k_r^2 is the reaction rate, ω is the reaction rate parameter, δ is the temperature difference parameter, $k_r^2 \left(\frac{T}{T_\infty}\right)^m e^{-E_a/RT}$ is the modified Arrhenius equation, E_a is the activation energy and m is the fitted rate constant which lies between -1 and 1 for the fluid flow.

The non-dimensionalised equations are as follows:

$$\frac{\partial u^*}{\partial t^*} + \left(u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*}\right) = -NuPr u^* + \frac{1}{Re} \left(\frac{\partial^2 u^*}{\partial x^{*2}} + \frac{\partial^2 u^*}{\partial y^{*2}}\right) - Mu^* + Gr\theta + GcC \tag{6}$$

$$\frac{\partial u^*}{\partial t^*} + \left(u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*}\right) = -NuPr u^* + \frac{1}{Re} \nabla^2 u^* - Mu^* + Gr\theta + GcC \tag{7}$$

$$\frac{\partial \theta^*}{\partial t^*} + \left(u^* \frac{\partial \theta^*}{\partial x^*} + v^* \frac{\partial \theta^*}{\partial y^*}\right) = \frac{1}{PrRe} \left(\frac{\partial^2 \theta^*}{\partial x^{*2}} + \frac{\partial^2 \theta^*}{\partial y^{*2}}\right) + \frac{Ec}{Re} (\phi + Ha^2) - St \left(\frac{\partial^2 \theta^*}{\partial x^{*2}} + \frac{\partial^2 \theta^*}{\partial y^{*2}}\right) \tag{8}$$

$$\frac{\partial C^*}{\partial t^*} + u^* \frac{\partial C^*}{\partial x^*} + v^* \frac{\partial C^*}{\partial y^*} = \frac{1}{ScRe} \left(\frac{\partial^2 C^*}{\partial x^{*2}} + \frac{\partial^2 C^*}{\partial y^{*2}}\right) + Sr \left(\frac{\partial^2 \theta^*}{\partial x^{*2}} + \frac{\partial^2 \theta^*}{\partial y^{*2}}\right) - \omega C ((1 + \delta\theta))^m e^{-E} \tag{9}$$

III. METHOD OF SOLUTION

In this study, we shall use the finite difference method to represent the solution to the governing equations. We employ this method in solving the resulting equations because the equations defining the flow are non-linear in nature and hence cannot be solved by analytical methods. The final set of the governing equations are presented and later solved using computer generated programs on MATLAB. The method is also used due to its stability and accuracy in solving the nonlinear partial differential equations. The finite difference technique of approximating solutions to partial derivatives are conveniently obtained by performing a Taylor series expansion of the dependent variable followed by a substitution of the truncated expressions into the differential equation. We will further approximate the differentials by using the differences in the solution at various points.

The final set of equations solved using the finite difference method are given below:

$$v_{(i,j)}^{n+1} = \Delta t \left\{ -v_{(i,j)}^n \left[\frac{v_{(i+1,j)}^n - v_{(i-1,j)}^n}{2\Delta x} \right] - v_{(i,j)}^n \left[\frac{v_{(i,j+1)}^n - v_{(i,j-1)}^n}{2\Delta y} \right] - NuPr u_{(i,j)}^n + \frac{1}{Re} \left[\frac{v_{(i+1,j)}^n - 2v_{(i,j)}^n + v_{(i-1,j)}^n}{(\Delta x)^2} + \frac{v_{(i,j+1)}^n - 2v_{(i,j)}^n + v_{(i,j-1)}^n}{(\Delta y)^2} \right] - M u_{(i,j)}^n + Gr\theta_{(i,j)}^n + GcC_{(i,j)}^n \right\} + v_{(i,j)}^n \tag{10}$$

$$\theta_{(i,j)}^{n+1} = \Delta t \left\{ -u_{(i,j)}^n \left[\frac{\theta_{(i+1,j)}^n - \theta_{(i-1,j)}^n}{2\Delta x} \right] - v_{(i,j)}^n \left[\frac{\theta_{(i,j+1)}^n - \theta_{(i,j-1)}^n}{2\Delta y} \right] + \frac{1}{PrRe} \left[\frac{\theta_{(i+1,j)}^n - 2\theta_{(i,j)}^n + \theta_{(i-1,j)}^n}{(\Delta x)^2} + \frac{\theta_{(i,j+1)}^n - 2\theta_{(i,j)}^n + \theta_{(i,j-1)}^n}{(\Delta y)^2} \right] + \frac{Ec}{Re} (\phi + Ha^2) - St \left[\frac{\theta_{(i+1,j)}^n - \theta_{(i-1,j)}^n}{2\Delta x} + \frac{\theta_{(i,j+1)}^n - \theta_{(i,j-1)}^n}{2\Delta y} \right] \right\} + \theta_{(i,j)}^n \tag{11}$$

$$C_{(i,j)}^{n+1} = \Delta t \left\{ -u_{(i,j)}^n \left[\frac{C_{(i+1,j)}^n - C_{(i-1,j)}^n}{2\Delta x} \right] - v_{(i,j)}^n \left[\frac{C_{(i,j+1)}^n - C_{(i,j-1)}^n}{2\Delta y} \right] + \frac{1}{ScRe} \left[\frac{C_{(i+1,j)}^n - 2C_{(i,j)}^n + C_{(i-1,j)}^n}{(\Delta x)^2} + \frac{C_{(i,j+1)}^n - 2C_{(i,j)}^n + C_{(i,j-1)}^n}{(\Delta y)^2} \right] + Sr \left[\frac{\theta_{(i+1,j)}^n - 2\theta_{(i,j)}^n + \theta_{(i-1,j)}^n}{(\Delta x)^2} + \frac{\theta_{(i,j+1)}^n - 2\theta_{(i,j)}^n + \theta_{(i,j-1)}^n}{(\Delta y)^2} \right] - \omega C (1 + \delta\theta)^m e^{-E} \right\} + C_{(i,j)}^n \tag{12}$$

These equations are solved subject to the initial conditions shown:

$$u = u_0(x) , v = 0 \quad u \rightarrow 0 \quad C^* = C_\infty \quad C^* \rightarrow C_\infty$$

$$T^* = T_\infty \quad T^* \rightarrow T_\infty \quad \text{as } y \rightarrow \infty$$

IV. RESULTS AND DISCUSSIONS

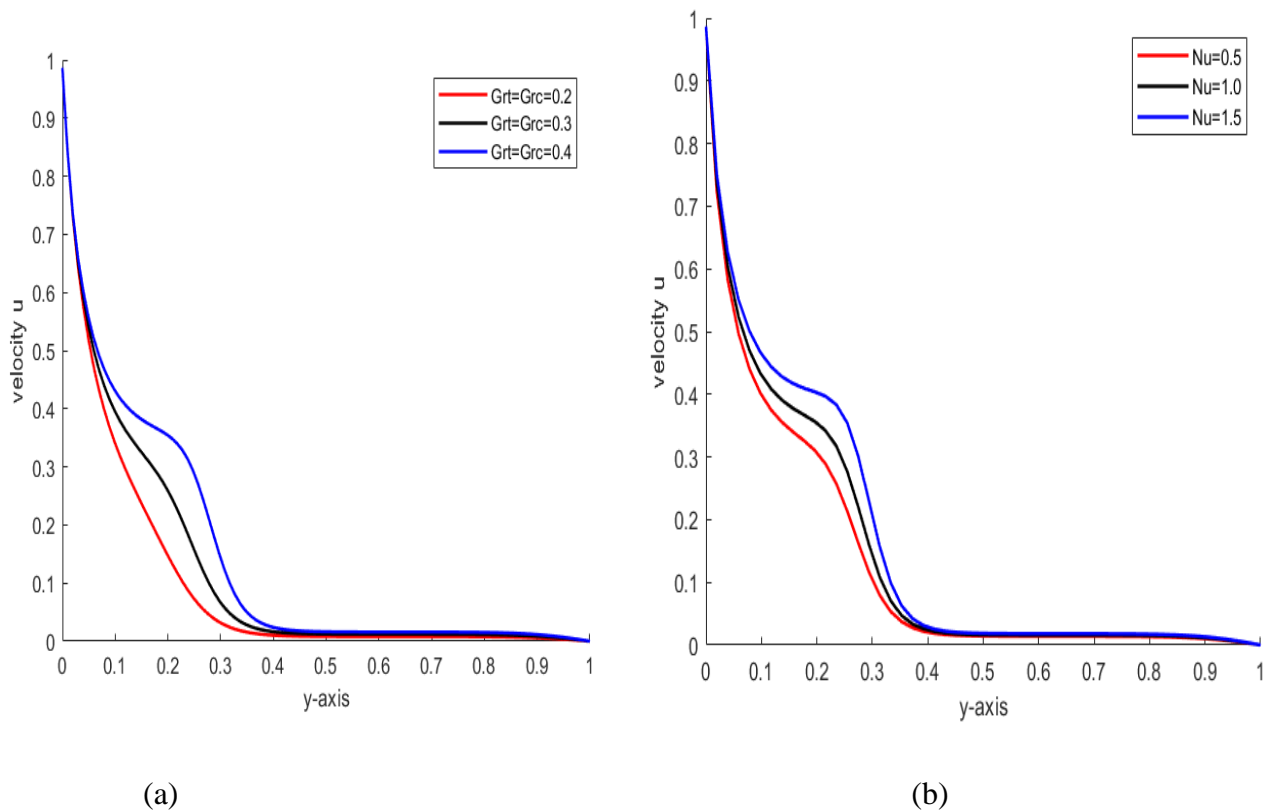
The dimensionless parameters affecting the fluid flow described in this study include the Grashof number, Gr, Eckert number, the Nusselt number, the Prandtl number, the Magnetic number or parameter, the Schmidt number, Sc, the non-dimensional activation energy, E, Reynolds number, Re, the Stanton number, St and the Soret number, Sr.

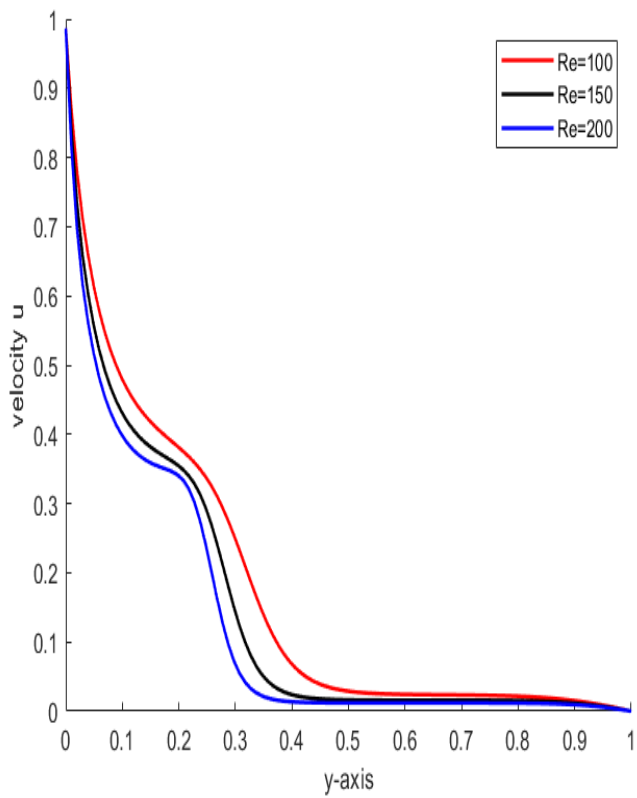
For a clearer understanding of the effects of these dimensionless parameters affecting the flow, the temperature, velocity and concentration profiles are graphically represented as shown and the effects of the parameters discussed.

4.1 Velocity profiles

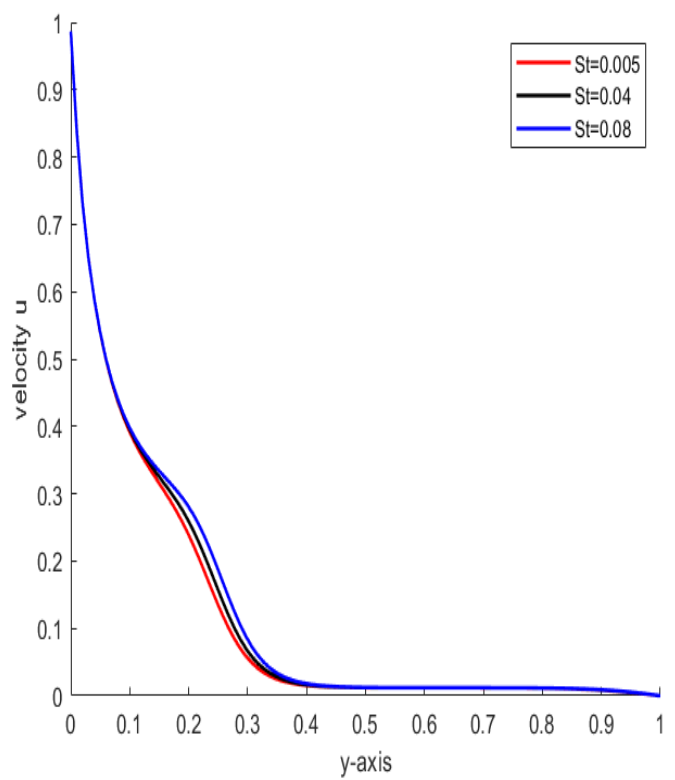
The velocity profiles are represented on the figures shown below. It is evident, in particular, that the fluid parameters including the Grashof number, Gr_c and the magnetic parameter, M on affect the velocity profiles as depicted in figures 2 and 3. We observed that the velocity of the fluid flow decreases with an increase in the modified Grashof number and magnetic parameter M due to the introduction of an orthogonal transverse magnetic field to the flow which creates a drag known as the Lorentz force that creates a resistance to the fluid flow. The present results are consistent with those obtained by N Vijaya et al (2020) and N Vajravelu et al (2011).

The velocity profiles are represented in figure 2 and 3 (a-e) for the various parameters affecting the flow.

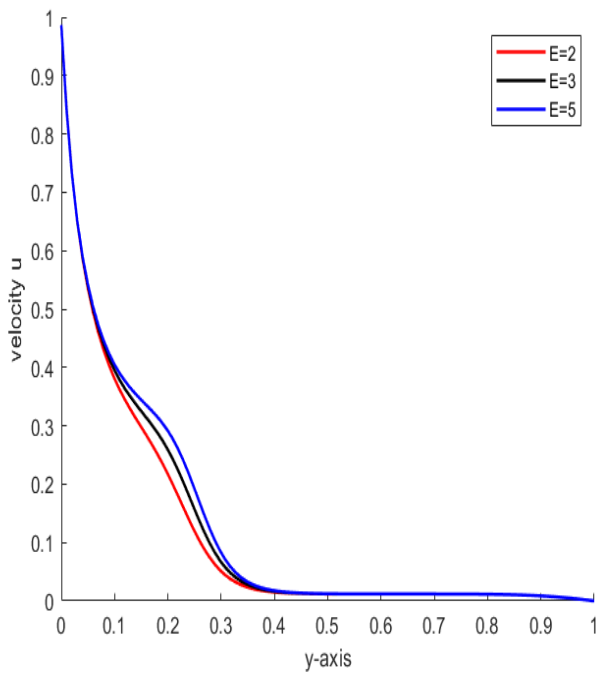




(c)

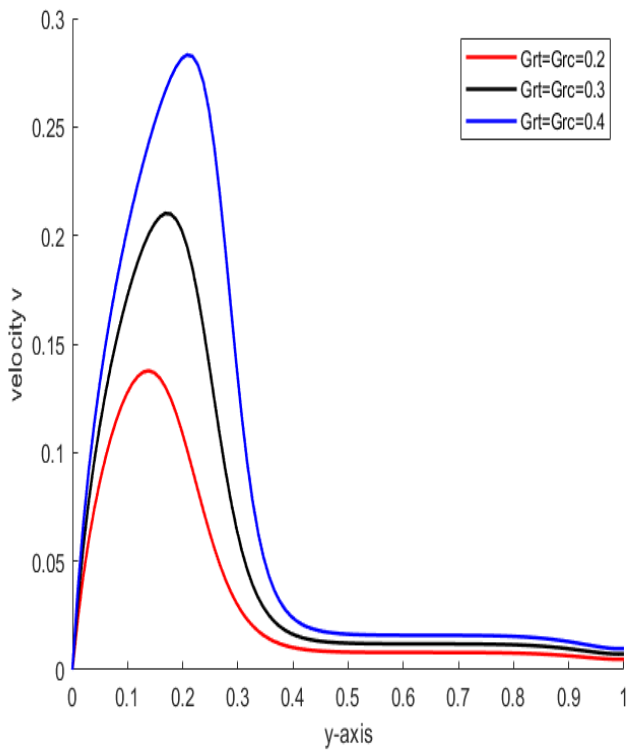


(d)

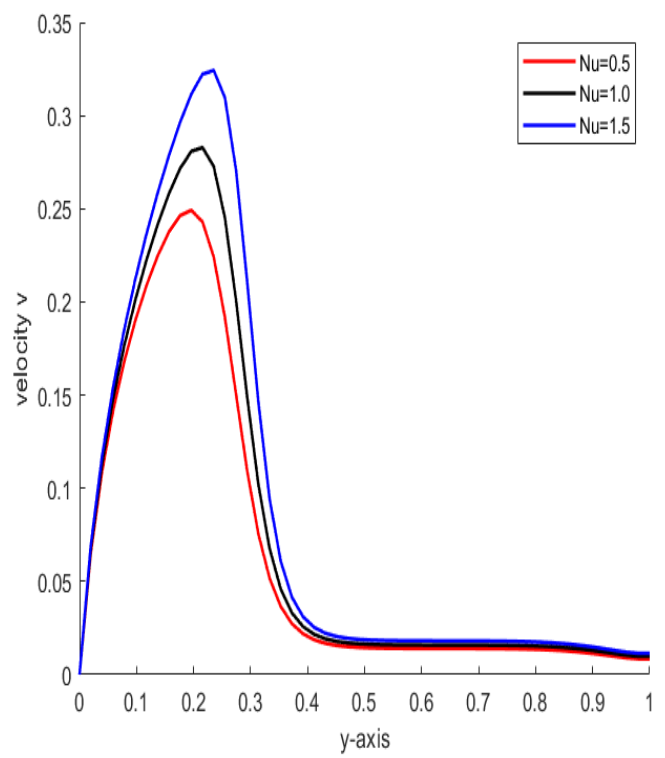


(e)

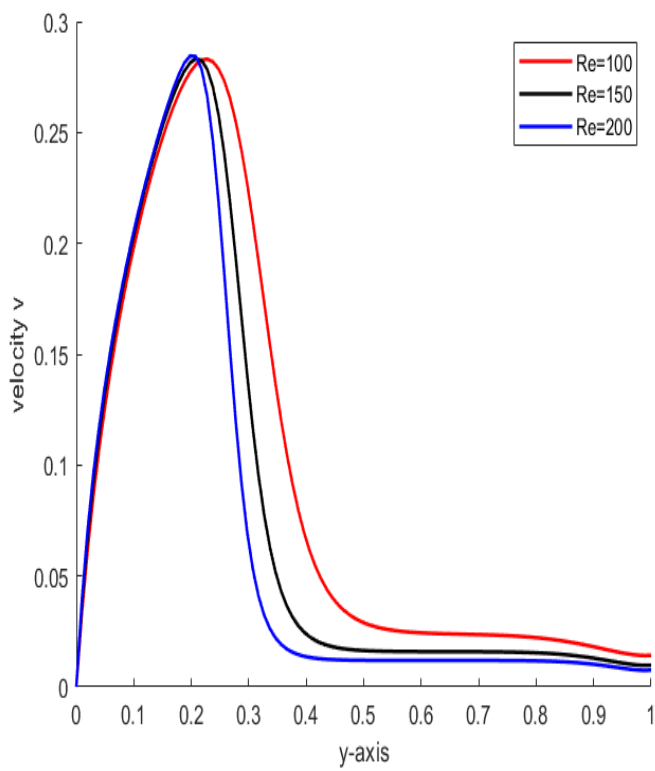
Figure 2 (a-e): Primary velocity, u profiles against Gr_c, Nu, Re, St and E.



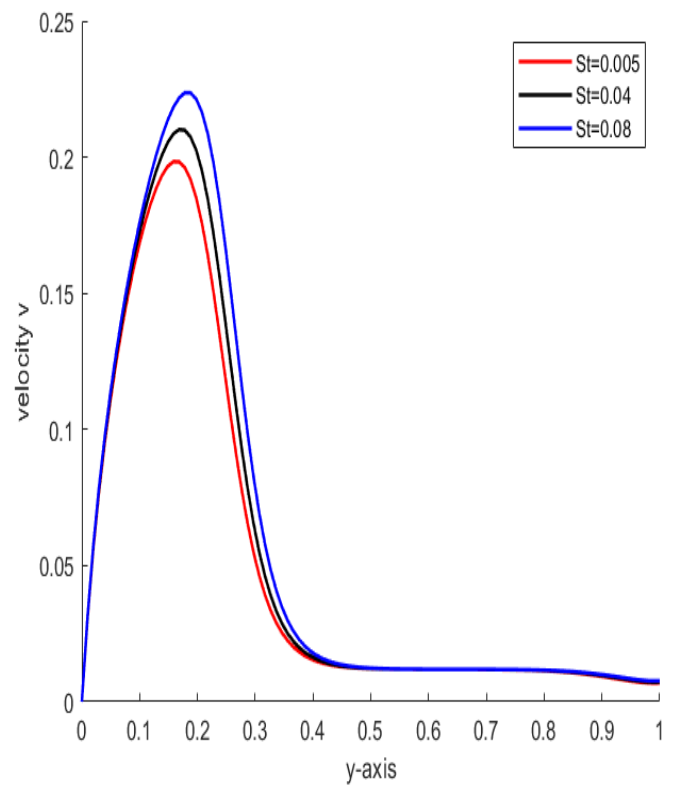
(a)



(b)



(c)



(d)

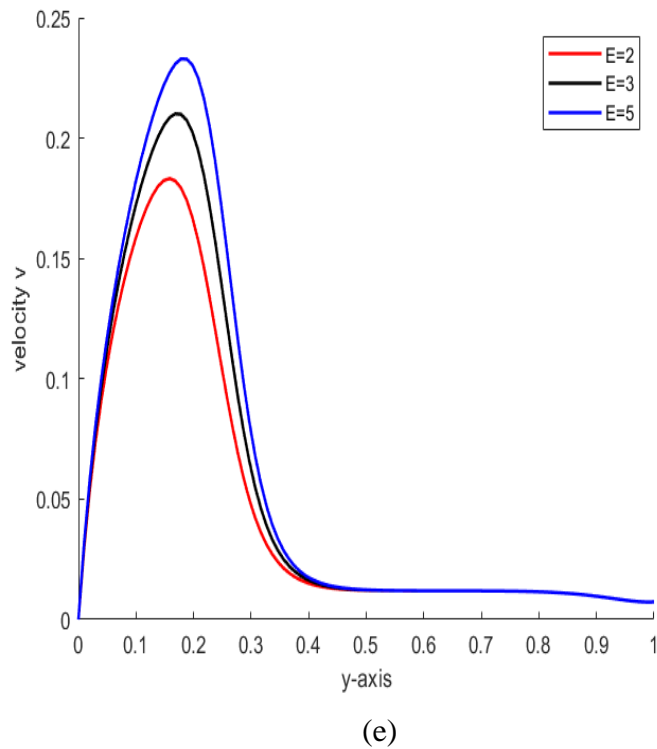


Figure 3 (a-e): Secondary velocity, v profiles against Grc , Nu , Re , St and E .

The results show that increases in Reynold's number gradually decreases velocity profiles away from the plate. The increased velocity near the upper plate is due to the convective heating caused by the heat internally generated within the fluid by a type of exothermic chemical reaction called bimolecular reaction. The overall drop in velocity profiles in the mainstream is caused by the increased heat transfer rate in the fluid.

It can also be seen in the results that the velocity profiles increase correspondingly with an increase in the Grashof number because of the increased temperature due to convective heating decreases the fluid viscosity leading to marginal increases in the fluid velocity through viscosity coupling. We observed that an increase in the Grashof number gave rise to an increased mass transfer gradient. Consequently, an enhancement of the velocity profiles was realised due to the enhanced fluid species' diffusion which then led to the increase of the boundary layer thickness.

The results further show that increases in Activation energy E leads to corresponding increases in fluid velocity. This is because the increased fluid temperature with increase in activation energy parameter in turn causes a reduction in fluid's viscosity and hence indirectly leading to increased fluid velocity.

The results in the displayed graphs indicate that Eckert number and Schmidt number affect the fluid flow significantly with regard to the velocity and temperature profiles. It is observed that the velocity and temperature profiles decrease with increasing values of Prandtl number within the boundary layer. The same trend is observed with Nusselt number, Reynolds number, Stanton and the activation energy.

4.2 The temperature profiles for the fluid flow

The results of the fluid flow representing the dimensionless parameters are shown graphically on figure 4 (a-e).

Figure (a) shows that higher Grashof number ($Gr_t = Grc$) corresponds to larger amounts of convective cooling occurring at the chemical walls thereby leading to a decrease in temperature on the walls of the channel near the plate, but lower Grashof number corresponds to lower degrees of convective cooling (convective heating) away from the chemical walls leading to increases in temperature at the walls of the channel or mainstream. The resulting temperature profiles for the flow therefore increases as the Grashof number increases while the bulk fluid consistently and continually adjusts itself to the wall temperatures that are lower.

Evidently, the temperature reduces as the Prandtl (Pr) number increases and increases with the Eckert number. It is noted that when the value of the Pr increases, the temperature decreases since the thermal boundary layer reduces and becomes thinner. Now, since the Prandtl number is the ratio of the fluid's momentum to the thermal diffusivity of the fluid, it is seen that larger values of the Pr number gives rise to stronger or higher momentum diffusivity as well as a lower thermal diffusivity.

It is clear in the results that an increase in Reynold's number gradually decreases temperature profiles away from the plate. It can be seen that the rate of heat transfer out of the upper plate is increased as a result of the increased velocity near the upper plate. This is due to the overall drop in the temperature profiles occurring in the mainstream.

Further observations show that an increase in the activation energy E leads to a decrease in temperature near the upper plate. However, as one moves away from the plate, the temperature increases in correspondence to the increase in activation energy. This is because

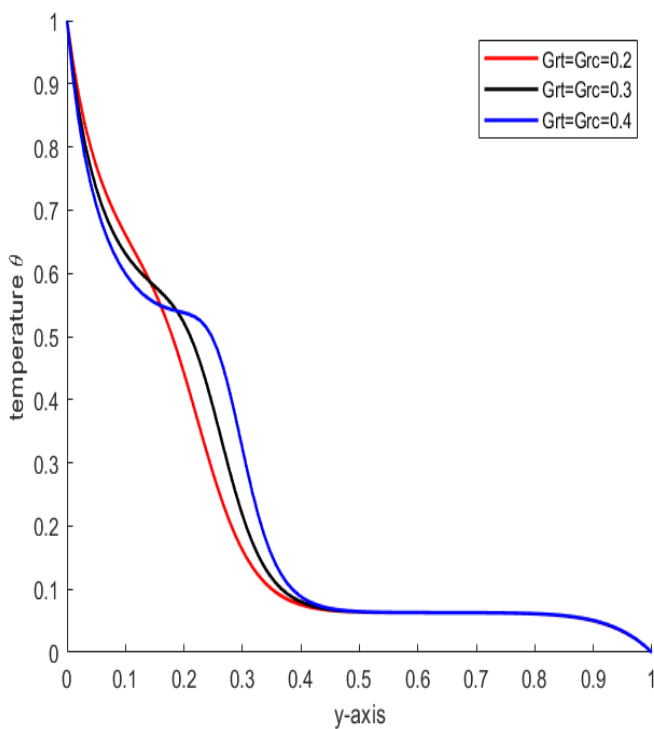
the viscous heating parameter due to Arrhenius heating function $\frac{L^2 Q c_0 A e^{-E_0/RT}}{\mu U^2}$, decreases as E increases near the plate. As seen in

the equation, this function occurs as one of the source terms in the equations of temperature that initiates the decrease in temperature of the fluid as the value of E increases, so that the maximum recorded temperature for E is seen when $E=2$.

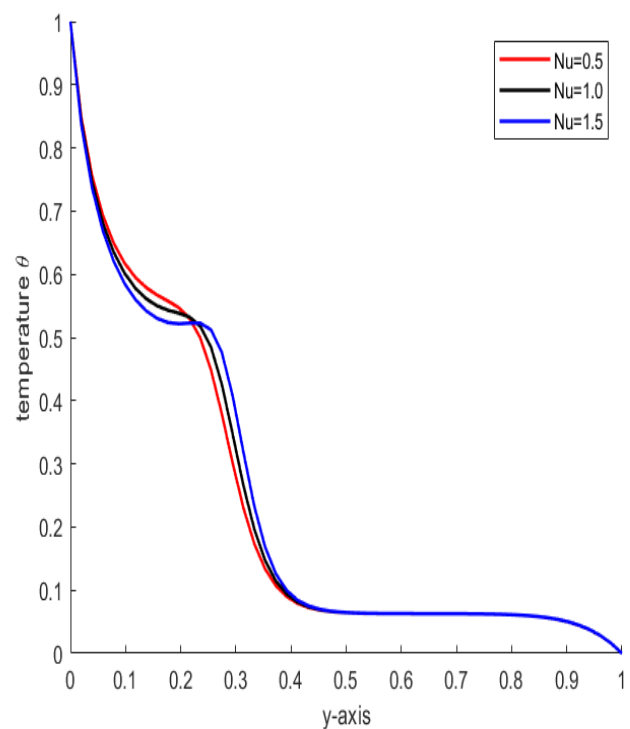
Looking at the flow region, an increase in temperature leads to an increase in the activation energy since the heat internally generated in the fluid in the course of bimolecular exothermic chemical reaction becomes higher as compared to the heat generated by either the Arrhenius activation energy or the sensitized type of reaction.

The results also indicate that comparing to conduction of the fluid, convection has a huge impact in the transformation energy associated with the boundary layer. This is because higher values of the Prandtl number there is an evident higher reduction in temperature. Higher values of the Eckert number enhance the temperature due to the release in the fluid's stored energy. Larger value of E amplifies the energy generated at the boundary and decreases as it moves to the mainstream.

It can be deduced also that temperature distribution increases via the magnetic parameter (M). This is attributed to the fact that as the temperature increases throughout the fluid, the resistive force generated by the MHD flow opposes the motion of the fluid. The increase in temperature throughout the fluid is a natural impact of the fluid's resistive force. As a result, the enhancement of the thermal energy in the fluid implies that the increase in the temperature between the thermal layers is evident as the fluid flows. It is noted that as the Prandtl number physically increases, the thermal conductivity of the fluid reduces hence resulting in the decay of the thermal field. The impact of Eckert number (Ec) also shows that there is a direct relation with the temperature profiles.



(a)



(b)

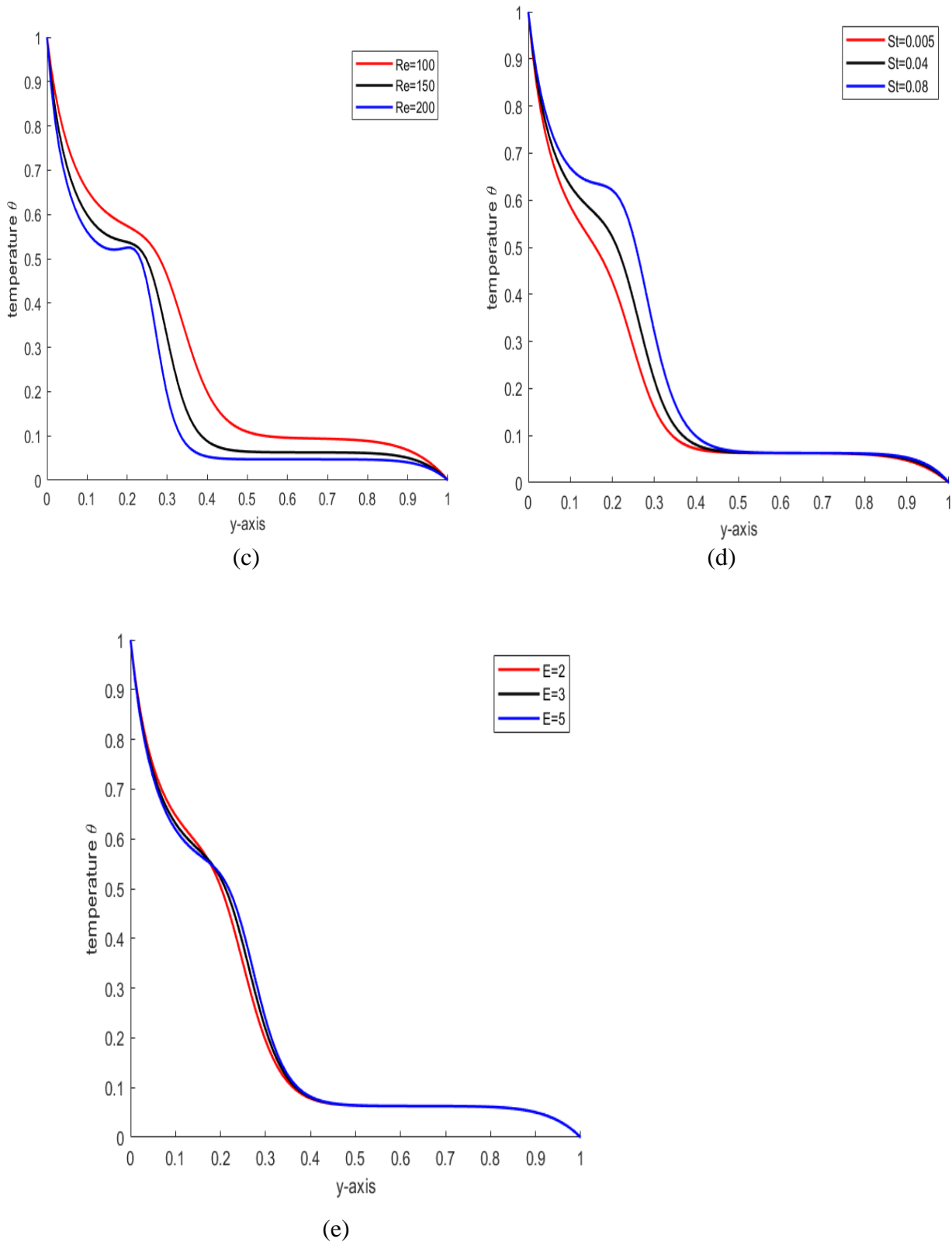


Figure 4 (a-e): Temperature profiles against Gr_c, Nu, Re, St and E.

4.3 The concentration profiles of the flow

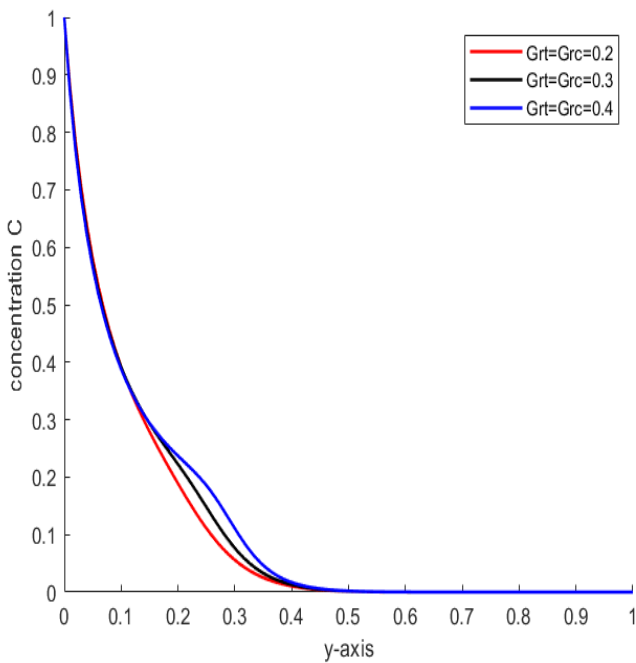
In this study, the overall impact of the dimensionless parameters on the concentration profiles is studied and the results displayed graphically as shown on figure 5(a-e). The impact of the Grashof number ($Gr_c = Gr_t$) and the Schmidt number Sc on the concentration profiles are respectively discussed for the fluid flow under consideration.

It is noted that an increase in the value of Gr_t leads to a decrease in the concentration boundary layer thickness, which is closely associated with the increase in the wall mass transfer gradient. This eventually produces a considerable increase in the fluid's surface rate of transfer.

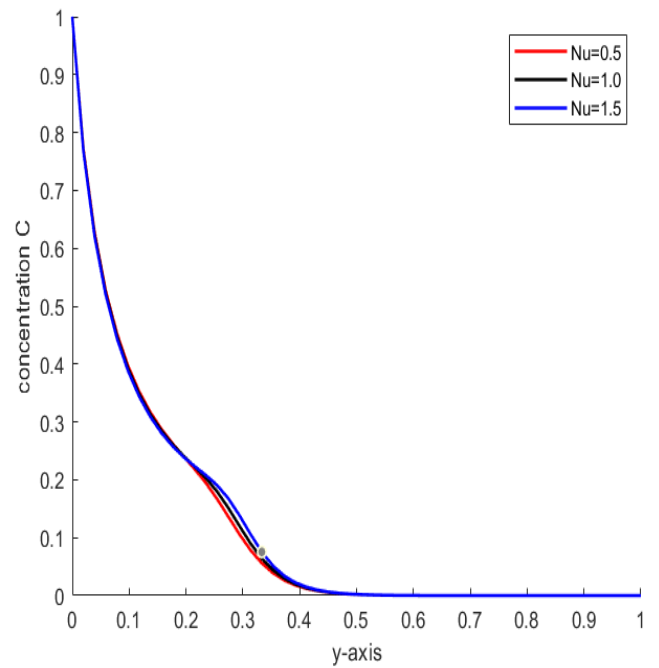
In the fluid flow, it is noted that the overall effects of the species diffusion are highly evident for a fluid flow that has a smaller Schmidt number. This happens due to the fact that the concentration gradient of the fluid increases and accelerates species' dispersion in the fluid. The same observation is made when the fluid in consideration is a Newtonian fluid. From the graphs

representing the concentration profiles, it is observed that an increase in the value of the reaction rate parameter decreases the concentration in the fluid flow profiles.

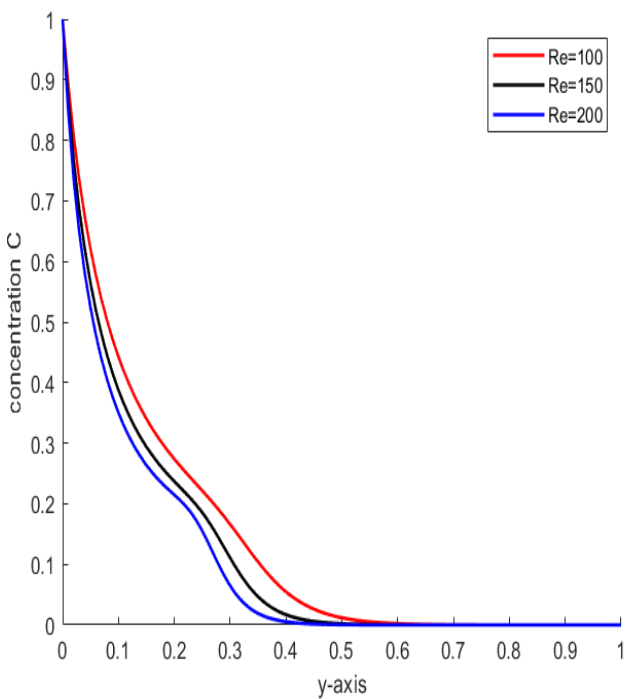
From the results, it is further observed that the concentration profiles of the fluid increase with a rise or increase in the activation energy E. This is because lower temperatures and higher activation energy in the reactive flow lead to weaker rates of reaction which eventually slows down the chemical reaction of the fluid.



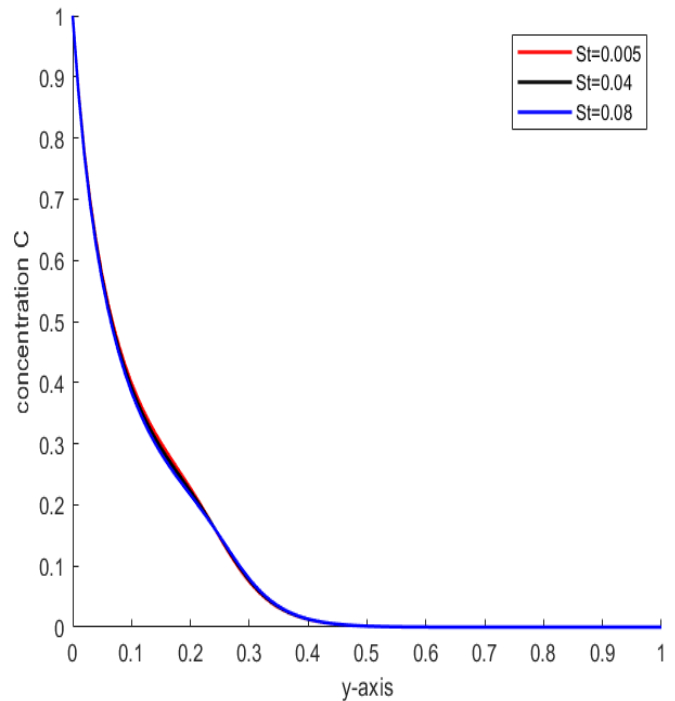
(a)



(b)



(c)



(d)

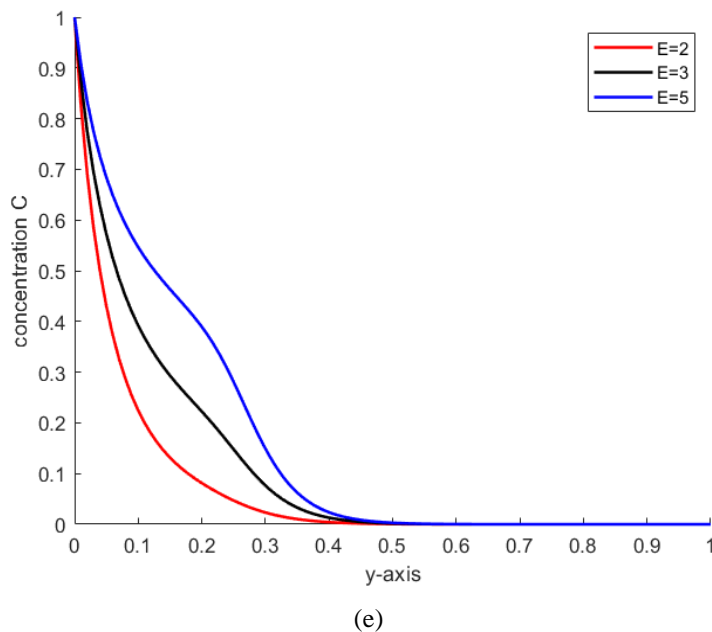


Figure 5 (a-e): Concentration profiles against Gr_c, Nu, Re, St and E.

V. Conclusion

The paper has extensively analyzed the effect of the Arrhenius activation energy for the considered fluid flow. From the results, it was observed that the concentration profiles of the fluid increase with a rise or increase in the activation energy E. This was because the lower temperatures and higher activation energy in the reactive flow lead to weaker rates of reaction which eventually slows down the chemical reaction of the fluid.

It was noted that the species concentration increases with an increase in activation energy E. This is because higher energy of activation coupled with reduced temperatures lead to weaker rate of reaction that eventually slows down the fluid's chemical reaction. The viscous dissipation and chemical reactions in the electrically conducting fluid flow in the elongated porous surface were analyzed and their effects discussed. It was evident from the study that the increased temperature due to convective heating in the fluid flow decreases the fluid viscosity leading to marginal increases in the fluid velocity through viscosity coupling.

The temperature of the fluid was found to decrease with an increase in activation energy parameter E near the upper plate but increased correspondingly with increases in activation energy away from the plate.

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