Unsteady radiative magnetohydromagnetic flow and entropy generation of maxwell nanofluid in a porous medium with arrhenius chemical kinetic

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Abstract: Parametric sensitivity of unsteady Maxwell magnetohydromagnetic nanofluid and second thermodynamic law analysis under Arrhenius kinetic is investigated in the presence of viscous heating and radiation. The porous flow channel is subjected to tension with material properties that vary with time without deformation. In the absence of fluid charge polarization, the conducting liquid is influenced by the sheet stretching velocity. The flow coupled derivatives model is reduced to dimensionless form by relevant transformation variables. These are computational solved by shooting numerical technique together with Fehlberg Runge-Kutta procedures. The essential characteristics of the flow and thermodynamic irreversibility are determined. The results are quantitatively and qualitatively compared with other studies and are established to agree well. The graphical results revealed that Lewis number increases the molecular species concentration and the thermodynamic stability for reversibility can be enhanced by the augmentation of magnetic field, thermophoresis, and radiation. Therefore, for thermal and chemical reaction systems, increasing heat propagation should be managed to keep the system from blowing up.

Subjects: Mathematical Modeling; Non-Linear Systems; Thermodynamics; Applied Mechanics; Heat Transfer; Computational Mechanics; Fluid Mechanics; Reaction Engineering

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The authors of this research are Nigeria Academic in Applied Mathematics in the area of fluid mechanics, reactive combustion, analytical dynamic, and heat and mass transfer. The authors are seasoned researcher who has contributed tremendously in his core areas of research. They have supervised first, second, and Doctorate degrees in their respective areas of specialization. They have several national and international publications in reputable journals to credits.

PUBLIC INTEREST STATEMENT
Parametric sensitivity of unsteady Maxwell magnetohydromagnetic nanofluid and second thermodynamic law analysis under Arrhenius kinetic is investigated in the presence of viscous heating and radiation. This present study will assist the chemical industry and thermal engineering to accurately predict almost all their activities or systems. The following highlight can be noticed in the study:

The essential characteristics of the flow and thermodynamic irreversibility are determined. The porous flow channel is subjected to tension and the material properties varies with time without deformation. Recharging microchannel shows lower entropy generation than simple microchannel. The thermodynamic stability for reversibility can be enhanced by the augmentation of magnetic field, thermophoresis and radiation.

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Keywords: Nanofluid; Arrhenius kinetic; Maxwell fluid; Entropy generation; MHD flow

1.0 Introduction

An increasing demand for an improved working fluid by the industry and technology brought about by various leading edge research works on the non-Newtonian fluid. These liquid have a large area of applications in different disciplines, for example, in geophysics, polymers, chemical industry, medical sciences, molten plastics, and many more (Fatumbi & Adeniyan, 2020; Khan et al., 2018). The fluid rheological properties are predicted using constitutive models which cannot be described by the Navier-Stokes models. Non-Newtonian liquid has no single precise model that can fully define its constitutive rheological properties, but they are developed from the grade fluids and power-law model (Khan et al., 2017; Moakher et al., 2016; Ogunseye et al., 2019). Shear-dependent fluid viscosity is widely modeled from the power-law equation while the fluid elasticity effect is formulated from the grade fluids. However, the shear relaxation impact is not captured by these models. Meanwhile, shear relaxation is defined by Maxwell model and it is a rate type subclass liquid. The fluid rheological characteristics found their usefulness in the industry and other areas of material synthesis. As such, Khan et al. (Z. Khan et al., 2018) examined upper convection in a porous channel of Maxwell fluid with heat source and magnetic effects. The model was analytically solved and comprehensive flow characteristics were reported. Mukhopadhyay and Bhattacharyya (Mukhopadhyay & Bhattacharyya, 2012) considered in the presence of reaction mixture, the energy transfer Maxwell liquid flow in an elongated sheet. It was reported that the Maxwell term dragged the incompressible flow fluid. Few other studies that discuss Maxwell fluid without emphasis on the nanofluid and Arrhenius chemical kinetic are (Motsa et al., 2012; Mukhopadhyay, 2012; Salah et al., 2013).

In the existence of nanofluid, Maxwell liquid flow characteristics and usages are improved by the convective and conducting strength of the nanoliquid. In the present century, nanotechnology is a strong propelling force in the industrial uprising and technological exploring area (Hong et al., 2005). The heat conducting power of nanofluid made it an advanced technology in augmenting heat transfer. At low species mixture, the thermal conductivity strength of the fluid can be increased depending on the nanoparticles thermal properties, size, and shape. In conformist-based fluids such as ethylene glycol, oil, and water, nanoliquid is a colloidal suspension of nanoparticles (Reddy et al., 2021; Salawu & Ogunseye, 2020). Also, due to the thermophoresis and Brownian movement properties, nanofluid with magnetic properties play an apparent role in cancer therapy and blood analysis. As such, Makinde and Aziz (Makinde & Aziz, 2011) examined thermal convective stretching plate boundary layer of a viscous nanofluid flow. It was noticed that the Brownian motion term increased heat transfer due to quick nanoparticles collision rate. Kotresh et al. (Kotresh et al., 2020) computationally provided a solution to the nanofluid flow through an elongated rotating disc in the presence of activation Arrhenius energy. The results show that the nanomaterial terms (Thermophoresis and Brownian term) enhanced the fluid particles thermal conductivity that leads to an improved heat transfer. Ishaq et al. (Khan et al., 2019) investigated combined Powell-Eyring magneto-nanofluid with radiation effect on a film thin flow in a permeable device. A semi-analytical solution of the model was carried out with motivating reports on the magnetic and radiation effects of the film thin flow. Khan (Khan, 2021) worked on the forced convective hybrid nanoparticles flow in rotating Darcy-Forchheimer disk media using numerical method. The study revealed that porosity term caused velocity profile decay and radiation term inspired temperature field. Most previous works did not examine the combined effect of Maxwell magneto-nanofluid and entropy generation despite their importance. Meanwhile, Maxwell nanofluid is considered as a significant force in enhancing working fluid performance in the industry due to their strong viscoelastic property and thermal conductivity.

In a thermal system, no matter how small is the heat transfer, energy is lost to the ambient which may not be reversed, and this can greatly impact the efficiency of industrial and
technological equipments. The amount of irreversible energy in a system determines the total entropy generated by the system (Salawu, Hassan et al., 2019). The thermodynamic second law is utilized in evaluating the volumetric entropy generation due to friction force, chemical reaction, liquid viscosity, and reaction diffusion (Fatunmbi & Salawu, 2020; Hayat et al., 2018). Hence, an improvement in Bejan number and entropy generation for the enhancement of energy conservation are innovative for proper and optimal productivity of thermal device and equipments. As a result, Saleem and El-Aziz (Saleem & Abd El-Aziz, 2019) examined heat convection transport and entropy generation of power-law non-Newtonian fluid flow with slip and radiation effect over a moving sheet. As obtained, the entropy generation reduces with increasing power-law index while Bejan number is lower with rising Reynolds number. Due to the importance of nanofluid, the authors (Khan et al., 2019; Salawu & Ogunseye, 2020) reported on the Bejan number and entropy generation of the flow of non-Newtonian magneto-nanofluid past a moving plate. Their results show that magnetic field minimized both friction and viscous heating irreversibility. Bhatti et al. (Bhatti et al., 2016) considered entropy reduction in a permeable moving sheet of the flow of Powell-Eyring nanofluid with magnetic field effect. It was reported that entropy production serves as a rising function for all examined physical quantities. However, with several studies on nanofluid, no study has provided reports on Arrhenius kinetics which is important in a chemical species.

This research considers the thermodynamic second law of an Arrhenius kinetic species with a combined Maxwell magneto-nanofluid in permeable media. This study is motivated by the work of Madhu et al. (Madhu et al., 2017) and various suggestions for further studies by researchers. It is as well stimulated by the momentous usefulness of nanofluids in nanotechnology development for industrial productivity. Also, this present study will assist the chemical industry and thermal engineering to accurately predict almost all their activities or systems. With activation energy and pre-exponential index, the Maxwell nanofluid chemical mixture is examined in the presence of heat dissipation and energy source. The present formulations have not been earlier posted or considered in this form. In the study, the dimensionless coupled models are numerically solved by

Figure 1. Flow geometrical coordinate.
shooting scheme along with Runge-Kutta solution procedures. For clarification, tables and graphs are presented for the obtained results, which are useful to the engineering and thermal science. The article is structured as follows: The introduction and background to the study is done in section 1, while the flow mathematical setup is carried out in section 2. Entropy generation analysis and solution procedure are, respectively, presented in sections 3 and 4. Results and its discussion are presented in section 5, followed by conclusion and references.

1. The flow mathematical setup

Consider a two-directional flow of unsteady MHD Maxwell nanofluid in a convective Maxwell permeable stretching device with time reliance injection/suction velocity \( w(t) = \frac{ax}{1 - et} \). The incompressible non-Newtonian conducting liquid is simulated by completely developed Maxwell model. The flow occurs at varying velocity \( U(x, t) = \frac{ax}{1 - xt} \) under the influence of varying strength of magnetic field \( B = \frac{dy}{\sqrt{1 - xt}} \) and time-dependent stretching rate \( \frac{dx}{1 - xt} \). Without material deformation, the elongated sheet is subjected to some measures of tension. The properties of the material are assumed to be varied with time for polymer extrusion case. Here, low Reynolds's magnetic number is assumed, and electric field resulting from the polarization of charges is ignored as electric field is absence. The Maxwell working liquid is induced with nanoparticles through surfactant to circumvent agglomeration of nanoparticles along the porous medium. The flow geometrical coordinate is illustrated in Figure 1 medium.

Taking from the stated assumptions, the dimensional flow equations for the Maxwell nanofluid with Arrhenius chemical reaction are given according to Madhu et al. (2017); Salawu et al. (2020); Salawu, Oladejo et al. (2019) as

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0,
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \nu \frac{\partial^2 u}{\partial x^2} + 2\nu \frac{\partial^2 u}{\partial x \partial y} + \frac{\partial^2 u}{\partial y^2} = \frac{\partial^2 u}{\partial y^2} - \frac{\nu}{K} \frac{\sigma B_0^2 u}{\rho_f},
\]

\[
\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} - \alpha \frac{\partial^2 T}{\partial y^2} + \rho c_p \frac{\partial Q}{\partial y} + \frac{T}{\sqrt{T_{\infty}}} \left( \frac{\partial T}{\partial y} \right)^2 + \frac{\mu}{\rho c_p} \left( \frac{\partial u}{\partial y} \right)^2 + \frac{Q}{\rho c_p} (T - T_{\infty}),
\]

\[
\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} - D_b \frac{\partial^2 C}{\partial y^2} - k_s \left( \frac{T}{T_{\infty}} \right)^n \exp \left( \frac{E_a}{kT} \right) (C - C_{\infty}) + \frac{D_s \partial T}{T_{\infty} \partial y^2} + \frac{D_s \partial C}{T_{\infty} \partial y^2},
\]

the appropriate boundary conditions taken from Kuznetsov and Nield (Kuznetsov & Nield, 2014) are defined as

\[
u = U, v = w, T = T_w, D_t \frac{\partial T}{\partial y} + D_b \frac{\partial C}{\partial y} = 0, \text{aty} = 0
\]

\[
u \rightarrow 0, T \rightarrow T_{\infty}, C \rightarrow C_{\infty}, \text{as} \rightarrow \infty.
\]

where \( v \) and \( u \) are the velocity Cartesian components. \( \sigma, \nu, \alpha, \rho_f, D_t, \rho_p, T, C, D_b, \beta, \rho, k_s, \) and \( B_0 \) are, respectively, the electric conductivity, viscosity, thermal conductivity, fluid density, thermophoretic diffusion, nanoparticle density, fluid temperature, volume fraction nanoparticle, Brownian diffusion, Maxwell term, heat source, medium porosity, and magnetic field strength. Also, the terms \( k_s, k_n, \) and \( E_a \) denote the reaction branch chain, Boltzmann constant, chemical kinetics index, and activation energy.
At time \( t < e^{-1} \), the definitions for \( \beta(t) \), \( \nu_\omega(x, t) \), \( U(x, t) \) and \( T_\omega(x, t) \) are valid with \( T_\omega(x, t) = T_\infty + bx(1 - e^t)^2 \) that denotes the varied temperature of the sheet, \( T_\infty \) is the free steam heat. Obtaining from Rosseland approximation, the radiation term in the second RHS of equation (3) according to Basilem et al. 2020; Hayat et al. 2016 takes the form

\[
\frac{\partial q}{\partial y} = -\frac{16\kappa \theta^2}{3k_0} \frac{\partial T}{\partial y^2}.
\]

where \( k_\omega \) and \( \kappa \) are coefficient of absorption and Stefan-Boltzmann constant. The subsequent relations for \( \phi, \theta, \nu, \) and \( u \) are considered

\[
\phi = \frac{C - C_\infty}{C_\infty}, \theta = \frac{T - T_\infty}{T_\omega - T_\infty}, \nu = -\frac{\partial \psi}{\partial x}, u = \frac{\partial \psi}{\partial y}
\]

where the stream function denotes \( \psi \). The subsequent transformation variables are adopted

\[
C = C_\infty + \frac{cX}{(1 - e^t)^2} \phi(\eta), T = T_\infty + \frac{cX}{(1 - e^t)^2} \theta(\eta), \psi = \sqrt{\frac{cU}{1 - e^t}} \frac{\nu f(\eta)}{\eta}, \eta = \sqrt{\frac{c}{(1 - e^t)^2}}.
\]

Introducing the transformation quantities of equations (6)-(8) in equations (1) to (5), the equations are transformed to dimensionless form as

\[
f'''' - \lambda (2ff'' + f'''') + A \left(f'' + \frac{\eta}{2} f'''\right) = f'''' - (M + Pr)f'f',
\]

\[
f'\theta - f\theta' + A(4\theta + \eta\theta') = Nt\theta'^2 + N\theta' \phi' + \frac{1}{Pr} \left(1 + \frac{\Delta R}{3}\right) \theta'' + \frac{1}{Pr} + Ec f'^2,
\]

\[
\phi'' - Le \left(f' \phi - f\phi' + A \left(4\phi + \eta \phi'\right)\right) + \frac{Nt}{NB} \phi'' - Le \frac{1 + n\phi' \phi}{1 + \theta''} \exp \left(-\frac{E}{1 + \theta''} \right) = 0
\]

with the following boundary conditions satisfied

\[
f' = 1, f = \theta = 1, Nt\theta' + N\phi' = 0, at_\eta = 0
\]

\[
f' \to 0, \theta \to 0, \phi \to 0, as_\eta \to \infty.
\]

where injection/suction term is \( S = \frac{10}{\sqrt{c_\omega}} \), Prandtl number is \( Pr = \frac{c_\omega}{c_\rho} \), Lewis number is \( Le = \frac{c_\rho}{c_\omega} \), magnetic term is \( M = \frac{c_\rho}{c_\omega} \), radiation term is \( R = \frac{c_\rho}{c_\omega} \), unsteady term is \( A = \frac{c_\rho}{c_\omega} \), Maxwell term is \( \lambda = c_\rho \), thermophoresis term is \( Nt = \frac{(T_\omega - T_\infty)D_c}{c_\omega} \), Brownian motion is \( Nb = \frac{(c_\omega - c_\omega)D_c}{c_\omega} \), Eckert number is \( Ec = \frac{c_\omega}{c_\omega} \), heat source term is \( \delta = \frac{c_\rho}{c_\omega} \), chemical reaction term is \( \gamma = \frac{c_\rho}{c_\omega} \), activation energy term is \( E = \frac{c_\rho}{c_\omega} \), relative temperature is \( \theta'' = \frac{T_\omega - T_\infty}{T_\omega} \), and porosity term is \( P = \frac{c_\rho}{c_\omega} \).

For the purpose of engineering practical and applications, the local skin friction \( C_f \), wall gradient heat \( Nu_x \), and wall species gradient \( Sh_x \) are, respectively, obtained in dimensionless form as

\[
C_f = \frac{1}{2} Re_x^{1/2} \phi''(0), Nu_x = -Re_x^{1/2} \left(1 + \frac{4R}{3}\right) \theta'(0), Sh_x = -Re_x^{1/2} \phi'(0).\]
where local Reynolds number \(Re_x = \frac{UV}{μ}\).

2. Entropy generation
The chemical reactive Maxwell nonfluid entropy generation volumetric is induced by current carrying liquid in permeable device. The irreversibility is generated by heat transfer, chemical diffusion, and fluid friction irreversibility. Following from Fatunmbi & Salawu (2021); Kareem et al. (2020); Salawu, Dada et al. (2019), the volumetric irreversibility in dimensional form can be described as

\[
E_v = \frac{μ}{T_c} \left[ \left( \frac{16nT^2}{3K} + 1 \right) \left( \frac{μ}{K} \right)^2 \right] + \frac{ν}{T_c} \left( \frac{μ}{K} \right)^2 + \frac{Re_b}{T_c} \left( kC \frac{dT}{dx} + kC \frac{dT}{dy} \right) + \frac{Re_b}{T_c} \left( \frac{μ}{K} \right)^2.
\]

the volumetric entropy creation characteristics is expressed as

\[
V_e = \left( \frac{αVT}{T_c} \right)^2.
\]

Using equations (6) to (8) on dimensional equation (14), the entropy generation \(N_g\) in the dimensionless quantity form is obtained as

\[
N_g = \frac{β_0}{T_c} = (1 + \frac{1}{2}R_e) \left( \frac{μ}{K} \right)^2 + \frac{Re_c}{α} \left( f' \right)^2 + \frac{Re_h}{α} \left( \frac{μ}{K} \right)^2 + \frac{θ}{T_c} \left( \frac{μ}{K} \right)^2,
\]

where \(χ = \frac{αC}{T_c}, \omega = \frac{αT}{T_c}, h = \frac{CRe_b}{K}\).

Denoting \(N_a = (1 + \frac{1}{2}R_e) \left( \frac{μ}{K} \right)^2\) and \(N_b = \frac{Re_c}{α} \left( f' \right)^2 + \frac{Re_h}{α} \left( \frac{μ}{K} \right)^2 + \frac{θ}{T_c} \left( \frac{μ}{K} \right)^2\).

The irreversibility ratio (Be) is defined as

\[
Be = \frac{(1 + \frac{1}{2}R_e) \left( \frac{μ}{K} \right)^2}{(1 + \frac{1}{2}R_e) \left( \frac{μ}{K} \right)^2 + \frac{Re_c}{α} \left( f' \right)^2 + \frac{Re_h}{α} \left( \frac{μ}{K} \right)^2 + \frac{θ}{T_c} \left( \frac{μ}{K} \right)^2} = \frac{N_g}{N_a}.
\]

where the Bejan number (irreversibility ratio) is \(Be\). Bejan number falls within the range \([0, (Khan et al., 2018)]\).

3. Solution techniques
A computational solution procedure is carried out on dimensionless equations (9) to (12). Due to strongly nonlinear nature of the equations, a consistent, stable, and convergent shooting scheme is used coupled with Fehlberg Runge-Kutta method. The fundamental idea of the technique is to transform the boundary conditions (equation (12)) to initial conditions through shooting method by assuming an appropriate finite value at free stream \((y \rightarrow \infty)\), and rewrite the main equations (9) to (11) in derivative of order one as given:

\[
d_1 = f, d_2 = f', d_3 = f'', d_4 = \theta, d_5 = \theta', d_6 = \phi, d_7 = \phi'.
\]

\[
d_1 = d_2
\]

\[
d_2 = d_3
\]
\[ d'_{3} = \frac{d_{2}^{2} - d_{1}d_{3} - 2\lambda d_{1}d_{2} + A(d_{2} + \frac{\theta}{d_{2}}) + (M + P)d_{2}}{(1 - \lambda d_{2})}, \]

\[ d'_{4} = d_{5} \]

\[ d'_{5} = \frac{d_{2}d_{4} - d_{1}d_{5} + \frac{A}{2}(4d_{4} + \eta d_{3}) - N_{t}d_{5}^{2} - N_{b}d_{5}d_{1} - \delta d_{4} + Ecd_{5}^{2}}{\beta (1 + \frac{\eta}{d_{2}})} \]

\[ d'_{6} = d_{7} \]

\[ d'_{7} = Le\left(d_{2}d_{6} - d_{1}d_{7} + \frac{A}{2}(4d_{6} + \eta d_{5})\right) - \frac{N_{t}}{N_{b}}d'_{5} + L_{e}\eta(1 + n_{t}d_{4})\exp\left(-\frac{E}{1 + \theta_{w}d_{4}}\right)d_{6}, \]

the reference boundary conditions becomes as follows

\[ d_{2}(0) = 1, d_{1}(0) = S, d_{4}(0) = 1, N_{t}d_{5}(0) + N_{b}d_{7}(0) = 0, d_{2}(\infty) = 0, d_{4}(\infty) = 0, d_{6}(\infty) = 0. \]

The equations (19) to (25) are solved with the conditions in equation (26) by first assuming an appropriate initial guesses for \( d_{1}(0), d_{2}(0) \) and \( d_{7}(0) \). The initial value-derivative equations are then solved through Fehlberg Runge-Kutta scheme. The shooting technique criterion for convergence is the residuals of the boundaries \( d_{2}, d_{4}, \) and \( d_{6} \) less than the tolerance of the error (i.e. \( 10^{-6} \)). Hence, the residuals boundary for third step are computed. If the residuals of the boundary are greater than tolerance error, by Newton method, the initial guesses are reviewed. This procedure is continuously re-adjusted until the criteria are fully satisfied. Here, for the overall solution procedures, a standard Shooting Fehlberg Runge-Kutta scheme for boundary value problem via Maple solver is used.

4. Discussion of results

For comprehensive clarity of the flow characteristics, tables and graphs of computed results are presented for some dimensionless physical terms. The chosen parameter ranges for the plots are based on the validated theoretical results by researchers. Investigations are carried out on some essential engineering quantities to determine the parameters influence on the irreversibility ratio (\( \beta_{e} \)), entropy generation (\( N_{s} \)), flow momentum (\( f'(\eta) \)), energy field (\( \theta(\eta) \)), and concentration profile for Maxwell nanoliquid under Arrhenius kinetics. The shooting numerical method is used to solve and compute the solutions. Computed numerical values are presented in Tables 1 and 2. Table 1 presents the validation of computed results with previous correlated works, and as seen, the values agree well quantitatively with existing ones. In Table 2, the flow physical quantities are demonstrated for shear stress, temperature, and mass gradients. As noticed, a variation in the individual terms is observed to have either increases or decreases in

| \( A \) | \( f''(0) \) | \( \lambda = 0, S = 0, M = 0 \) and \( k_{f} = 0 \) |
|---|---|---|
| 0.8 | -1.261512 | -1.261211 |
| 1.2 | -1.377850 | -1.377625 |
| $P$ | $\lambda$ | $Le$ | $R_i$ | $\delta$ | $\gamma$ | $E$ | $C_f$ | $N_u$ | $Sh$ |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.2 | 0.1 | 0.1 | 0.5 | 0.1 | 0.2 | 0.2 | -1.638618649 | 0.9755805669 | -0.975580567 |
| 0.5 | | | | | | | -1.731384162 | 0.9650389631 | -0.965038963 |
| 1.0 | | | | | | | -1.875363875 | 0.941014186 | -0.94101419 |
| 0.02 | | | | | | | -1.617264564 | 0.9785880679 | -0.978588069 |
| 0.05 | | | | | | | -1.625263262 | 0.9774589631 | -0.977458963 |
| 1.0 | | | | | | | -1.638618655 | 0.9576115244 | -0.957611524 |
| 3.0 | | | | | | | -1.638618792 | 0.9467512156 | -0.946751216 |
| 1.0 | | | | | | | -1.638618729 | 0.8206552786 | -0.820655278 |
| 1.5 | | | | | | | -1.638618725 | 0.7199833919 | -0.719983391 |
| 0.2 | | | | | | | -1.638618647 | 0.9527441148 | -0.952744115 |
| 0.5 | | | | | | | -1.638618642 | 0.8797758549 | -0.879775855 |
| 0.3 | | | | | | | -1.638618649 | 0.9754241214 | -0.975424121 |
| 0.7 | | | | | | | -1.638618649 | 0.9748278661 | -0.974827866 |
| 1.0 | | | | | | | -1.638618649 | 0.975447113 | -0.975447111 |
| 2.0 | | | | | | | -1.638618649 | 0.9758386737 | -0.975838674 |
the wall shear stress or heat and mass gradients. The impact factor depends on the fluid interaction with the flow boundary layers that influence the chemical reaction and heat diffusion to the ambient.

The impacts of magnetic term (M) and porosity term (P) on the Maxwell nanofluid velocity are verified in Figures 2 and 3. Both terms resist free flow of reactive mixtures in the presence of activation energy and heat generation. The magnetic term in Figure 2 exerts a force called Lorentz force on the motioning conducting nanoliquid. The force is also referred to as electromagnetic force, which act relatively opposite to a moving fluid; this, therefore, causes
the current carrying nanoparticle to damp. Hence, the velocity profiles retarded. Meanwhile, Figure 3 shows the porosity effect on the flow rate, this measures the material pore space and denotes a volume fraction of the pore space over the whole volume fraction of material pore space. Rising the porosity values reduces the permeability of the flowing liquid due to the increasing bulk fractional volume of the material pore space. As a result, the material flow rate is dragged thereby decreases the Maxwell nanomaterial flow velocity in the medium.

The response of the material heat transfer in the chemical mixture to changes in some physical quantities such as Eckert number Ec, heat source δ, and radiation Rd are correspondingly displayed.
The heat transfer magnitude monotonically rises across the flow regime due to an enhancement in the viscous heating terms that strengthening the nanomaterial heat conductivity. As such, the reactive Maxwell nanoparticles under Arrhenius kinetic conducts heat quickly and encourage temperature distribution as the fluid particles collided freely. Therefore, the heat transport fields are enhanced as revealed in the plots. However, converse result is gotten for Prandtl number Pr variation demonstrated in Figure 7. The term is utilized to measure the heat transfer quantity between a solid object and moving liquid. It described the kinematic viscosity to heat ratio diffusivity, and it depends solely on the material and material state. The energy transfer diminishes because the momentum diffusivity controls the system. The relative thickness of the boundary layers (thermal and momentum layers) is controlled by Prandtl number; hence, quick
heat diffusion to the environ is noticed. This thereby decreases the temperature profile progressively.

Under Arrhenius kinetic, the nanoparticle volume fractions of the reactive mixture for the confirmation of the plot of $\phi(\eta)$ versus $\eta$ for the dimensionless terms Brownian motion $Nb$, relative temperature $\theta_w$, and Lewis number $Le$ are separately offered in Figures 8, 9 and 10. Figure 8 denotes the irregular haphazard motion of liquid infinitesimal particles, as a result of the uninterrupted barrage from surrounding molecules. A noteworthy increment in the fluid nanoparticle volume fraction is noted as the molecules bombardment continues to raise the fluid particles random movement. Hence, the non-Newtonian fluid species is boosted. Variation in the relative
Temperature proportional encourages the reactive species volume fraction as revealed in Figure 9. A rise in the relative heat propels activation energy for the chemical reaction, this stimulates the Maxwell nanofluid mass transfer thereby create a monotonically rise in the species distribution. Figure 10 indicates the Lewis number influence on the nanoparticle volume fraction field. The term Le describes flow liquids where there is concurrent mass and heat transport, and it defined the heat to the molecular mass ratio diffusivity. An increase in Lewis number causes thickness of the mass boundary layer in relation to thermal boundary layer which then incline the mass transfer profile. Hence, Lewis number is an essential number in the study of combustion along with other dimensionless quantities. The impact of thermophoresis term Nt on the fluid molecular mass is established in Figure 11. Different fluid mobile particle mixture is observed to have reacted significantly to temperature gradient force that cause the macroscopic mixture concentration
distribution to decrease. The term is a phenomena that usually applied to fluid mixtures that leads to solution colloidal particle migration under the influence of heat gradient force. Thus, the liquid species molecular volume fraction reduces as the term \( N_t \) rises.

Here, variation in the dimensionless physical quantities is presented for the second thermodynamic energy conservation law in response to irreversibility ratio and entropy generation. Figures 12, 13, 14, and 15 confirm the entropy generation study for the radiation \( Rd \), magnetic term \( M \), thermophoresis \( N_t \), and Eckert number \( Ec \) through thermodynamic second law analysis. The amount of mass and heat transport in an irreversible process defined entropy generation, which includes solids deformation, fluid flow, heat exchange, substance mixture, motion of bodies, and other thermodynamic irreversible cycle. The effect of subatomic moving particles of large
energy transmission that lead to ionization is verified in Figure 12. As noticed, particle emission of energy through a Maxwell nonmaterial medium reduces because the particle energy ionization requires to break the chemical bond decreases throughout the flow regime. In Figure 13, magnetized material and motion relative to electric changes decline thereby enhancing irreversibility which then reduces entropy generation. Against its velocity, a perpendicular force is experienced by a moving charge parallel to induce current in relation to other particle charges, this therefore decreases the entropy production field. Likewise, thermophoresis term substantially inspires reversibility by dampening entropy generation as depicted in Figure 14. As obtained, the parameters Rd,

Figure 14. $N_s$ against $\eta$ for various $N_t$.

Figure 15. Entropy generation for diverse $E_c$. 

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\( M \), and \( Nt \) improve the thermodynamic equilibrium by boosting the system stability. The heat dissipation characteristic (i.e. Eckert number) effect is shown in Figure 15. The enthalpy difference for boundary layer relative to flow kinetic is increased, this leads to high breaking down of molecular chemical bond, and boosting of irreversibility process with high energy loss to the ambient. Therefore, entropy generation is enhanced and thermodynamic stability reduces.

Figure 16. Irreversibility ratio for rising \( Rd \).

Figure 17. Bejan profile for increasing \( Ec \).
The Bejan number (irreversibility ratio) for varying physical terms is established in Figures 16, 17, 18 and 19. In the mechanics of mass and heat transfer, along the length of the device, Bejan number described diffusion and pressure drop. Meanwhile, in a thermodynamic system, is the amount of total liquid viscosity and heat transmission irreversibility relative to the ratio of irreversibility as a result of heat transport. In either case, the species concentration, energy, and momentum are the same for Bejan number. A respective rise in the considered physical quantities discourages Bejan number due to the dominance of the combined effects of the thermal and fluid friction irreversibility over the energy transport irreversibility. As such, the terms decreases entropy.
generation relative to very low energy dissipation. Therefore, reversible of a thermodynamic system is inclined by raising the radiation, Eckert number, Lewis number, and Brownian motion value to boost the Maxwell nanofluid reactive system stability for effective engineering usages.

5. Conclusion
In the investigation, unsteady hydromagnetic flow and thermodynamic irreversibility of Maxwell nanofluid with Arrhenius chemical kinetic and radiation are examined in a stretching device. In the presence of joule heating and enthalpy, the conducting fluid flows in a porous medium without material deformation. The dynamical flow formulated coupled model with appropriate conditions are solved by employing Maple standard solver for the shooting Fehlberg Runge-Kutta technique. For the overall solutions of the physical essential engineering quantities, the solution procedures are adopted because of its consistence and convergence. The obtained results are quantitatively and qualitatively compared with other studies and found to agree well. Summary of the key observations from the offered exploration is revealed below.

Dimensionless momentum \( f(\eta) \) is a monotonically declining function of \( \eta \) for the varying bodily porosity and magnetic terms.

The impacts of the Eckert number, heat source and radiation on the dimensionless temperature distribution in between the selected range are qualitatively related except for Prandtl number that is otherwise.

Species concentration magnitude in the flow regime increases over the stream distance for the rising parameters \( Nt, \theta_w \) and \( Le \) while the species molecular mass decay for \( Sc \) as \( \eta \) is raised.

The thermodynamic irreversibility and its ratio are largely influenced correspondingly by the terms \( Rd, M, Nt, Ec, \) and \( Le \). Hence, the terms should be augmented to improve the system thermodynamic equilibrium for energy conservation.

The study carried out here arises from the attempt to examine the parametric sensitivity of Maxwell nanofluid chemical reaction under Arrhenius kinetic in an elongated porous plate. Following this, further studies are encouraged for the combustible reaction of Maxwell nanofluid in an annular cylinder.

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References
Baslem, A., Sowmya, G., Gireesha, B. J., Prasannakumar, B. C., Rahimi-Gorji, M., & Hoang, N. M. (2020). Analysis of thermal behavior of a porous fin fully wetted with nano-fluids: Convection and radiation. Journal of Molecular Liquids, 307(6), 112920. https://doi.org/10.1016/j.molliq.2020.112920
Bhatti, M. M., Abbas, T., Rashidi, M. M., Ali, M. S., & Yang, Z. (2016). Entropy generation on MHD Eyring-Powell nano-fluid through a permeable stretching surface. Entropy, 18(6), 224–238. https://doi.org/10.3390/e18060224
Fatunmbi, E. O., & Adeniyi, A. (2020). Nonlinear thermal radiation and entropy generation on steady flow of magneto-micropolar fluid passing a stretching sheet with variable properties. Results in Engineering, 6, 100142. https://doi.org/10.1016/j.rineng.2020.100142
Fatunmbi, E. O., & Salawu, S. O. (2020). Thermodynamic second law analysis of magneto-micropolar fluid flow past nonlinear porous media with non-uniform heat source. Propulsion and Power Research, 9(3), 281–288. https://doi.org/10.1016/j.jppr.2020.03.004
Fatunmbi, E. O., & Salawu, S. O. (2021). Analysis of entropy generation in hydromagnetic micropolar fluid flow over an inclined nonlinear permeable stretching sheet with variable viscosity. Journal of Applied and Computational Mechanics, 6(SI), 1301–1313. https://doi.org/10.22055/jacm.2019.30990.1807
Hayat, T., Khan, M. I., Farooq, M., Alsaedi, A., Waqas, M., & Yasseen, T. (2016). Impact of Cattaneo-Christov heat flux model in flow of variable thermal conductivity fluid over a variable thickness surface. *International Journal of Heat and Mass Transfer*, 99, 702–710. https://doi.org/10.1016/j.ijheatmasstransfer.2016.04.016

Hayat, T., Khan, M. I., Qayyum, S., & Alsaedi, A. (2018). Entropy generation in flow with silver and copper nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 539, 335–346. https://doi.org/10.1016/j.colsurfa.2017.12.021

Hong, T. K., Yang, H. S., & Choi, C. J. (2005). Study of the enhanced thermal conductivity of Fe nanofluids. *Journal of Applied Physics*, 97(6), 1–4. https://doi.org/10.1063/1.1861145

Kareem, A., Salawu, S. O., & Yan, Y. (2020). Analysis of transient Rivlin-Ericksen fluid and irreversibility of exothermic reactance hydromagnetic variable viscosity. *Journal of Applied Computing Mechanical*, 6(1), 26–36. https://doi.org/10.22055/jacm.2019.28216.1460

Khan, M. I. (2021). Transportation of hybrid nanoparticles in forced convective Darcy-Fourier flow by a rotating disk. *International Communications in Heat and Mass Transfer*, 122, 105177. https://doi.org/10.1016/j.ijheatmasstransfer.2021.105177

Khan, N. S., Gul, T., Islam, S., & Khan, W. (2018). Thermophoresis and thermal radiation with heat and mass transfer in a magnetohydrodynamic thin-film second-grade fluid of variable properties past a stretching sheet. (2017). *The European Physical Journal Plus*, 132(1), 11 pages. https://doi.org/10.1140/epjp/i2017-11277-3

Khan, N. S., Islam, S., Gul, T., Khan, I., Khan, W., & Ali, L. (2018). Thin film flow of a second grade fluid in a porous medium past a stretching sheet with heat transfer. *Alexandria Engineering Journal*, 57(2), 1019–1031. https://doi.org/10.1016/j.aej.2017.01.036

Khan, N. S., Kumam, P., & Thounthong, P. (2019). Renewable energy technology for the sustainable development of thermal system with entropy measures. *International Journal of Heat and Mass Transfer*, 145, 118713. https://doi.org/10.1016/j.ijheatmasstransfer.2019.118713

Khan, Z., Rasheed, H. U., Alkanhal, T. A., Ullah, M., Khan, I., & Till, I. (2018). Effect of magnetic field and heat source on Upper-convedcted-maxwell fluid in a porous channel. *Open Physics*, 16(1), 917–928. https://doi.org/10.1515/physp-2018-0113

Katresh, M. J., Ramesh, G. K., Shashikala, V. K. R., & Prasannakumar, B. C. (2020). Assessment of Arrhenius activation energy in stretched flow of nanofluid over a rotating disc. *Heat Transfer, 2011*, 1–22. https://doi.org/10.30024/htr.22006

Kuznetsov, A. V., & Nield, D. A. (2014). Natural convective boundary layer flow of a nanofluid past a vertical plate: A revised model. *International Journal of Thermal Sciences*, 77, 126–129. https://doi.org/10.1016/j.ijthermalsci.2009.07.015

Madhu, M., Kishan, N., & Chamkha, A. J. (2017). Unsteady flow of a Maxwell nanofluid over a stretching surface in the presence of magnetohydrodynamic and thermal radiation effects. *Propulsion and Power Research*, 6(1), 31–40. https://doi.org/10.1016/j.jppr.2017.01.002

Makinde, O. D., & Aziz, A. (2011). Boundary layer flow of a nanofluid past a stretching sheet with a convective boundary condition. *International Journal of Thermal Sciences*, 50, 1326–1332. https://doi.org/10.1016/j.ijthermalsci.2011.02.019

Mooakher, P. G., Abbasi, M., & Khaki, M. (2016). Fully developed flow of fourth grade fluid through the channel with slip condition in the presence of a magnetic field. *Journal of Applied Fluid Mechanics*, 9 (5), 2239–2245. https://doi.org/10.18869/acadpub.jafm.68.236.24689

Motso, S. S., Khan, Y., & Shateyi, S. (2012). A new numerical solution of Maxwell fluid over a shrinking sheet in the region of a stagnation point. *Mathematical Problems in Engineering*, 290615, 11 pages. https://doi.org/10.1155/2012/290615

Mukhopadhyay, S. (2012). Heat transfer analysis of the unsteady flow of a Maxwell fluid over a stretching surface in the presence of a heat source/sink. *Chinese Physics Letters*, 29(5), 523–530. https://doi.org/10.1088/0256-307X/29/5/054703

Mukhopadhyay, S., & Bhattacharyya, K. (2012). Unsteady flow of a Maxwell fluid over a stretching surface in the presence of chemical reaction. *Journal of the Egyptian Mathematical Society*, 20(3), 229–234. https://doi.org/10.1016/j.joems.2012.08.019

Mukhopadhyay, S., Ronjan, P., & Layek, G. C. (2013). Heat transfer characteristics for Maxwell fluid flow past an unsteady stretching permeable surface embedded in a porous medium with thermal radiation. *Journal of Applied Mechanics and Technical Physics*, 54(3), 385–396. https://doi.org/10.1134/S0021894413030061

Ogunseye, H. A., Salawu, S. O., Tijani, Y. O., Riliwan, M., & Sibanda, P. (2019). Dynamical analysis of hydromagnetic Brownian and thermophoresis effects of squeezing Eyring–Powell nanofluid flow with variable thermal conductivity and chemical reaction. *Multidiscipline Modeling in Materials and Structures*, 15(6), 1100–1120. https://doi.org/10.1108/MMMS-01-2019-0008

Reddy, M. G., Kumar, N., Prasannakumar, B. C., Rudraswamy, N. G., & Kumar, K. G. (2021). Magnetohydrodynamic flow and heat transfer of a hybrid nanofluid over a rotating disk by considering Arrhenius energy. *Communications in Theoretical Physics*, 73(4), 045002. https://iopscience.iop.org/article/10.1088/1572-9494/abd0a5

Salawu, S. O., Hassan, A. R., Abolarinwa, A., & Oladejo, N. K. (2019). Thermal stability and entropy generation of unsteady reactive hydromagnetic Powell-Eyring fluid with variable electrical and thermal conductivities. *Alexandria Engineering Journal*, 58(2), 519–529. https://doi.org/10.1016/j.aej.2019.05.004

Salawu, S. O., Odenu, R. A., & Ohaegbue, A. D. (2020). Thermal runaway and thermodynamic second law of a reactive couple stress hydromagnetic fluid with variable properties and Navier slips. *Scientific African*, 7, e00261. https://doi.org/10.1016/j.sciif.2019.e00261

Salawu, S. O., & Ogunsaye, H. A. (2020). Entropy generation of a radiative hydromagnetic Powell-Eyring chemical reaction nanofluid with variable conductivity and electric field loading. *Results in Engineering*, 5, 100072. https://doi.org/10.1016/j.rineng.2019.100072
Salawu, S. O., Oladejo, N. K., & Dada, M. S. (2019). Analysis of unsteady viscous dissipative poiseuille fluid flow of two-step exothermic chemical reaction through a porous channel with convective cooling. Ain Shams Journal of Engineering, 10(3), 565–572. https://doi.org/10.1016/j.asej.2018.08.006

Saleem, S., & Abd El-Aziz, M. A. (2019). Entropy generation and convective heat transfer of radiated non-Newtonian power-law fluid past an exponentially moving surface under slip effects. European Physical Journal Plus, 134, 184–196. https://doi.org/10.1140/epjp/i2019-12656-4

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