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# MHD heat and mass transport of Maxwell Arrhenius kinetic nanofluid flow over stretching surface with nonlinear variable properties

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Introduction

ABSTRACT

The study of nonlinear radiation and mixed convection of the MHD heat and mass transfer of Maxwell nano liquid flow in porous media with Arrhenius kinetic reaction is examined. The non-Newtonian fluid is charac terized by Maxwell model, and the species molecular mixture is inspired by the Arrhenius pre-exponential kinetics. Reaction mixture occurs in a boundless slippery plate subject to a considerable quantity of tension that can prevent material deformity. With appropriate similarity variables, the flow model reduces to quasilinear coupled system of derivatives. A numerical simulation of the flow characteristics is carried out, and the results presented in tables and graphs for various thermodynamic phenomena. The results show that the flow momen tum is damped by the material term, but augmented by nonlinear heat convection and radiation. The heat transfer rate is significantly propelled by temperature ratio and viscous heating, while the Lewis number, molecular Brownian motion and the chemical reaction term encourage species mass transfer. As such, the study involving activation energy plays a critical part in the diffusion of binary chemical mixtures of energy and spe cies transport which will assist the chemical engineering and others in their activities to prevent reaction blowup.

well fluid, micropolar fluid, Casson fluid, Williamson fluid, tangent hyperbolic fluid, Eyring-Powell, etc. Maxwell fluid belongs to the rate

The unquantifiable and unparalleled engineering alongside indus trial applications derivable from the investigations of non-Newtonian fluids have made them to become a sought-after by engineers, scien tists and researchers. The occurrence of these applications is common in food processing, biological fluid transport, oil drilling, manufactur ing of drugs and pharmaceuticals, paint rheology, to mention a few [1,2]. Distinct from the linear relationship of shear stress and rate exhibited by the Newtonian fluids, the constitutive equations of non- Newtonians fluids are usually complex and complicated due to the existence of a nonlinear association between the shear rate and the shear stress, Hassan et al. [3]. More so, the existence of shear thin ning/thickening properties, tendency to yield stress and prediction of stress relaxation behaviour of these fluids often lead to a birth of highly nonlinear equations from them. To effectively capture the var ious attributes of the non-Newtonian fluids, several theories and mod els have been publicized to describe their flow owing to the disparate nature of fluid characteristics [4,5]. For instance, there exists the Max

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type fluids, its popularity among others is due to its simplicity and ten dency to predict stress relaxation coupled with its enormous usefulness in engineering and industrial works especially in polymer fields. Rele vant information on Maxwell fluid can be found in the investigations of [6–9].

Over the years, engineers and scientists have battled with the prob lem of low thermal conductivity and the consequent weak heat trans fer coefficients offered by the convectional fluids (e.g. water, oil, ethylene glycol, etc.) since the effectiveness of thermal systems and appliances are connected to heat transfer rates. However, Choi [10] discovered and proved that the much needed higher conducting liquid suitable for enhancing the cooling system in most engineering and industrial devices can be achieved by the composition of nanometer-sized particles (made of metals, oxides, carbides, or carbon nanotubes, etc.) and the traditional heat transport fluids. Nima et al [11] reported that, such a blend leads to a greater conducting heat transport liquid with significant applications in transportation, electronics and phar




maceutical industries, biomedicine, power manufacturing and atomic reactors, etc. Researches have shown that nanofluids heat absorption capacity is much greater than those of ordinary fluids and the thermal conductivity has been found to rise up to 40% [6] based on the geom etry, size, and thermal characteristics of the solid nanomaterials, East man et al. [12]. Subject to these critical applications, different thermophysical properties of nanofluids have been examined by vari ous scholars as found in Refs [13–16] and their cited references.

The understanding of radiative heat transport mechanism is non-negotiable in the fields of solar power technology, fossil fuel combus tion, nuclear reactor cooling, power generation, etc. This knowledge is much needed to build advanced energy conversion devices operating at high temperatures, Salawu et al. [17]. In the existence of large tem perature difference between the sheet and surrounding, it becomes imperative to apply the nonlinear thermal radiation model as against the linear model which is suitable for low temperature differences. Such a phenomenon was investigated through microwave heating by Oke et al. [18]. Fatunmbi and Adeniyan [19] engaged micropolar fluid to scrutinize such a concept, whereas Kumar et al. [20] worked on the transport of Carreau nanofluid, while Pal et al. [21] reported such a subject on Jeffrey nanofluid along a stretchable sheet. Also, Okedoye and Salawu [22] examined the impact of nonlinear radiation on a spe cies and heat transport over a moving surface with variable properties. It was reported that the temperature distribution is discouraged with rising thermal radiation.

The previously mentioned investigations above were conducted under a steady case assumption, however, unsteady cases do arise due to an impulsive movement of the stretching sheet. Akinbobola and Okoya [23] studied the flow of second grade liquid with variable properties and heat source past a stretching plate. An abrupt change in either the surface/ambient velocity as well as temperature and concen tration can result in an unsteady situation and at such occasions, the transport mechanisms assume unsteadiness behaviour. To this end, Ogunmilade and Okoya [24] presented unsteady closed form solutions of Maxwell unidirectional flow liquid. It was observed that a Newto nian fluid is obtained when kinematic viscosity is one and relaxation time is zero. Mukhopadhyay et al. [25] numerically discussed the flow of Casson fluid along an unsteady stretched sheet under a prescribed wall temperature. It was mentioned that the unsteadiness parameter caused both velocity and temperature profiles to shrink. Ahmad and Nazar [26] deliberated on MHD time-dependent mixed convective transport of viscoelastic fluid past a vertical stretchable surface. Madhu et al. [6] explored unsteady stretching sheet flow of a mixture of Maxwell fluid and nanoparticles with radiation impact and reported on a decline in the skin friction coefficient with unsteadiness term. Ullah et al. [27] incorporated the impact of chemical reaction on such a concept and declared an uplift in the wall shear stress and heat trans port with a hike in the unsteadiness parameter. Other contributions on this concept can be obtained in Refs [28–30] and the cited references.

Mixed convection flow describes the combined free and forced con vection which has significant contributions in diverse industrial and engineering operations including lubrication and drying processes, solar collectors, nuclear reactors, cooling of electronic appliances by fans, heat exchangers mounted in a low-velocity position, etc., [31,32]. In most of these operations, the density has been found to alter with temperature/concentration, Thriveni and Mahanthesh [33]. More so, the assumption of linear density variation with temper ature (LDT) or concentration (LDC) in the buoyancy force term has

of a Newtonian fluid in a porous medium was carried out by Prasad et al. [37]. Mandal and Mukhopadhyay [35] carried out such investi gations with micropolar fluid and radiation effect, while Ibrahim and Makinde [34] recently conducted such a research with Eyring-Powell fluid along a nonlinear stretchable sheet. However, none of these stud ies have conducted on an unsteady fluid flow the impact of nonlinear thermal radiation, chemical reaction coupled with activation energy which the current intends to investigate.

In view of the above analysis, no investigation has been carried out on the combined effect of nonlinear mixed convection and radiation for a Maxwell nanomaterial under Arrhenius kinetic. The study involv ing activation energy and chemical Arrhenius kinetics plays a critical part in the diffusion of binary chemical mixtures of energy and species transport which will assist the chemical engineering and others in their activities to prevent reaction blowup. Hence, the particular concern of the current study is to examine an unsteady flow, heat and mass trans port of Maxwell Arrhenius kinetic nanofluid past a permeable sheet with respect to quadratic density temperature and concentration, non linear radiation and mixed convection, thermophoresis and Brownian movement in a porous device an extension of the study by [6,40]. The usefulness of Maxwell Arrhenius kinetic nanofluid in industrial advancement and previous related suggestions and reports has moti vated the present investigation. This study is significance to the ther mal sciences, industrial chemical production, polymer extrusion, biomedical device and treatment, technological advancement and many more in enhancing the thermal conduction and heat convection. Going by the literature analyzed above, no such study has been posted and investigated before in the present form to the authors knowledge. The computed values obtained from selected parameters are in confor mity with existing results in the literature in the limiting situations while tables and graphs have been constructed and discussed to dis seminate the reactions of the dimensionless quantities.

## The flow mathematical setup

Consider a laminar, upper convected Maxwell magneto-nanofluid flow in porous media subject to nonlinear buoyancy force acted in the z-direction and non-constant perpendicularly applied magnetic field B ¼ B0ffiffiffiffiffiffiffiffiffiffi p (see [13]). The resting free stress of the conducting 1 βt fluid creates an impulsive sheet stretched on the device. The reactive molecular mixture is stimulated by Arrhenius kinetic with nonlinear radiation and dissipation in a stretching device moving with varying velocity Uðx; tÞ ¼ ax

1 βt (see [13]), where a and β are non-negative constants. The transient liquid, energy and concentration moves out of slit origin ðx ¼ 0; y ¼ 0Þ at t ¼ 0 in the x-direction with y-axis normal to it under the influence of chemical kinetic and increasing plate slip rate a

1 βt (see [6]). With very low Reynolds number and absence of electric filed, charges polarization of electric field is neglected. Considerable amount of tension is applied to the stretching porous sheet to prevent material structure deformation. The base fluid is induced with nanoparticles through surfactant to prevent nanoparticles agglomera due to its effects on the

tion with temperature and/concentration transport fields. For instance, the flow confined between two parallel sheets with quadratic density variation with temperature was reported by Vajravelu and Sastri [36], whereas a nonlinear convective transport been found to be unrealistic when high temperature difference exists between the material surface and the ambient [34,35]. In this view, researchers have been compelled to study the nonlinear density varia tion along the porous medium. The flow schematic coordinate diagram is presented in Fig. 1.

In components form, based on the given assumptions, the boundary layer flow equations are taking as [6,38,39] and the flow characteristic solutions are obtained in the Cartesian coordinateðx; y; zÞ

@u
@x þ@v
@y ¼ 0; ð1Þ

@u
@t þ u @u
@x þ v @u
@y ¼ μ ρf @2u
@y2 σB2 0u
ρf γ u2 @2u
@x2 þ 2uv @2u
@x@y þ v2 @2u
@y2 μu
ρf Kr þ g
ρf ε1ðT T1Þ þ ε2ðT T1Þ2 þ ε3ðC C1Þ þ ε4ðC C1Þ2 ;ð2Þ

2

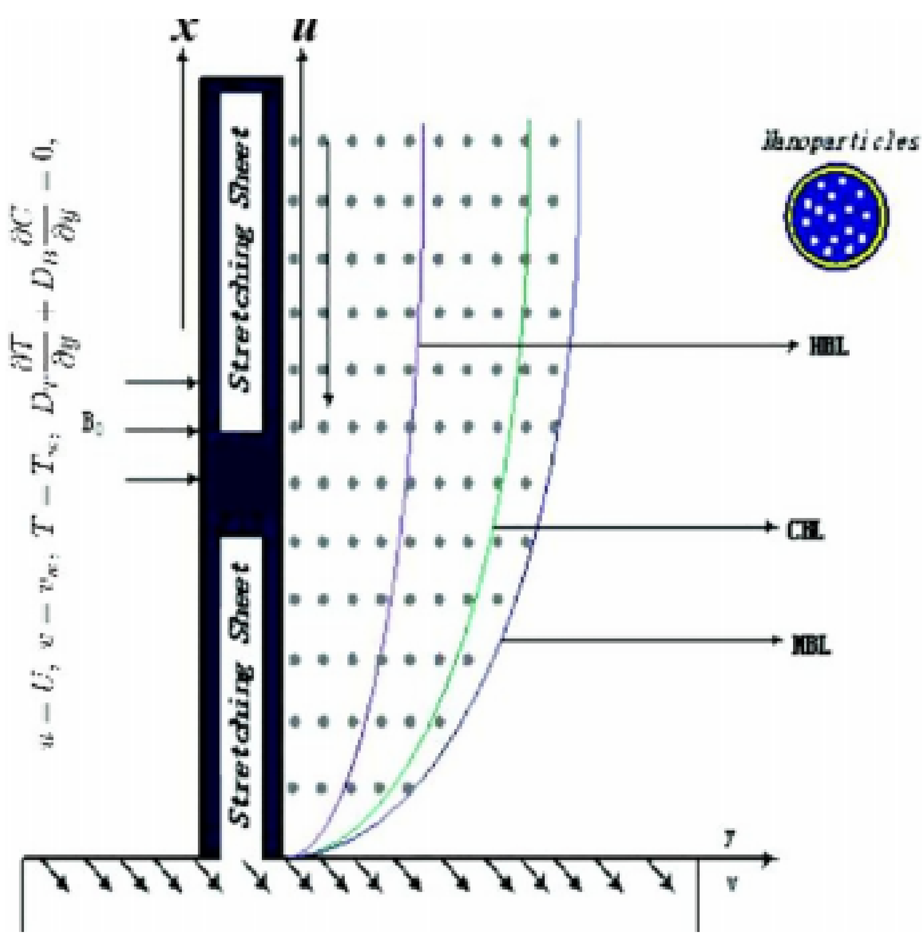



Fig. 1. Flow schematic coordinate.

@T
@t þ u @T
@x þ v @T
@y ¼ αf @2T
@y2 þ μ 2 4σ0 2 þ χ DB @T
@y þ DT

Cwðx; tÞ ¼ C1 þ axð1 βtÞ 2 respec
Twðx; tÞ ¼ T1 þ axð1 βtÞ 2

ð Þ ρc p f@u @y

@C
@y

$T_1$
@T @y

is negative (positive), then $C_w$ðx; tÞ and ð3Þ

$T_w$ðx; tÞ decreases

(increases). Here, $v_w$ðtÞ ¼ ν0ffiffiffiffiffiffiffiffiffiffiffi p defines the injection

tively (see [6]). When a
@y

1
ρc p f
@
3φ 4T3 @T
;

$v_w$ðx; tÞ, $C_w$ðx; tÞ, $T_w$ðx; tÞ and Uðx; tÞ satisfied t < β 1.

1 βt
ð$v_0$ < 0Þ or suction ð$v_0$ > 0Þ.
The expansion for γðtÞ,
transformation similarity

m

@C
@y ¼ $D_B$@²C
Adopting the following established local

@tþ u @C

@x þ v@C ðC C1Þexp Er kT @T
@y² C²r T T1 þDT T1 @y² ;
ð4Þ

Madhu et al. [6] as variables and stream function ψ used by
i
ffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffi av

the subjected boundary conditions are taken as Kuznetsov and Nield [40]

ϕ ¼ C C1
$C_w$ C1; θ ¼ T T1
$T_w$ T1; ψ ¼

¼ @ψ
@x ; u ¼ @ψ
r
ν xfðηÞ; η ¼
1 βt

r
ffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffiffi a
yν
ð1 βtÞν

(5) to dimensionless form as obtained

u ¼ U; v ¼ $v_w$; T ¼ $T_w$;$D_T$ @T
@y þ $D_B$ @C
@y ¼ 0; aty ¼ 0

u ! 0; T ! T1; C ! C1; asy ! 1: ð5Þ

f² ff00 þ A f0 þ η 2 f00 Λ 2ff0f00 f²f000
¼ f000 ð Þ P þ M f0þ Grf g θð Þþ 1 þ φtθ ϕð Þ 1 þ φcϕ ; ð7Þ f0θ þ A 2
4θ þ ηθ0 ð Þ f θ0

where C and T are species nanoparticle volume fraction and temperature, C1 and T1 are the far flow species and temperature, v and u are the Cartesian components of velocity. The terms σ, $D_B$, $B_0$, $σ_0$, $K_r$, $α_f$, φ, $ρ_f$, $D_T$, μ, $c_p$, g, γ and χ ¼ ðρcpÞp ðρcfÞf are consequentially the electric conductivity, Brownian diffusion, magnetic strength, Stefan-Boltzmann constant, porosity, thermal conductivity, coefficient absorption mean,

nanofluid density, thermophoretic diffusion, fluid viscosity, heat capacity, gravity, Maxwell and capacities ratio. The terms $E_r$, m, k and $C_r$ represent the activation reaction energy, Arrhenius kinetic exponent, Boltzmann constant and branched-chain reaction. Meanwhile, $ε_1$; $ε_2$

¼ 1 Prθ00 þ R Pr 3ð Þ θr 1 θ²ðð Þ θr 1 θ þ 1Þ²þðð Þ θr 1 θ þ 1Þ³θ00 h i

ð8Þ

@y : ð6Þ

With appropriate simplification, similarity variables of Eq. (6) with the flow assumptions are used to transform the dimensional Eqs. (1)–

þEcf 2 þ Nbθ0ϕ0þ Ntθ²;

and $ε_3$; $ε_4$ are the nonlinear/linear thermal and mass expansion. The last term in the energy equation defines nonlinear radiation taken from Rosseland approximation according to [22,29]. The Maxwell nanofluid concentration $C_w$ðx; tÞ and surface temperature $T_w$ðx; tÞ are taken to vary in time along the plate as

ϕ00 Le f0ϕ þ A 2 4ϕ þ ηϕ0 ð Þ fϕ0 Nb θ00
ð9Þ
þNt
Leλð1 þ θcθÞm exp E 1 þ θcθ ϕ ¼ 0





subject to the dimensionless boundary conditions

f0 ¼ 1; f ¼ f w; θ ¼ 1; Ntθ0 þ Nbϕ0 ¼ 0; at η ¼ 0

f0 ! 0; θ ! 0; ϕ ! 0; as η ! 1: ð10Þ
h0 1 ¼ h2 ð13Þ h0 2 ¼ h3 ð14Þ

þ h1h3

h0 3 ¼ Gr hf g 4ð Þþ 1 þ φth4 ϕð Þ 1 þ φch6 ð Þ P þ M h2 þ 2Λh1h2h3 h² 2 A h2 þ η 2 h3

1 Λf² —; ð15Þ

h0 4 ¼ h5 ð16Þ h0 5 ¼ 3 R Pr ðθr 1Þh² 5ððθr 1Þh4 þ 1Þ² þ h1h5 A 2 ð Þ 4h4 þ ηh5 h2h4 þ Ech² 3 þ Nbh5h7 þ Nth² 5

Pr 1 þ R ð Þ θr 1 h4 þ 1 3 ____; ð17Þ 1

term M ¼ σB² 0

where Prandtl number Pr ¼ ν αr, porosity term P ¼ νð1 βtÞ aKr, magnetic

ρf a, Maxwell term Λ ¼ aγ
h0 6 ¼ h7 ð18Þ

ð1 βtÞρf, relative temperature
T1, Eckert number Ec ¼ μx²a² ð$T_w$ T1ÞνðρcpÞf, unsteady term A ¼ β a,

Nt

h0 7 ¼ Le h2h6 h1h7 þ A 2 ð Þ 4h6 þ ηh7 Nb h0 5
θc ¼ T $T_w$ T1

injection/suction term f w ¼ v0ffiffiffiav p , radiation term R ¼ 4T3 1σ0

3vkf , Brownian motion Nb ¼ D BχðCw C1Þ v , temperature ratio θr ¼ T w T1, Lewis number

Le ¼ v DB, activation energy term E ¼ Er kT1, chemical reaction term

λ ¼ C2r a , thermophoresis term Nt ¼ D T χðTw T1Þ T1v , Grashof number Gr ¼ gε1

aρf,

vection φc ¼ ε4 ε3ðCw C1Þ.

ε1ðTw T1Þ and nonlinear mass con

þ Leλð Þ 1 þ θch4 exp E 1 þ θch4 h6; ð19Þ

nonlinear heat convection φt ¼ ε2

with reference to the boundary conditions

h2ð0Þ ¼ 1; h1ð0Þ ¼ f w; Nth5ð0Þ þ Nbh7ð0Þ ¼ 0; h4ð0Þ ¼ 1; h2ð1Þ ¼ 0; h4ð1Þ ¼ 0; h6ð1Þ ¼ 0: ð20Þ

The reduced reference initial conditions of equation (20) is solved

The physical quantities for the engineering practical and usefulness are the local wall friction $C_f$, temperature gradient $Nu_x$ and concentra tion gradient $Sh_x$. The dimensionless form of these quantities are respectively expressed as follows

$C_f$ ¼ 0:5Re 0:5 x f''ð0Þ; Nux

x 1 þ 4R 3 ððθr 1Þ þ 1Þ3 ¼ θ0ð0Þ; Shx ¼ Re0:5 x ϕ0ð0Þ; ð11Þ

2Re0:5

where local Reynolds number $Re_x$ ¼ Ux v .

## Special cases

This investigation corresponds to Devi et al [44] without thermal and mass transport in which P ¼ M ¼ 0. For a steady fluid flow with linear radiation and convection, the present study reduces to Nadeem et al [7] when Arrhenius kinetics and porosity are neglected. Without gyrotactic microorganism, for a Maxwell fluid, this study satisfied the analysis reported by Khan et al [39] when Ec ¼ P ¼ $\theta_r$ ¼ R ¼ A ¼ 0. Without Maxwell fluid, nonlinear variable properties, when M ¼ P ¼ 0, the current study is equivalent to Mustaf et al. [45] For unsteady flow, in the absence of nonlinear radiation, mixed convection and exothermic reaction terms, the study resulted to Madhu et al [6] in a stretching surface. For a nanofluid, [46,47] studies resulted to the present without nonlinear radiation, porosity, Maxwell and mixed convection.

## Solution techniques

The solution technique adopted for the study is Nachtsheim-Swigert shooting technique. The method is used to reduce the bound ary value Eqs. (7)–(10) to initial value problem. A satisfying finite val ues for the free stream η→∞ is assumed. The main dimensionless coupled nonlinear derivatives are presented as follow in first order form:

h

1

¼

f

along with the first order translated Eqs. (13) to (19). The initial guess values of the unknown points are taken for the computation. With step length rη ¼ 0:0001, a Runge-Kutta Fehlberg method is used to com pletely obtain solutions to the problem. The solution procedures is adopted due to coupled nonlinear nature of the equations as well as the consistence, stability and convergence of the methods.

## Results and discussion

;
h
2
¼
f
0
;
h
3
¼
f
0
0
;
h
4
¼
θ
;

h
5
¼
θ
0
;
h
6
¼
ϕ
;
h
7
¼
ϕ
0
;
ð
1

2

Þ

4

The sensitivity of the flow characteristics to variation in the ther mophysical terms is presented in tables and graphs for clear under standing of the obtained results. Based on previous theoretical analysis by different scientists, the parameter values were chosen. The default values are Λ ¼ 0:2, $\theta_c$ ¼ 0:1, $\theta_r$ ¼ 0:2, A ¼ 1, $\varphi_t$ ¼ 2, $\varphi_c$ ¼ 2, M ¼ 0:5, P ¼ 0:2, m ¼ 1, Pr ¼ 7:0, R ¼ 0:5, Le ¼ 0:2, E ¼ 0:2, Ec ¼ 0:3, λ ¼ 0:2, Gr ¼ 0:5, $f_w$ ¼ 0:1, Nt ¼ 0:5, Nb ¼ 0:5 except otherwise indicated on each plot. In Tables 1 And 2, the numer ical results are compared with the works of [6,41–43]. The quantita tive results are found to agree well with existing ones, this proved the validity of the numerical method used. Meanwhile, Table 3 depicts the wall shear, temperature gradient and species mass gradient for dif ferent parameters. As seen, some terms have an increasing or a decreasing effect on the various wall quantities as demonstrated in the table.

The plot depicting the velocity distribution as a reaction to an increasing value of the terms Maxwell ðΛÞ, Magnetic ðMÞ and porosity ðPÞ are respectively offered in Figs. 2–4. At different significance, the parameters reduces the magnitude of the velocity field. This is because of the lost of influence by the exothermic Arrhenius kinetic that damped the activation energy and internal heating of the non- Newtonian reaction, as such, the fluid shear stress and friction are encouraged that in turn diminishes the flow velocity profiles. Hence, the parameters will assist in enhancing the fluid viscosity that support the industrial usages of the nanofluid. The parameters impact is very momentous in Figs. 3 and 4 due to the respective rise in the induced Lorentz force and increasing flow medium pore that opposed free Max



Table 1

Comparison values for f00ð0Þ for A when Gr ¼ $f_w$ ¼ M ¼ P ¼ Ec ¼ 0 and λ ¼ 0.

| A | Sharidan et al. [41] | Chamkha et al. [42] | Mukhopadhyay et al. [43] | Present results |
|---|---|---|---|---|
| 0.8 | −1.261042 | −1.261512 | −1.261512 | −1.2613217 |
| 0.2 | −1.377722 | −1.378052 | −1.377850 | −1.3778426 |

Table 2

Comparison of values for θð0Þ and ϕð0Þ when.P ¼ Gr ¼ Ec ¼ $\theta_1$ ¼ λ ¼ 0.

Madhu et al. [6] Present study

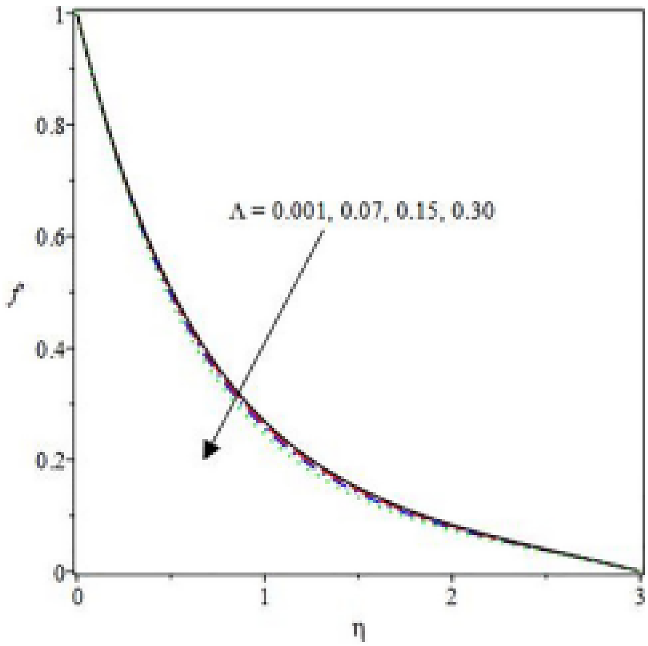
Pr R Le Nt Nb θ0ð0Þ ϕ0ð0Þ θ0ð0Þϕ0ð0Þ 0.71 1.0 5.0 0.1 0.1 0.459556–0.42468 0.459548–0.42463 1.0 0.574585–0.53229 0.574577–0.53228 1.0 0.899109–0.83710 0.899101–0.83709 1.0 1.157080–1.08057 1.157080–1.08056

Table 3

Numerical results for the wall impact with f00ð0Þ, θ0ð0Þ and. ϕ0ð0Þ

A R Gr Ec Nb M P f00ð0Þ θ0ð0Þ ϕ0ð0Þ

1.0 0.5 0.3 0.3 0.5 1.0 0.5 −1.422407694 1.3645050849 −1.3645050849 0.0 −0.598095077 0.7709636031 −0.7709636031 0.4 −1.224834806 1.0491754914 −1.0491754914 1.0 −1.423810455 1.4048971802 −1.4048971802 2.0 −1.425946329 1.481900024 −1.4819000246 0.5 −1.264225865 1.3858827946 −1.3858827946 0.7 −1.108698892 1.4053936378 −1.4053936378 1.0 −0.579260028 1.1271696441 −1.1271696441
2.0 −1.382077499 0.8056170068 −0.8056170068
1.0 −1.423948356 1.3643669009 −0.6821834505
1.5 −1.423391863 1.3644028700 −0.4548009567
0.5 −1.422407694 1.3645050849 −1.3645050849
1.5 −1.725422511 1.3162084359 −1.3162084359
1.0 −1.668749053 1.3251407959 −1.3251407959
2.0 −1.937051701 1.2832637131 −1.2832637131



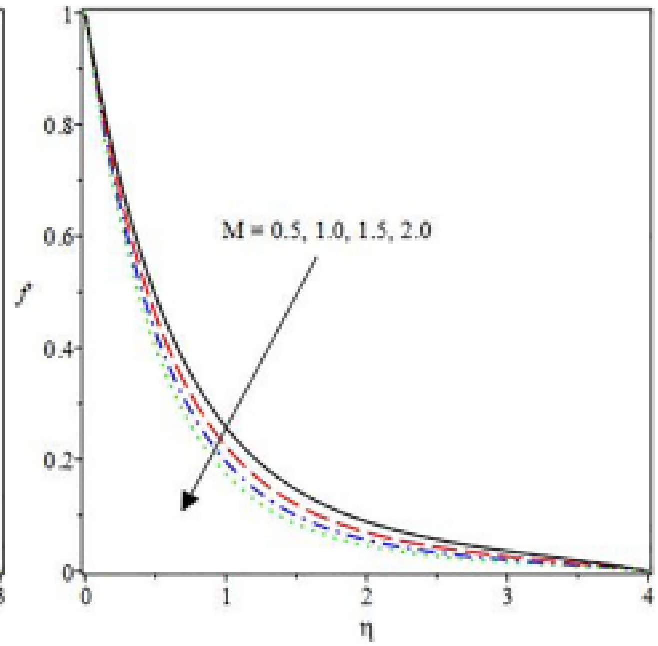
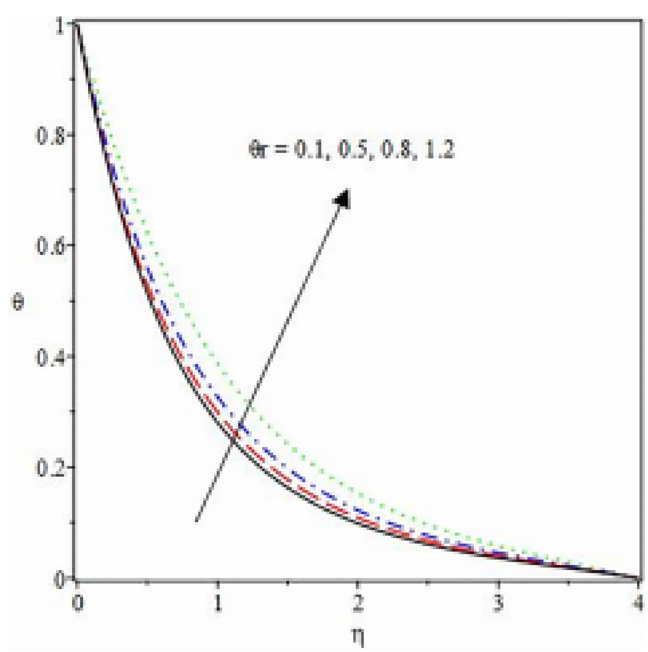




Fig. 2.
Velocity distribution for various Λ. Fig. 3. Velocity profile for different M.

well nanofluid flow in a stretching surface. The effect is significant to the chemical and the lubricant oil industry in improving the perfor mance of their products. Meanwhile, in Fig. 2, due to low Maxwell shear stress effect, parameter values variation of the term ðΛÞ is not too significant due to low impact of activation energy and chemical kinetics. However, the impact of the variation in the values of convec





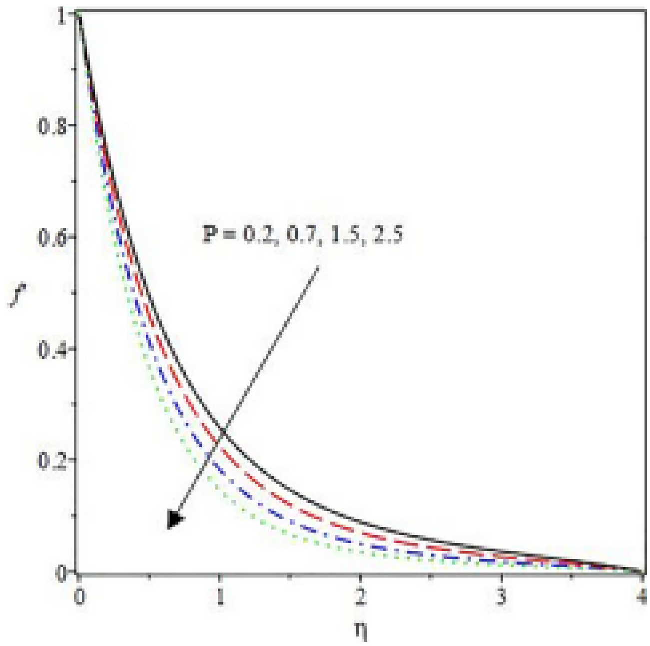



Fig. 4. Plot of f0ðηÞ against η for diverse P.

Fig. 6. Impact of rising $\theta_r$ on heat field.

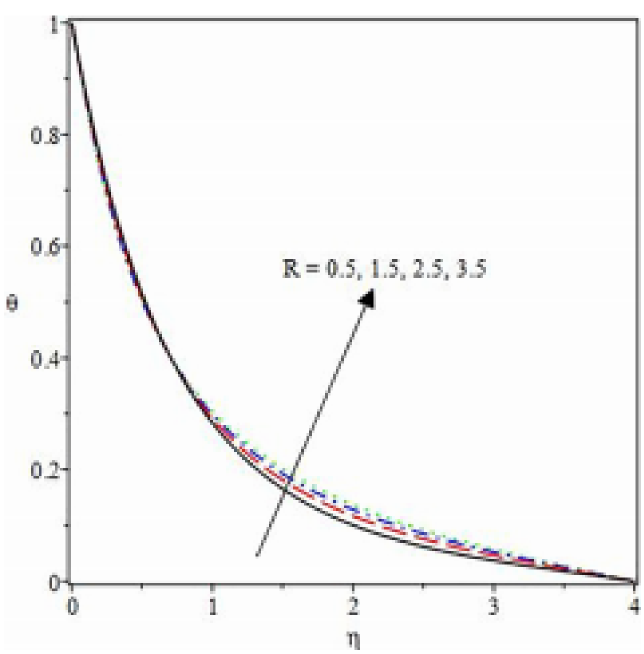
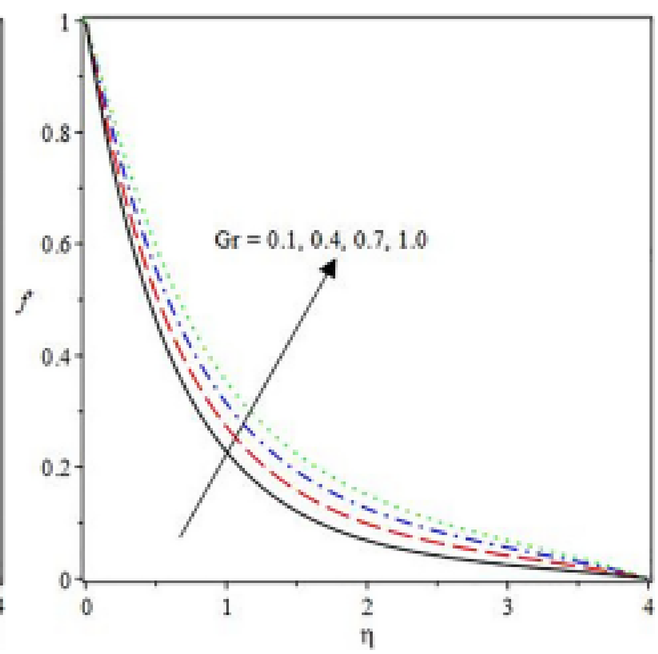



Fig. 5. Velocity field for various Gr.

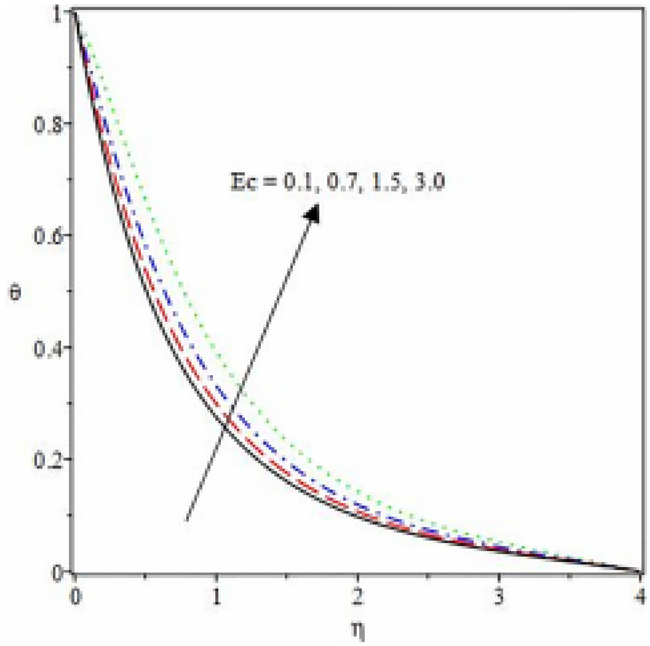



tive heat Grashof number ðGrÞ on the combined liquid material flow rate are correspondingly offered in Fig. 5. The nonlinear mixed con vection buoyancy terms increase the liquid reaction velocity by raising the internal exothermic reaction heating and reduces fluid viscosity, this thereby allows free molecular reaction diffusion that resulted in upward exerts force on the velocity field magnitude. Therefore, bulk heat transfer of the molecular diffusion dominates the system that causes fluid thermal expansion, thereby influences the fluid density and raises the flow rate as depicted in the plots.

The plot of θðηÞ versus the flow free stream distance ðηÞ are demon strated in Figs. 6–9. The parameters values variation impact on the temperature distribution is significant in magnitude as obtained in the plots. The temperature ratio ð$\theta_r$Þ at the device surface of the adia

Fig. 7. Temperature field for increasing R.

batic temperature wall increases as offered in Fig. 6. The absolute tem perature characteristic rises in magnitude due to an enhance internal heating and activation energy. The increasing impact continue throughout the stretching flow medium as the boundary layer viscosity is inspired to reduce heat dissipation. Steady rise in the energy trans mission through the Maxwell nanomaterial medium is observed in Fig. 7. The radiation ionization is encouraged to ionize the material molecules, atoms and break the chemical bonds, this leads to an increasing exothermic reaction that thereby causes a rise in the tem perature profile. The chmical binary reaction mixture is motivated to stimulate molecular diffusion which leads to an enhanced temperature distribution. Also, in Fig. 8, the enthalpy difference of the boundary layer and its relationship with the flow kinetic energy denoting the





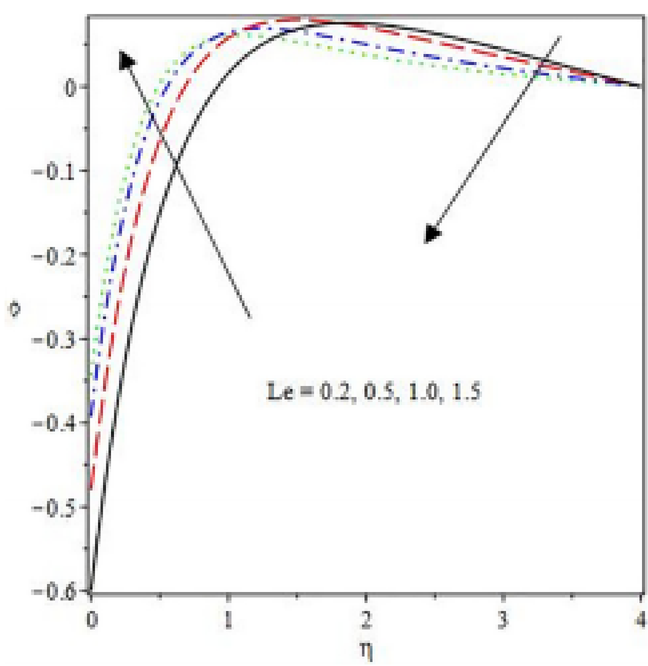




Fig. 8. Temperature profile for various Ec.

Fig. 10. Le on nanoparticle volume fraction.

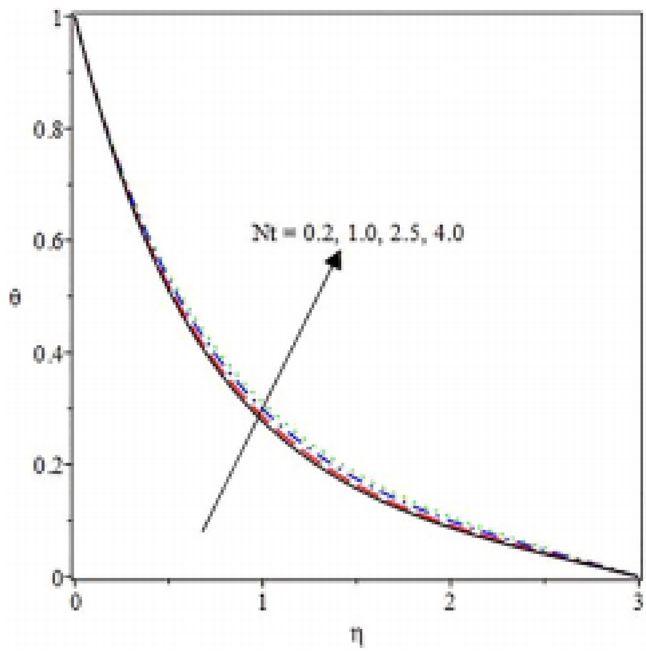



Fig. 9. Variation of Nt on heat field.

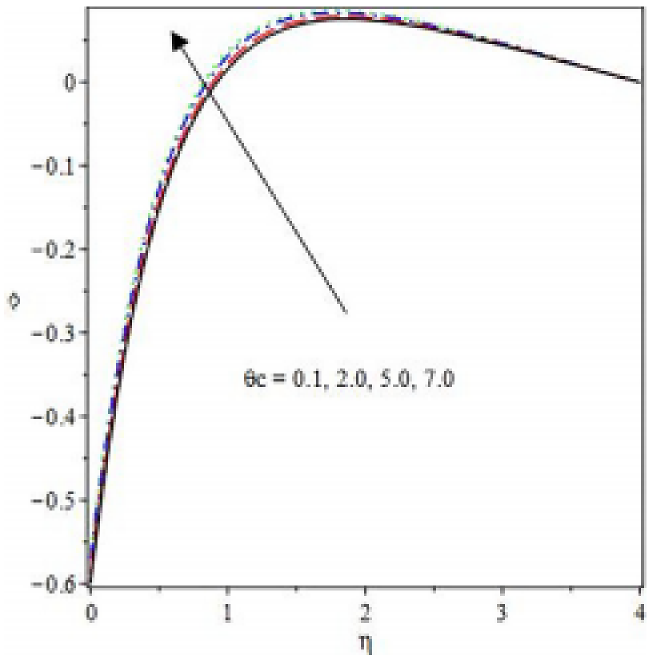


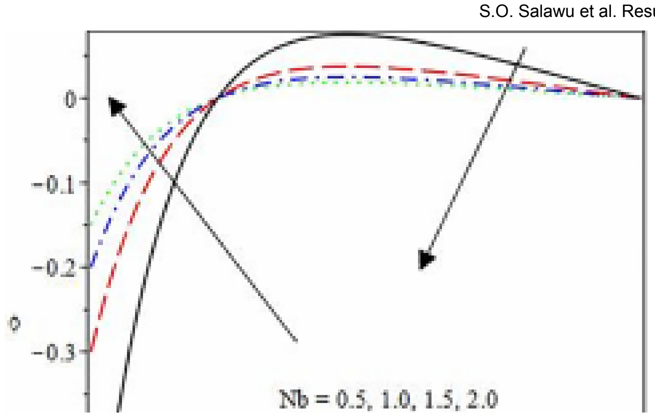

Fig. 11. Nanoparticle volume fraction for.$\theta_c$.

heat dissipation is established. As noticed, an advective transport con trols the non-Newtonian exothermic reaction by significantly increas ing the heat distribution. Hence, energy dissipation occurs at low flow velocity due to neglect pressure changes and body force in the energy equation. In Fig. 9, due to diverse response to the heat gradient by the fluid molecules mobile mixture, the temperature field increases as a result of free fluid particle collision. Therefore, a rise in the ther mophoresis term ðNtÞ raises the fluid phases of matter and enhances fluid mixtures that boost the exothermic heat transfer as observed in the plot. Generally, for chemical reactive species, parameters that encourages temperature distribution must be controlled to mitigate binary mixture blowup of the Maxwell nanofluid.

The sensitivity of the nanoparticle volume fraction field to varying parameter values Le, θc, Nb and Nt are respectively established as Figs. 10–13. The ratio of the temperature to the nanoparticle diffusiv ity (Lewis number) and relative temperature ðθcÞ progressively increase the nanofluid particle volume fraction near the moving wall as the exothermic reaction is propelled by the activation energy to stimulate internal heat. Simultaneously, thermal and mass transfer occurs early of the chemical reaction. However, some distance away from the slippery wall, the species molecular diffusion decreases, thereby enhances the fluid viscosity and friction, as such, the nanopar ticle fractional volume profile damped over the far stream as seen in Figs. 10 and 11. Therefore, chemical diffusion of binary mixture stim








heating. Therefore, the nanoparticle species volume fraction profile is enhanced along the infinite flow stream.

## Conclusion

The study focuses on the transient analysis of heat and species transport of Maxwell magneto-nanomaterial fluid flow through perme able media with nonlinear variable properties in a slippery boundless plate. The flow thermodynamic phenomena are examined for the reac

Fig. 12. Nbon nanoparticle volume fraction.

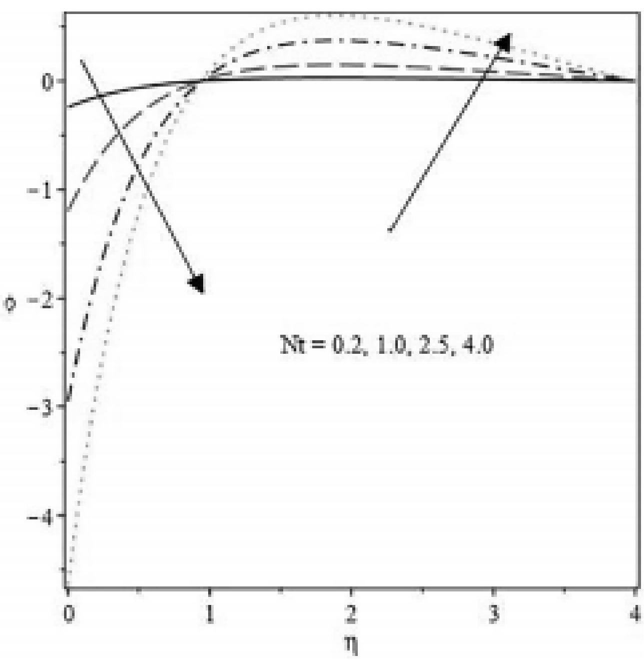



Fig. 13. Nton nanoparticle volume fraction.

ulates reaction criticality which must be protected to avoid Maxwell nanofluid blowup. Fig. 12 depicts the Brownian motion effect on the nanofluid particles transfer. The energy flux as a result of volume frac tion gradient is encouraged close to the motioning surface, this resulted in an exothermic temperature change that boosts the nano molecular fractional volume distribution. But, the concentration field is dragged along the boundless stream due to a reduction in the fluid particle heat transfer that affected the system thermal conduction. On the other hands, in Fig. 13, the thermophoresis reduces the concentra tion near the wall due to the bonding force increment that opposite the volume fraction of the nanoparticle dispersion, but along the bound less stream, the resisting force is dominated by an increase internal

tive molecular species diffusion under Arrhenius kinetics. A numerical computation is carried out on the dimensionless boundary value derivatives. The novelty outcomes of the findings are:

The velocity of the flowing fluid f0ðηÞ is monotonically a diminish ing function along the flow stream η for a rising fluid material, porosity and magnetic terms, but an increasing function for the nonlinear heat convection.

The heat transfer magnitude is encouraged for varying values of the temperature ratio, radiation, Eckert number and thermophoresis parameters. Hence, for thermal science and technological devices, heat transfer rate must be managed for optimal performance of their devices.

The species mass transfer is momentously enhanced by Lewis num ber, relative temperature term and molecular Brownian motion near



the slippery plate, but declines by thermophoresis term. On the wall, there is decrease/increase in the technology quantities (skin friction, heat and mass gradients) as some parameters is varied. The parameter sensitivity of the thermodynamic flow phenomena and the usefulness of Maxwell magneto-nanoliquid have motivated the study. As such, further investigations can be conducted on the chemical mixtures in a cylinder and the thermodynamic second law of the fluid materials.

CRediT authorship contribution statement

S.O. Salawu: Conceptualization, Data curation, Formal analysis, Writing - original draft. E.O. Fatunmbi: Validation, Writing - original draft, Writing - review & editing. S.S. Okoya: Resources, Visualization, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influ ence the work reported in this paper.

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