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Analysis of Reactive Flow of Third-grade Exothermi Chemical Reaction with Variable Viscosity and Convective Cooling

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Authors' contributions

This work was carried out in collaboration among all authors. Authors JFB and MAM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors OAE and TOO managed the analyses of the study. Author OEE managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The study examines incomprssible laminar Poiseuille flow of a non-Newtonian fluid and heat transfer in a cooling convective fixed wall. The third-grade exothermic reactive fluid is stimulated by heat generation, gradient pressure and thermal buoyancy force. The convective exchange of temperature with the ambient takes after Newtons cooling law. Translation of the formulated equations to the non-dimensional form is done using relevance quantities and solutions to the nonlinear equations are provided by employing Weighted residual techniques. The obtained solutions for the flow rate, energy, flow wall friction and temperature gradient are graphically plotted for the reactive flow system. Numerical validation of results in comparison with the presented method of solution is carried out. The results revealed that some parameters which are strong heat generation or source should be consciously guided to avoid reactive solution blow up in the exothermic system.

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1. INTRODUCTION

The science of exothermic reaction is concerned with the characteristics of combustilbe liquids. The study of liquid convection processes in a channel generated a lot of interest due to it applications from engineering and applied scientific point of view. In contemporary technology, different disciplines combine fluid mechanic with conventional discipline. For instance, theory of electromagnetic and fluid dynamics are together studied as magnetohydrodynamics, Hughes and Brighton [1]. Heat transfer of a reactive flow fluid is considered as a problem in the theory of boundary layer and it can be found in some bodily occurrences like nuclear reactor, industrial processes, combustion modeling and so on by [2-4]. From application standpoint, chemical exothermic reaction is essential in pratical such as industrial and technology processes which relies mainly on mathematical models. To predict the behaviour and characteristics of heat transfer of such fluids flowing through a channel accurately, it becomes necessary to study the flow rate and heat fields of the fluid.

The flow behaviour of different liquids as applied in technology and manufacturing processes may not be sufficiently discribed based on the viscous traditional Newtonian formulation. Such processes includes paper products, polyglycols, hydrocarbon oils, muds drilling, suspensions and coating and so on, Salawu and Dada [5]. Investigation of the second law and criticality of hydromagnetic liquid steadily flowing with the effect of a transversely imposed magnetic field with isothermal in a fixed wall was reported by Makinde and Anwar Beg [6]. A study of the effects of Frank-Kamenetskii and viscous heating parameters on thermal ignition of reactive fluids in non-Darcy permeable media as conducted by Makinde [7]. The criticality of a viscous flowing reactive liquid in permeable non-Darcy media with wall cooling by convection was examined by [8,9]. It was reported that a rise in the Biot number enhances the thermal stability and assist in the delaying of the presence of thermal explosion. An investigation into the solutions of a steady state of highly decomposition exothermic explosive material with constant heat distribution in a proportionally heated horizontal wall under Arrhenius, Sensitized and Bimolecular rate of reactions without material intake was carried out by Makinde [10].

In a related study, the continuation of an analytical study of bifurcation of reactive fluid was examined using power series method of solution. The branch chain parameters solutions is used to study the ignition exothermic reaction in a pipe cylinder by Makinde [11]. The technique shows, correctly, the thermal ignition steady state conditions and branches solution for large activation energy. Investigation of the effects of disspation and non-constant viscosity on the reactive exothermic thermal criticality of visco-elastic flow in a pipe cylindrical neglecting reactant consumption was carried out by Ajadi [12]. Okoya [13] examined the effects of heat conductivity and ohmic heating within parallel infinite walls and obtained the critical conditions under hydromagnetic thermal explosion which is in line with previous results. Okoya [14] also determined the transition and thermal explosion for some terms in a viscous reactive, incom-pressible, Couette flow of regular third grade liquid under different reaction rates m. It was reported that the terms that governing the viscoelastic liquid has no influence on the flow momentum and the impact on the heat degeneracy was as well studied. In a related study, Chen [15] confined his attention to the MHD flow and energy transport of viscoelastic liquid over a moving plate, focusing on the impacts of viscous and ohmic Joule heating, heat production, workdone as aresult of distortion and heat emission. In his study, it was established that when liquid injection or suction is enacted on the plate, wall skin coefficient friction may reduces or rises subject to opposition of the magnetic term effect, second order grade fluid and suction/ injection parameter. The reaction flow fluid to heat source term is of significance in the heat damping as reported by Gbadeyan and Hassan [16]. In their study, the effects of heat production internally due to hydromagnetic reactive viscosity in a Couette device is investiagted. Recently, Salawu and Oke [17] examined Poiseuille hydromagnetic reactive liquid flow in a channel where it was obtained and compared the effects of magnetic intensity and heat source on the temperature profiles for the Arrhenius, Bimolecular and Sensitized exponential index. The analysis of second law rates and heat stability of the flow liquid for various kinetics were considered. The flow is taken to be balanced and established in a horizontal isothermal wall.

The present study intend to examine the rate of fluid flow and heat fields, wall friction and temperature gradient for Arrhenius chemical kinetics. The effect of force of buoyancy and thermal production on the reactive flow liquid through a channel as well as the effects of viscoelastic parameter on the flow under Arrhenius chemical kinetics will be investigated. The weighted residual semi analytical method will be adopted in carry out the analysis.

2. MATHEMATICAL FORMULATION

The third-grade isotropic reactive species with varying viscosity fluid in a fixed device is investigated as demostrated in Fig. 1. The viscoelastic effects is caused by non-Newtonian parameter. The flow is induced by kinetics pre-exponential power of Arrhenius law, and it is driven by the gradient pressure and thermal buoyancy force. The flow is along x direction with y -axis perpendicular to it. Convective heat exchange occurs at the surface of the wall with the surrounding .

Neglecting time variation influences, and the viscous reactive fluid consumption, the temeperature and velocity equations according to Salawu and Oke [17] are as presented:

$$-\frac{d\bar{P}}{d\bar{x}}+\frac{d}{d\bar{y}}\left[\bar{\mu}(T)\frac{d\bar{u}}{d\bar{y}}\right]+6\gamma\frac{d^2\bar{u}}{d\bar{y}^2}\left(\frac{d\bar{u}}{d\bar{y}}\right)^2+\rho g\beta(T-T_0)=0, \quad (1)$$

$$k\frac{d^2T}{d\bar{y}^2}+\left(\frac{d\bar{u}}{d\bar{y}}\right)^2\left[\bar{\mu}(T)+2\gamma\left(\frac{d\bar{u}}{d\bar{y}}\right)^2\right]+QCA\left(\frac{KT}{\upsilon l}\right)^m e^{-\frac{E}{RT}}+Q_0(T-T_0)=0, \quad (2)$$

the impose boundary conditions are:

$$\begin{aligned}&\bar{y}=a;\bar{u}=0,-k\frac{dT}{d\bar{y}}=h(T-T_0)\\&\bar{y}=0;\bar{u}=0,k\frac{dT}{d\bar{y}}=h(T-T_0).\end{aligned} \quad (3)$$

Here $\bar{u}$, T, T_0, a, $\bar{P}$, ρ, γ and β are respectively the axial velocity of the fluid, fluid temperature, temperature of the ambient, channel width, fluid pressure, density, material coefficients and expansivity coefficient. The terms E, k, h, Q, Q_0, R, A, C, l, K, m and υ are the activation energy, thermal conductivity, heat transfer coefficient, heat of reaction, heat source, universal gas constant, reaction rate constant, initial species concentration, Planck's number, Boltzmann's constant, numerical exponent and vibration frequency respectively.

The temperature dependent viscosity ($\bar{\mu}$) is defined to be $\bar{\mu}(T)=\mu_0 e^{-\epsilon(T-T_0)}$ where ϵ is the variation viscosity term and μ_0 is the initial dynamic viscosity of the fluid. Using the following dimensionless variables, the following equations are gotten:

$$\begin{aligned}&y=\frac{\bar{y}}{a},u=\frac{\rho a\bar{u}}{\mu_0},\theta=\frac{E(T-T_0)}{RT_0^2},x=\frac{\bar{x}}{a},\mu=\frac{\bar{\mu}}{\mu_0},P=\frac{\bar{P}\rho a^2}{\mu_0^2},G=-\frac{dp}{dx},\alpha=\frac{bRT_0^2}{E},\\&\gamma=\frac{\beta_1\mu_0}{\rho^2a^4},Gr=\frac{\rho^2a^3g\beta RT_0^2}{\mu_0^2E},Q^*=\frac{Q_0T_0^2RKe^{\frac{\epsilon}{RT_0}}}{E^2QAC}\left(\frac{\upsilon l}{kT_0}\right)^m,\lambda=\frac{QCAEa^2}{T_0^2Rk}\left(\frac{kT_0}{\upsilon l}\right)^m,\\&\delta=\frac{\mu_0^3e^{\frac{\epsilon}{RT_0}}}{Q\rho^2a^4AC}\left(\frac{\upsilon l}{kT_0}\right)^m,\gamma=\frac{\beta_1\mu_0}{\rho^2a^4},\epsilon=\frac{RT_0}{E},Bi=\frac{ah}{k}\end{aligned} \quad (4)$$

Introducing the dimensionless quantities of equation (4) into equations (1)-(3) along with the temperature dependent viscosity, the following equations are obtained:

$$G+e^{-\alpha\theta}\frac{d^2u}{dy^2}-\alpha e^{-\alpha\theta}\frac{d\theta}{dy}\frac{du}{dy}+6\gamma\frac{d^2u}{dy^2}\left(\frac{du}{dy}\right)^2+Gr\theta=0, \quad (5)$$

$$\frac{d^2\theta}{dy^2}+\lambda\left\{(1+\epsilon\theta)^m e^{\frac{\theta}{1+\epsilon\theta}}+\delta\left(\frac{du}{dy}\right)^2\left[e^{-\sigma\theta}+2\gamma\left(\frac{du}{dy}\right)^2\right]+Q^*\theta\right\}=0. \quad (6)$$

$$u = 0, \frac{d\theta}{dy} = -Bi\theta at y = 1$$
$$u = 0, \frac{d\theta}{dy} = Bi\theta at y = 0 \quad (7)$$

where $G, Gr, \lambda, \delta, \omega, Bi, \sigma$ and r represent the pressure gradient parameter, thermal Grashof number, Frank Kamenetskii term, third grade material term, viscous heating term, Biot number, varying viscosity term and activation energy term respectively.

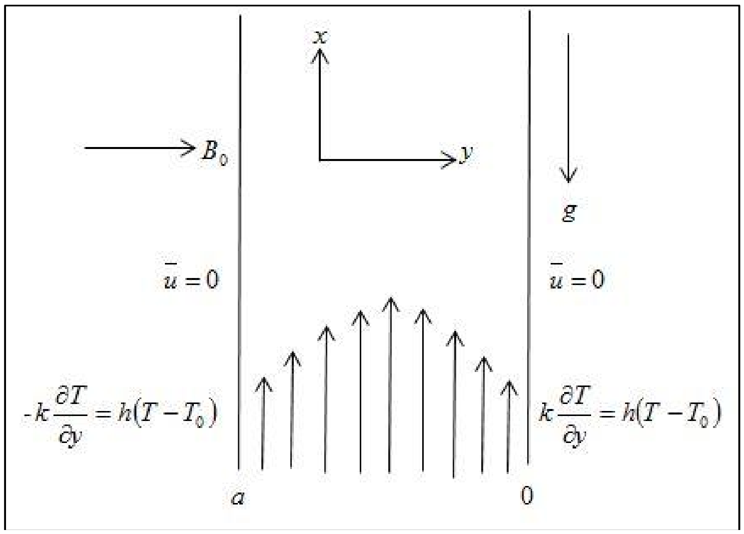

Fig. 1. Flow coordinate system

By employing Weighted residual method (WRM) on equations (5) to (7) as used by Salawu et al [18, 19, 20], taking basis polynomial with unknown constant coefficients which are to be obtained later, the polynomial is known as the basis function which is expressed as:

$$u(y) = \sum_{i=0}^{n} a_i y^i, \theta(y) = \sum_{i=0}^{n} b_i y^i \quad (8)$$

By using the basis function on the boundary conditions (7) and on the equations (5) and (6) the residual equations are:

$$u_r = G + e^{-\sigma (y^{10}b_{10}+y^9b_9+y^8b_8+y^7b_7+y^6b_6+y^5b_5+y^4b_4+y^3b_3+y^2b_2+yb_1+b_0)}(90\, y^8 a_{10} + 72\, y^7 a_9 + 56\, y^6 a_8 + 42\, y^5 a_7 + 30\, y^4 a_6 + 20\, y^3 a_5 + 12\, y^2 a_4 + 6\, y a_3 + 2\, a_2) - \sigma\, e^{-\sigma (y^{10}b_{10}+y^9b_9+y^8b_8+y^7b_7+y^6b_6+y^5b_5+y^4b_4+y^3b_3+y^2b_2+yb_1+b_0)}(10\, y^9 a_{10} + 9\, y^8 a_9 + \ldots \quad (9)$$

$$\theta_r = 90\, y^8 b_{10} + 72\, y^7 b_9 + 56\, y^6 b_8 + 42\, y^5 b_7 + 30\, y^4 b_6 + 20\, y^3 b_5 + 12\, y^2 b_4 + 6\, y b_3 + 2\, b_2 + \lambda((r\, (y^{10} b_{10} + y^9 b_9 + y^8 b_8 + y^7 b_7 + y^6 b_6 + y^5 b_5 + y^4 b_4 + y^3 b_3 + y^2 b_2 + y b_1 + b_0) + 1)^m e^{-\frac{y^{10}b_{10}+y^9b_9+y^8b_8+y^7b_7+y^6b_6+y^5b_5+y^4b_4+y^3b_3+y^2b_2+yb_1+b_0}{r\,(y^{10}b_{10}+y^9b_9+y^8b_8+y^7b_7+y^6b_6+y^5b_5+y^4b_4+y^3b_3+y^2b_2+yb_1+b_0)+1}} + \ldots \quad (10)$$

The residual error are reduced to zero at some set of collocation points at a consistent location inside the domain when $G_r = 2, m = 0.5, Bi = 1, r = 1, \sigma = 0.1, \omega = 1, \lambda = 0.5, Q *= 1, \delta = 1$ and $G = 0.5$. That is, $y_k = \frac{(b-a)k}{N}$ where $k = 1,2,\ldots,N-1$ and $a = 0, b = 1, N = 10$. These are solved via MAPLE software to get the constant coefficients.

Hence, the dimensionless velocity and heat equations become

$$u = -24.22541072\, y^{10} + 121.1270536\, y^{9} - 258.3851231\, y^{8} + 306.7781705\, y^{7} - 222.6386435\, y^{6} + 102.9259587\, y^{5} - 30.74682807\, y^{4} + 5.604150107\, y^{3} - 0.8883527363\, y^{2} + 0.4490251210\, y \tag{11}$$

$$\theta = 1.598167156 \times 10^{-37}\, y^{10} - 8.019179894 \times 10^{-37}\, y^{9} + 1.737351190 \times 10^{-36}\, y^{8} - 2.127976190 \times 10^{-36}\, y^{7} + 1.620173611 \times 10^{-36}\, y^{6} - 7.937918162 \times 10^{-37}\, y^{5} + 2.503503638 \times 10^{-37}\, y^{4} - 4.937301587 \times 10^{-38}\, y^{3} - 0.250\, y^{2} + 0.250\, y + 0.250 \tag{12}$$

The WRM algorithm is repeated for various values $G_r, m, Bi, r, \sigma, \omega, \lambda, Q^*, \delta$ and G.

2.1 The skin Friction

The skin friction is the friction acting on a moving body through fluid. It is as a result of the friction of the fluid against the "skin" of the moving object and forms a vector at each point of the surface. For this case, the shear stress on the channel boundaries $y = 0$ and $y = 1$ is given by

$$\tau = \frac{\partial u}{\partial y} \tag{13}$$

2.2 The Nusselt Number

The Nusselt number can also be called heat gradient at the wall which is the proportion of heat convective to conductive at the boundary. The heat transport rate at the channel boundaries $y = 0$ and $y = 1$ is given by

$$Nu = -\frac{\partial \theta}{\partial y} \tag{14}$$

3. DISCUSSION OF RESULTS

Table 1 depicts the results comparison of the method used and other methods of solutions. From the table, there is good agreement between our method and other method of solutions

Fig. 2 depicts the effects of variations in gradient pressure (G) on the rate of fluid flow. Increase in the pressure gradient causes increase on the fluid velocity i.e. the highest flow rate ensues as the gradient pressure rises which indicates that the higher the applied pressure on the third-grade fluid in the channel, the faster the flow liquid.

The influence of various values of the heat Grashof number (Gr) on the flow rate field is illustrated in the Fig. 3. It is observed that a rise in the values of relative effect of the thermal buoyancy relative force effect to the hydromagnetic viscous force in the boundary layer causes a rise in the third-grade fluid distributions.

Figs. 4 and 5 show the effects of Biot number (Bi) on the fluid velocity and energy fields. As it was observed in the heat boundary condition (7), an increase in the Biot nubers causes huge cooling convection at the surface of the walls, this respectively reduces the heat and bulk fluid at the wall. The entire energy profile decreases with a rise in the convective term values as the third-grade liquid continously controls the lower heat surface. The reduction in the heat similarly reduces the non-Newtonian liquid viscosity that in turn diminishes the flow velocity over the coupling viscosity that enhance the variations in the flow fluid and energy profiles.

Table 1. Comparison of result for velocity field $u(y)$

y	ADM [21]	Perturbation [21]	WRM
-1.0	0.000000	0.000000	0.000000
-0.75	0.215486	0.215486	0.215486
-0.5	0.370497	0.370497	0.370495
-0.25	0.463957	0.463957	0.463961
0.0	0.495188	0.495188	0.495183
0.25	0.463957	0.463957	0.463961
0.5	0.370497	0.370497	0.370475
0.75	0.215486	0.215486	0.215486
1.0	0.000000	0.000000	0.000000

Fig. 6 illustrates the reaction of the non-Newtonian third-grade fluid to varying in the viscosity term (α). It is noticed that an increase in the term α weakens the viscosity of the viscoelastic liquid and similarly declines the resistance to the fluid forces. This fundamentally causes strengthening in the flow rate as demostrated in the plot.

Figs. 7 and 8 show the impact of the reaction material term (λ) on the velocity and heat field. An increase in the values of the term (λ) leads to a noteworthy increase in the reaction rate and ohmic heating source. This accordingly augments the rate of flow and energy profiles. Due to enhancement in the fluid velocity coupling viscosity that causes a sensible upsurges in the flow heat field.

Fig. 9 displays the impact of non-Newtonian third-grade term (γ) on the rate of entropy production. From the figure, entropy generation decreases as the third-grade material term is enhanced. This is due to an upsurge in the fluid bonding particle force that causes the liquid to be extra viscoelastic. Thus, system entropy production shrinks. The downward movement is due to the unevenness amid the nonlinear heat and convective surface cooling as the viscoelastic term rises.

Figs. 10 and 11 depict the effects of G and Gr on the skin friction. From the figures, it can be observed that the skin friction increases as the values of the parameters G and Gr increase between the range $0 \leq y \leq 0.5$ because the boundary walls get thinker as the values of the parameters rises and found decreases as it moves far away from the surfaces i.e $y \geq 0.5$ due to decrease in the influences of the parameters on the fluid flow far away from the surfaces.

The responses of the skin friction to an increase in the values of the convective parameter Bi is illustrated in Fig. 12. It is noticed that the skin friction decreases as the channel surfaces been coolied within the range $0 \leq y \leq 0.5$ by reducing the amount of heat been transported by the fluid that in turn increases the viscoelastic of the fluid and thereby decreases the skin friction. But the skin friction increases as the convective term keep distance from the surface that in turn increases the skin friction as it moves far away from the channel surfaces.

Fig. 13 shows the influence of the reaction parameter (λ) on the temperature gradient. It is found that the heat effect at the wall increases as the reaction parameter increases due to the deposition of chemical reaction particles on the channel surfaces that increases the thermal boundary layer and thereby decreases the amount of heat leaving the system which resulted in an increase in the Nusselt number within the the range $0 \leq y \leq 0.5$ but the heat gradient decreases as it moves far from the surfaces i.e $y \geq 0.5$ due to thinner in the thermal boundary layer as it moves distance away from the walls by decreasing the reaction particles deposited on the wall surfaces.

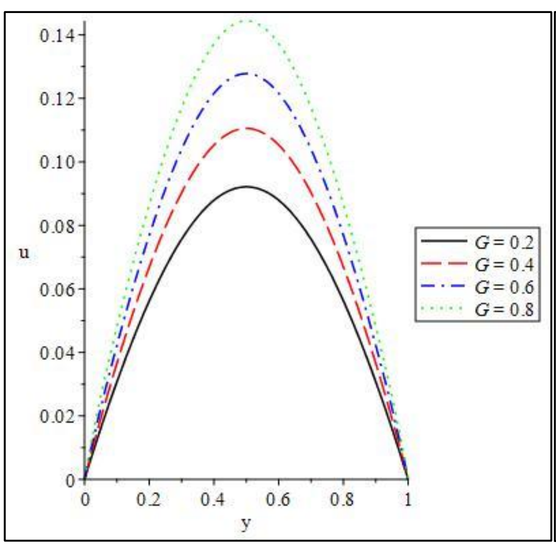

Fig. 2. Effects of (G) on velocity

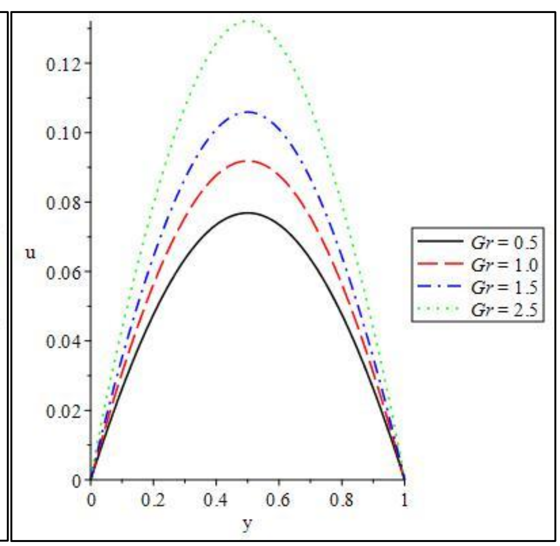

Fig. 3. Effects of (Gr) on velocity

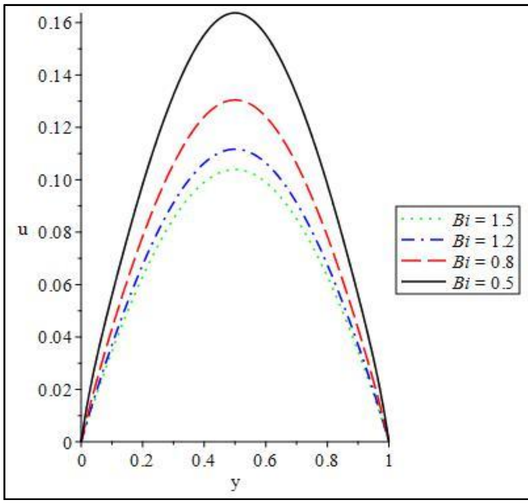

Fig. 4. Effects of (Bi) on velocity

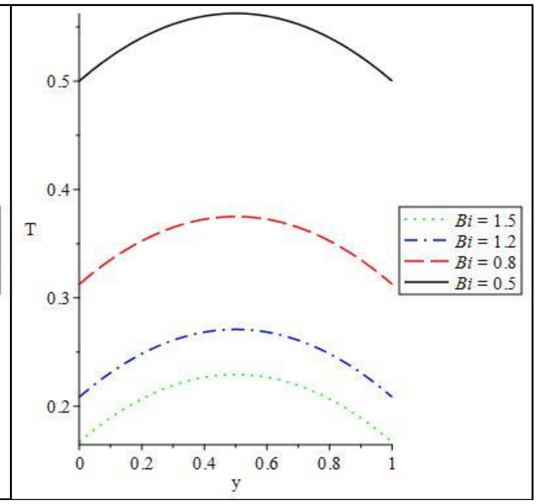

Fig. 5. Effects of (Bi) on temperature

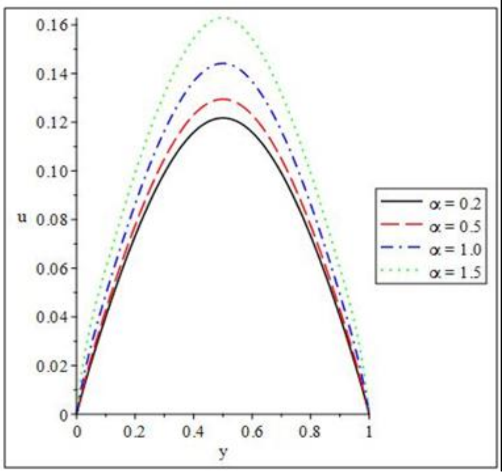

Fig. 6. Effects of (α) on velocity

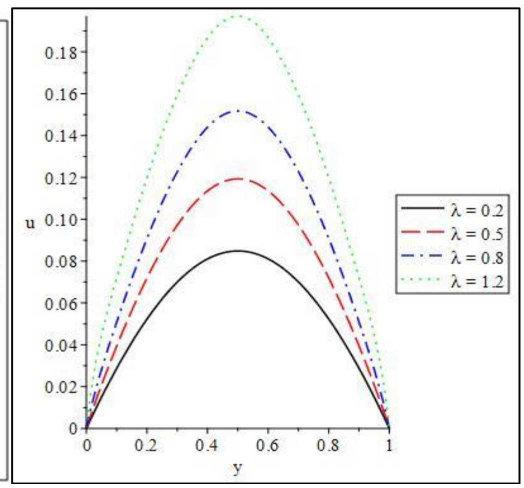

Fig. 7. Effects of (λ) on velocity

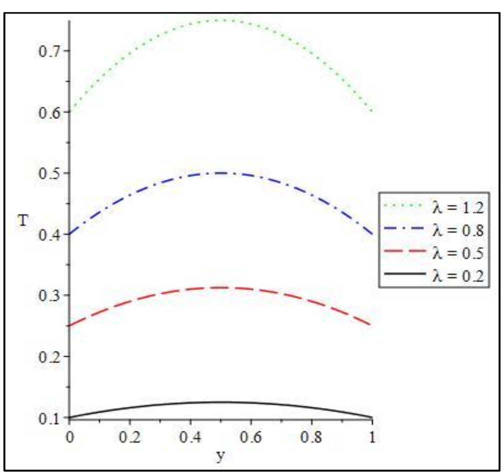

Fig. 8. Effects of (λ) on temperature

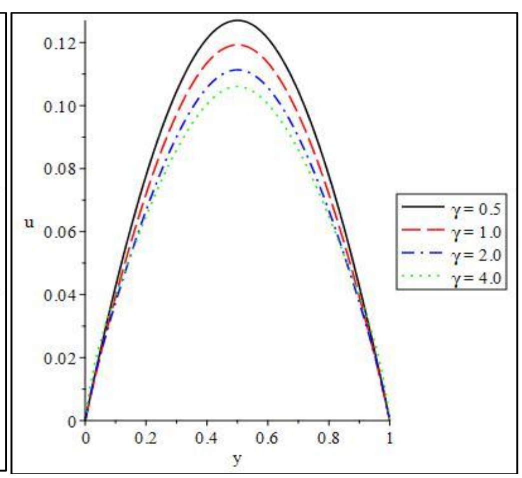

Fig. 9. Effects of (γ) on velocity

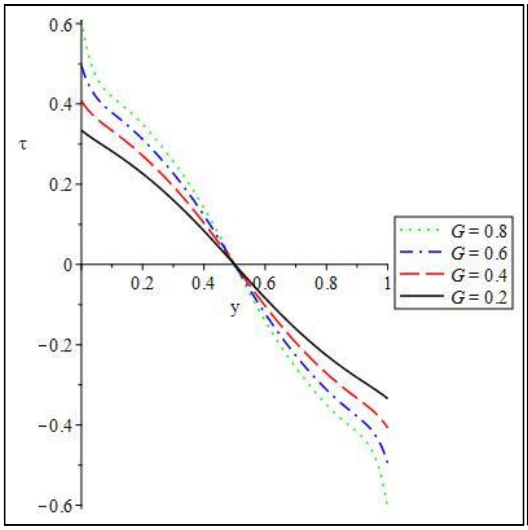

Fig. 10. Effects of (G) on skin friction

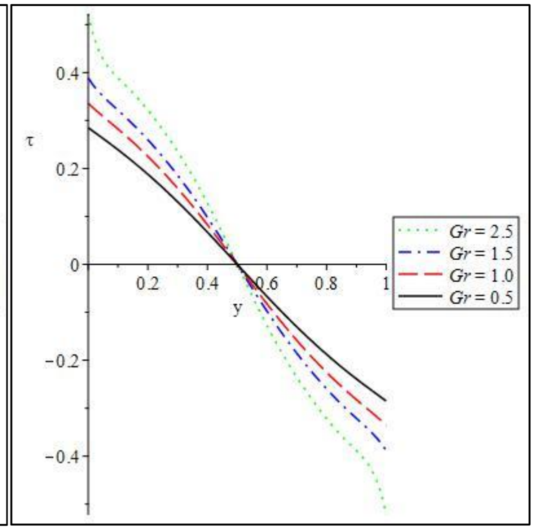

Fig. 11. Effects of (Gr) on skin friction

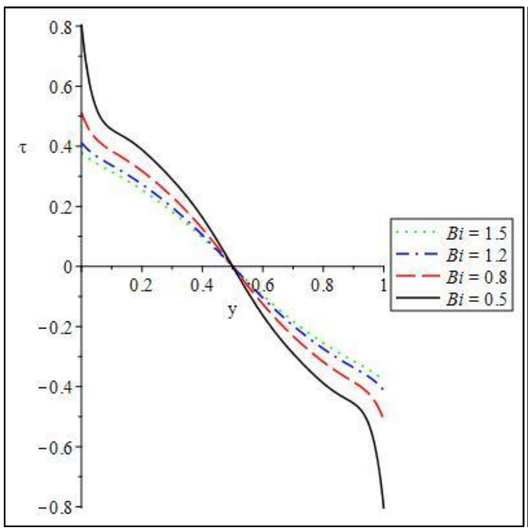

Fig. 12. Effects of (Bi) on skin friction

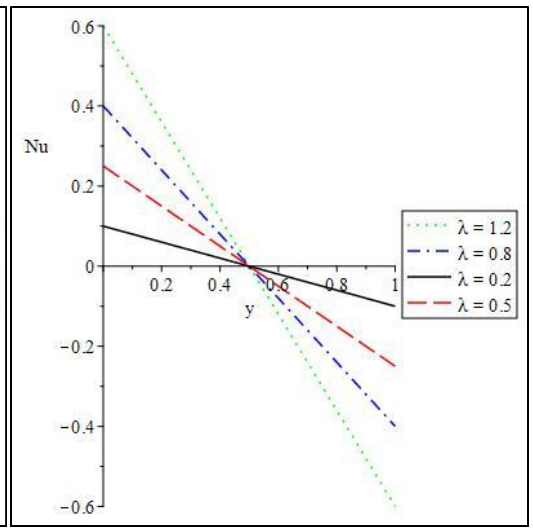

Fig. 13. Effects of (λ) on nusselt number

4. CONCLUSION

The influences of variable viscosity and heat transfer on steady reactive internal heat generating fluid flow through a channel with exothermic chemical reaction have been investigated. The governing equations from the formulation of the problem are non-dimensionalised and solved using a weighted residual method (WRM) to obtain the velocity, temperature distributions, skin friction and Nusselt number. Computed results are presented graphically to study their dependence on the important controlling physical parameters. It is observed that:

(i) An increase in pressure gradient G and Gr cause a rise in the velocity profile.
(ii) An increase in heat generation and Frank-Kamenestkii parameter λ leads to an increase in the velocity profils or temperature profiles.
(iii) An increase in Biot number retarded flow and temperature effect of the fluid flow field.
(iv) An increase in the viscoelastic of the fluid has a significant effects on the flow fluid.
(v) An increase in the variable viscosity parameter is seen to have magnified the flow fluid velocity

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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