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Effect of Radiation on Thermal Explosion Characteristics of Non-Newtonian Fluids

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Effect of Radiation on Thermal Explosion Characteristics of Non-Newtonian Fluids

Alalibo T Ngiangia [α] & Sozo T. Harry [σ]

Abstract- An analytical approach to the study of thermal explosion characteristics was examined and observation showed that an external heat source brought about by Semenov parameter and radiation delayed the initiation of thermal explosions while Frank-Kamenestkii parameter and heat due to chemical reaction enhanced the initiation of thermal explosions. The work also revealed that internal friction reduces ignition time and increases reaction rates.

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A = reactant

B = product

T= temperature of the reacting fluid

t= reaction time

k = thermal conductivity

$x =$ space coordinate

$\psi =$ consistency index

u = fluid velocity

$\alpha =$ flow behaviour index (power law exponent)

$\chi =$ heat transfer coefficient

S = surface area of fluids

V = volume of fluids

$T_0 =$ characteristic temperature

Q = heat released or absorbed

C = reactant concentration

R = universal fluid constant

$k_0 =$ constant

m = numerical exponent

E = activation energy

$\rho =$ fluid density

P = fluid pressure

$\delta =$ Frank-Kamenestkii parameter

$\psi =$ Semenov parameter

$\theta =$ dimensionless temperature

y = dimensionless space coordinate

$\rho' =$ dimensionless fluid density

$\beta =$ dimensionless thermal conductivity

$\mu =$ dimensionless heat absorbed or released

$\lambda =$ dimensionless activation energy

$\tau =$ dimensionless time

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q = quantity of heat in the reaction

$T_\infty =$ reserviour temperature

$\wedge =$ Planck's function

$\alpha_{K^*} =$ absorption coefficient

$\kappa^* =$ frequency of radiation

$q_x =$ radiative term

I. Introduction

Fluid dynamics is one of the most important of all areas of physics. Life as we know it would not exist without fluids. Fluids occur, and often dominate physical phenomena on all macroscopic length scales of the universe, from the mega per seconds of galatic down to the nanoscales of biological cell activity [1]. In reality communication would not have been possible without fluid (air) and the study as well as the practice of engineering cannot be complete without fluids. However, it is of common knowledge that most of the common and popular fluids in our day to day interactions are classified as Newtonian fluids and therefore most studies of fluid, concentrated on Newtonian fluids because, they obey the simple relationship between shear stress and shear strain. However, many common fluids are also Newtonian. Non-Newtonian fluids are fluids that do not obey the Newton's law of viscosity. For such fluids the shear stress is not proportional to the velocity gradient. These classes of fluids possesses flow power index of two and above. The viscosity of such fluids is also of higher magnitude than the Newtonian fluids. In the analysis of non-Newtonian fluids, Hughes and Briton [2] opined that, the properties of non-Newtonian fluids do not lend themselves to the elegant and precise analysis that has been developed for Newtonian fluids but the flow of non-Newtonian fluids does possess some interesting, useful and even exciting characteristics. In the construction industries, the use of paints, drilling mud and coal tar cannot be overemphasized owing to their chemical composition and physical properties. Scholars have made invaluable contribution to the study of non-Newtonian fluids and thermal explosion characteristics. When the heat loss due to Newtonian cooling can no longer keep pace with the heat release due to exothermic reaction, an additional heat source is considered [3-4]. Dik [5] also proposed a constant additional heat source in order to answer the question of degeneracy and also to estimate the ignition limits in such a system. Ajadi and Gol'dshtein [6], in their study, presented chemical and mechanical heat sources to thermal explosion characteristics and reported results which in part were a clear departure from existing results. Truscott et al [7] stated that, by assuming a slow rate of consumption of fuel and oxygen, the behaviour of a full system can be approximated and the safe and dangerous regions of parameter space can be identified. Adegbie [8] and Ngiangia et al [9] in their separate studies also reported that increase in Semenov parameter, decreases the temperature and this could lead to delay in the initiation of thermal explosions. Ngiangia [10], considered thermal explosion characteristics on Newtonian and non-Newtonian fluids and opined that in both cases, an additional heat source, delayed early initiation of thermal explosions but in varying degrees. Our aim in this study is to consider radiation as an additional heat source and investigate its contribution to the initiation of thermal explosions.

II. Formalisms

The mathematical statement of the study suggests that the velocity gradient is a function of temperature and the power law exponent varies. Using these facts and assuming that the reaction taking place in the region under study is one-step and irreversible

$$A \to B \qquad (1)$$

The simplified energy equation takes the form

$$\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x'^2} + \varphi\left(\frac{\partial u}{\partial x'}\right)^{\alpha} - \chi\frac{S}{V}(T-T_0) + q - \frac{\partial q_x}{\partial x} \qquad (2)$$

and the heat released by the chemical reaction is expressed by the Arrhenius law and obey the characteristics of non-Newtonian fluids

$$q = Q^{k_0\left(\frac{T}{T_0}\right)^m} C\exp\left(-\frac{E}{RT}\right) \qquad (3)$$

$$\frac{\partial^2 q_x}{\partial x^2} - 3\sigma^2 q_x - 16\sigma T_\infty^3 \frac{\partial T}{\partial x} = 0 \qquad (4)$$

For optically thin medium with relatively low density in the spirit of [10], equation (4) reduces to

$$\frac{\partial q_x}{\partial x} = 4\delta^2 (T - T_\infty) \qquad (5)$$

where $\delta^2 = \int_0^\infty (\alpha_{K^*} \frac{\partial \wedge}{\partial T}) dk^*$

with the boundary conditions $T(0)=0,\ T(1)=1$ (6)

It has been established by Hughes and Brighton [2] that

$$\varphi\left(-\frac{\partial u}{\partial x}\right)^{\alpha} = -\frac{x}{2}\left(\frac{\partial p}{\partial x}\right) \qquad (7)$$

The equation of state for an ideal fluid is given by

$$p = \rho RT \qquad (8)$$

For non-Newtonian fluid flow and application of expansion using linear approximation of the second term on the right hand side we get

$$\frac{\rho C_p}{k}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \left(\frac{3}{2}x\right)\left(\frac{3\rho R}{2\delta}\right) - \frac{\chi S}{Vk}(T-T_0) + \frac{1}{k}Q^{k_0\left(\frac{T}{T}\right)^m} C\exp\left(-\frac{E}{RT}\right) - \frac{4\delta^2(T-T_\infty)}{k} \qquad (9)$$

III. Dimensionless Variables

The following dimensionless quantities have been used

$$,\rho' = \frac{\rho u^2 x}{p}, R' = \frac{Rpx^2}{T_0}, \psi = \frac{\chi SRT_0^2}{VQkCE}\exp\left(\frac{-E}{RT_0}\right), \xi = \frac{3\rho RT}{P}, \vartheta = \frac{\rho VC_p}{kMC_v}$$

$$\tau = \frac{t}{t_0}, \theta = \frac{T}{T_0}, \delta = \frac{\varphi}{k}, \beta = \frac{RT_0}{E}\ \mu = \frac{QC}{E\rho}, y = \frac{3x}{2ut}, r = k_0\exp\left(-\frac{1}{\beta}\right)$$

and equation (9) can be written as

$$\vartheta\frac{\partial\theta}{\partial\tau} = \frac{\partial^2\theta}{\partial y^2} + \frac{\xi}{\delta}y\frac{\partial\theta}{\partial y} - \psi\theta + r\theta^m \log_e \mu - N\theta \qquad (10)$$

with the boundary conditions $\theta(0)=0, \theta(1)=1$ (11)

IV. Solution

If m = 1, ignition time is of utmost importance in thermal ignition. In the absence of reactant consumption and other simplification, equation (11) takes the form

$$\tau = \int_0^\infty \frac{d\theta}{-\psi\theta + (r\log_e \mu)\theta - N\theta} \qquad (12)$$

In the explosion region, the heat loss can be neglected $(\psi = N = 0)$ and taking high activation energy, ignition time approaches the adiabatic ignition time hence

$$\tau = \int_0^\infty \frac{d\theta}{(r\log_e \mu)\theta} = (\log_e \mu)\log_e \theta \exp\left(\frac{E}{RT}\right) \qquad (13)$$

which is an extension of known result for ignition time [12]

The presence of internal friction as a result of additional heat source, results in reduction of ignition time and also increases the rate of reaction.

To solve (10), we take steady state and using the Frobenius method for special functions, we assume a solution of the form

$$\theta = \sum_{n=0}^{\infty} a_n y^{n+c} \qquad (14)$$

We put (14) into (10) and simplify, we get roots of the indicial equations as

$$C = 0 \text{ or } 1 \qquad (15)$$

which lead to the recurrence relation

$$a_{n+2} = \frac{-\left(\frac{\xi}{\delta}(n+c) - \psi + r\log_e \mu - N\right)a_n}{(n+c+2)(n+c+1)} \quad n = 0, 1, 2, \ldots\ldots (16)$$

The complete solution after the imposition of (11) is

$$\theta = C_0\left(\frac{y - \left(\frac{\xi}{\delta} - \psi + r\log_e \mu - N\right)y^2}{3!}\right) + C_1\left(\frac{y^2 - \left(\frac{2\xi}{\delta} - \psi + r\log_e \mu - N\right)y^4}{4!}\right) \qquad (17)$$

where $C_0 = \left(\frac{3!}{1 - \left(\frac{\xi}{\delta} - \psi + r\log_e \mu - N\right)}\right), C_1 = \left(\frac{4!}{1 - \left(\frac{2\xi}{\delta} - \psi + r\log_e \mu - N\right)}\right)$

V. Results and Discussion

In order to get physical insight and numerical validation of the problem, an approximate value $r = 12.34$ and $\xi = 2.5$ is chosen. The values of other parameters made use of are

$$\mu = 2.5, 3.5, 4.5, 5.5, 6.5$$
$$\delta = 0.5, 1.0, 1.5, 2.0, 2.5$$
$$N = 1.6, 2.6, 3.6, 4.6, 5.6$$
$$\psi = 0.7, 1.2, 1.7, 2.2, 2.7$$

Frank-Kamenestkii considered a situation whereby heat is transported with relatively low thermal conductivity within the reactants, at such, increase in its parameter as depicted in Figure 1, showed a corresponding increase in the temperature of the reacting fluid which in turn brings about early initiation of thermal explosions. This observation is in agreement with the studies of [6], [9] and [10]. Increase in Semenov parameter as depicted in Figure 2, shows a corresponding decrease in the minimum temperature of the fluid owing to intermolecular interactions of a viscous reactive substance. This observation is consistent with the work of [6]. The presence of additional heat source provoked by chemical reaction led to the presence of internal friction. This additional heat contribution leads to increase in minimum temperature and an early occurrence of thermal explosion as depicted in Figure 3. The result is in agreement with [6]. Radiation, which is energy in motion decreases the minimum temperature of the reacting fluid as its parameter is increased as shown in Figure 4. Its presence, boast the Semenov parameter thereby further delayed the initiation of thermal explosions.

VI. Conclusion

The influence of radiation as an additional heat source in combination with chemical reaction and Semenov parameter were analyzed theoretically and its interest in the industries, particularly where dynamics of viscous reactive materials are considered, is a suitable area of application of this study.

VII. Acknowledgements

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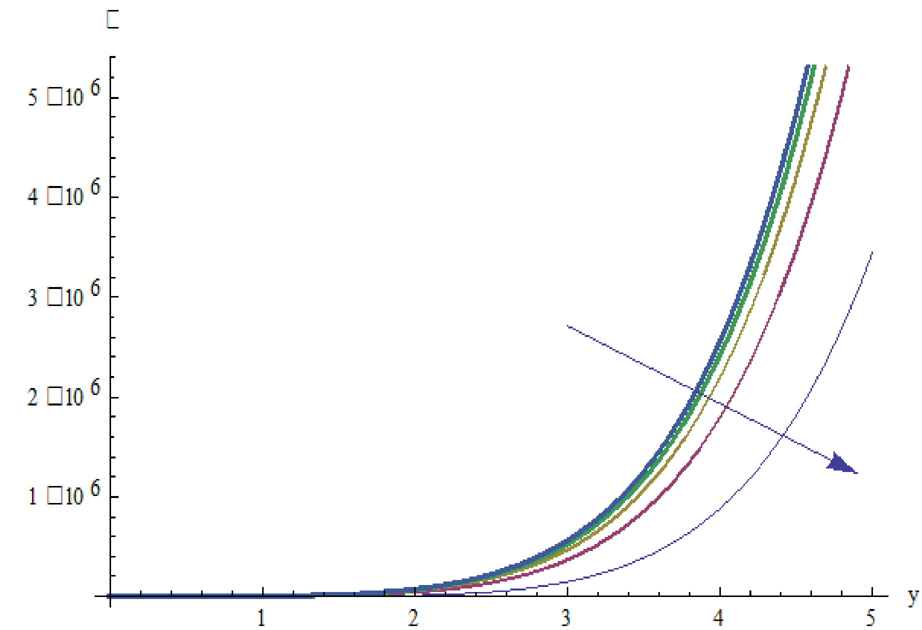

Figure 1: Temperature profile θ against boundary layer y for varying Frank-Kamenestkii parameter δ

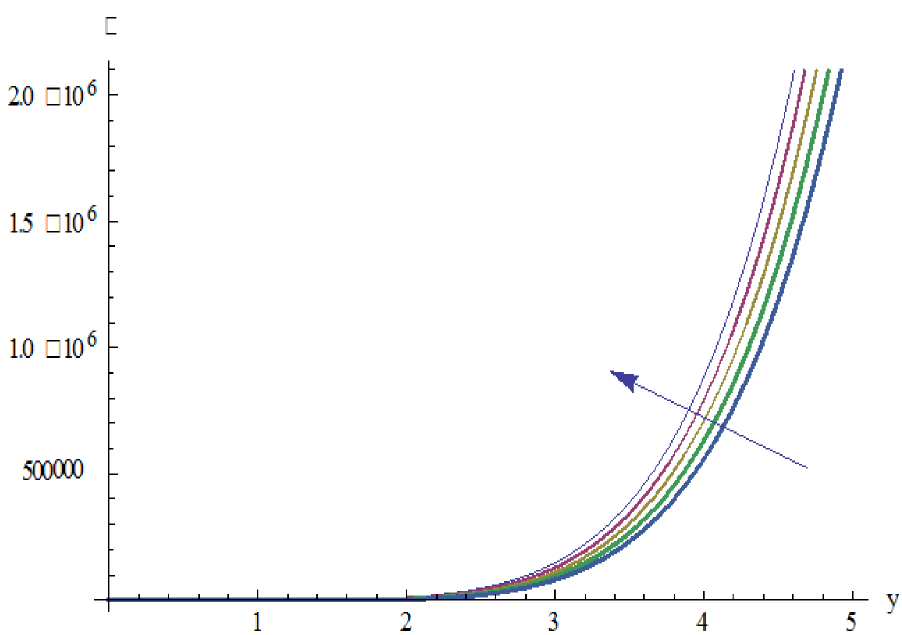

Figure 2: Temperature profile θ against boundary layer y for varying Semenov parameter ψ

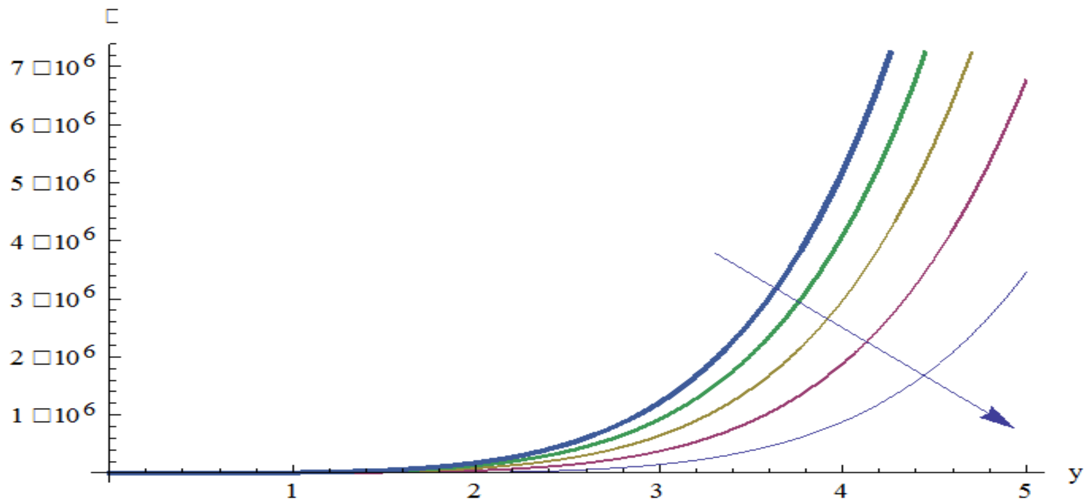

Figure 3: Temperature profile θ against boundary layer y for varying Heat source μ

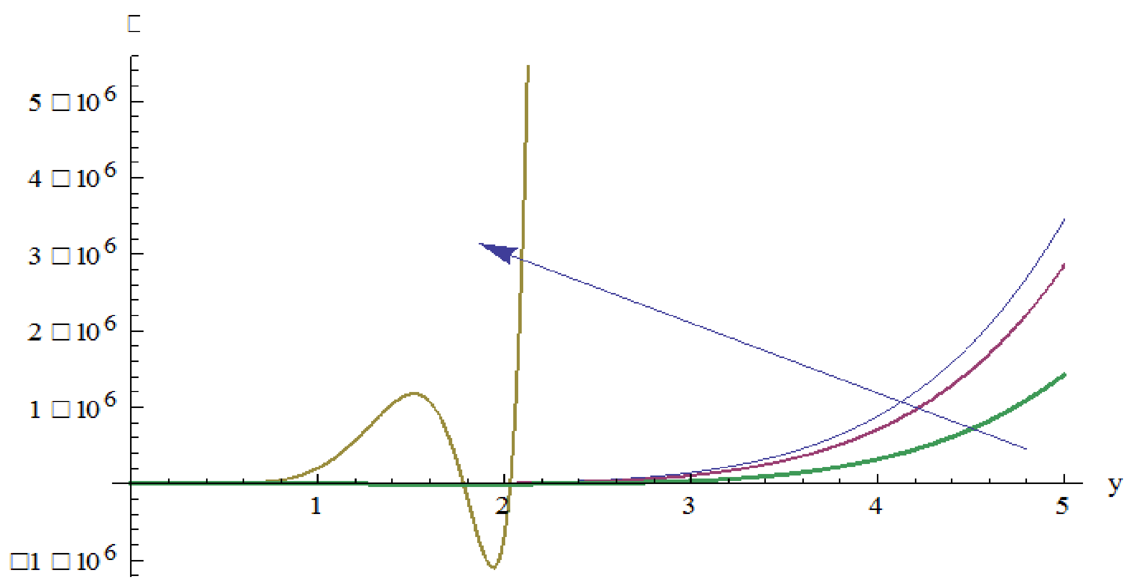

Figure 4: Temperature profile θ against boundary layer y for varying Radiation parameter N

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