



Thermodynamic Second Law Analysis of Hydromagnetic Gravity-Driven Two-step Exothermic Chemical Reactive Flow with Heat Absorption Along a Channel

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ABSTRACT

This study examines the second law of thermodynamic gravity-driven viscous combustible fluid flow of two-step exothermic chemical reaction with heat absorption and convective cooling under bimolecular kinetic. The flow is acted upon by periodic changes in the axial pressure gradient and time along the axis of the channel with the existence of magnetic field. The heat convection at the channel surfaces with the environment are the same and satisfies Newtons law of cooling. The dimensionless main equations of the flow are solved using a convergent and stable semi-implicit finite difference method. The effect of some fluid parameters associated with the problem on momentum and temperature are obtained. The expression for irreversibility ratio, volumetric entropy generation and Bejan number along with the graphically results are presented and quantitatively discussed.

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INTRODUCTION

The fast reduction in energy resources globally has stimulated nearly every nation on the planet to devote attention on energy preservation and enhancing existing energy systems to decrease energy waste. The community of researchers has reacted to the challenge by developing new systems of investigation and plans with the goal that the available work destruction is either wiped out or limited. Unlike the old tactics which depend entirely on the first law of thermodynamics, this approach utilizes a blend of the first and second laws of thermodynamics. This exertion has brought forth the new study of entropy production reported in literature [1, 2]. Computational analysis of the proficiency of thermal systems are usually done using the idea of thermodynamic second law effectiveness, defined as the ratio of actual thermal efficiency to reversible thermal efficiency with similar conditions. The main approach is to measure the influence of the irreversible processes arising in the systems in terms of the rate of entropy generation. The analysis of entropy generation has showed to be an active tool in improving the performance of second law of existing systems. The quantity of research work on the subject keeps running into the

hundreds, the reported data [3-12] a demonstrative case of those with instantaneous significance to the present study.

Due to its essential usefulness in engineering systems, entropy generation of reactive hydromagnetic flows are often follow with heat transfer as encountered in several systems of engineering. Many machines operate under differ harsh conditions with various types of fluids as lubricants. Largely, the lubricating oils viscosity often reduces as the temperature increases. This variation in the viscosity of lubricant will definitely affect it proficiency. In order to escape unwanted change as a result of increase in heat, the use of magnetic fluids and electrically conducting liquids has attracted the attention of many scholars [8,13-16]. Hydromagnetic lubricants have electric conductivity and higher thermal with reduced viscosity than ordinary lubricating oils. The higher thermal conductivity mean viscous friction produced by heat may be readily conducted away while small viscous property produced low capacity of load-carrying. Meanwhile, this low-load is not good for a fluid lubricated electrically conducting bearing, but this can be encouraged by introducing electromagnetic fields externally. Therefore, ohmic heating as a result of electrical current enhances the lubricant viscosity.

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Related examples are noticed in examine the magnetic influences on hydrostatic bearings [14,17-20].

Follow the above studies, the analysis of second law of thermodynamic for gravity-driven two-step exothermic chemical reaction with convective heat exchange in a channel have not yet been studied. Two-step chemical reactions is a reaction that has only one intermediary between them. The important of two-steps chemical reaction in combustion processes can not be over emphasis due to it support in complete combustion of unburned ethanol [21]. This assists in lowering the release into the atmosphere the toxic air pollutant called carbon monoxide (CO) that degrade the environment. The thermal stability of two-step exothermic chemical reaction in a slab was studied by Makinde et al. [22]. The authors considered the reactant diffusion and assumed the pre-exponential variable factor for both steady and unsteady state. Recently, the problem of an unsteady two steps exothermic chemical combustible, viscous, reactive flowing fluid past porous media with radiation under different chemical kinetics was investigated [23]. The authors coupled Laplace transform along with differential transform method to obtain solution to the problem under consideration. Little or no study on the thermodynamic second law analysis of two-step exothermic chemical reaction have been considered.

The objective of present study is to analyze the irreversibility second law of unsteady incompressible hydromagnetic fluid flow of a reactive two-step exothermic chemical reaction moving through fixed walls with asymmetric convective cooling and uniform transverse magnetic field. The flow model is presented in section 2. In section 3, the semi-implicit finite difference method is employed in space and time for the computation. In section 4, the computational with the graphical results are established and quantitatively explained with respect to existing fluid parameters entrenched in the flow.

MATERIAL AND METHODS

Mathematical formulation

Consider the viscous combustible, isothermal, incompressible reactive fluid of two-step exothermic chemical reaction flow through two fixed vertical plates of width a . The flow is stimulated by the action of bimolecular kinetic, gravity and constant pressure gradient. It is taken that the flow is induced by an applied magnetic field B_0 . The plates are subjected to the same coolant heat convection with the ambient temperature, thus providing an asymmetric cooling effect. The x -axis is assumed to be along the center of the channel and the y -axis is taken to be normal to it. The flow coordinate geometry is depicted in Figure 1; the mechanisms of two-

step reaction and the equations governing the flow are defined as follows:

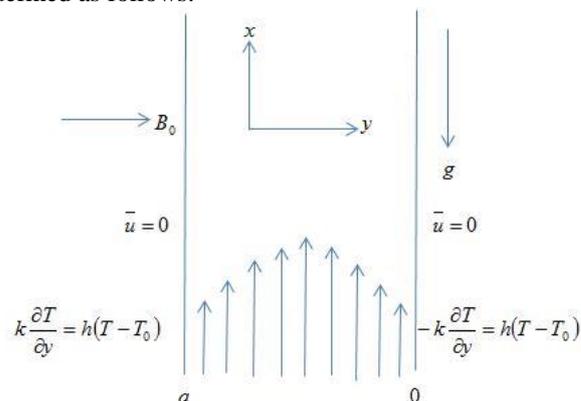
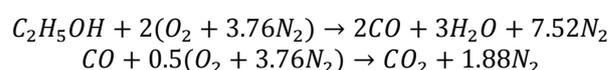


Figure 1. The formulation geometry

Mechanisms of two-step reaction



The equations governing the flow

$$\rho \frac{\partial \bar{u}}{\partial \bar{t}} = -\frac{\partial \bar{P}}{\partial \bar{x}} + \mu \frac{\partial^2 \bar{u}}{\partial \bar{y}^2} - \sigma B_0^2 \bar{u} + \rho g \beta_T (\bar{T} - T_w) \quad (1)$$

$$\rho C_p \frac{\partial \bar{T}}{\partial \bar{t}} = k \frac{\partial^2 \bar{T}}{\partial \bar{y}^2} + \sigma B_0^2 \bar{u}^2 + \mu \left(\frac{\partial \bar{u}}{\partial \bar{y}} \right)^2 - Q(\bar{T} - T_w) + Q_1 C_1 A_1 \left(\frac{K\bar{T}}{\nu l} \right)^m \frac{E_1}{e^{R\bar{T}}} + Q_2 C_2 A_2 \left(\frac{K\bar{T}}{\nu l} \right)^m \frac{E_2}{e^{R\bar{T}}} \quad (2)$$

Subject to relevant boundary conditions stated as follows:

$$\bar{u}(\bar{y}, 0) = 0, \bar{u}(0, \bar{t}) = 0, \bar{u}(a, \bar{t}) = 0, \bar{T}(\bar{y}, 0) = T_0, -k \frac{\partial \bar{T}}{\partial \bar{y}}(0, \bar{t}) = h(\bar{T}(0, \bar{t}) - T_0), k \frac{\partial \bar{T}}{\partial \bar{y}}(a, \bar{t}) = h(\bar{T}(a, \bar{t}) - T_0) \quad (3)$$

where $\bar{x}, \bar{y}, \bar{t}, \rho, k, C_p, \mu, \sigma, B_0, K, Q_1, C_1, l, \nu, A_1, E_1, R, Q_2, C_2, A_2, E_2, Q$ and T_w are respectively the dimensional flow coordinate along the surface, dimensional flow coordinate normal the surface, dimensional flow time, fluid density, thermal conductivity, specific heat at constant pressure, fluid viscosity, electrical conductivity, magnetic strength, Boltzmann's constant, first step heat of reaction term, first step reactant species concentration, planck's number, vibration frequency, first step reaction rate constant, first step activation energy, universal gas constant, second step heat of reaction term, second step reactant species concentration, second step reaction rate constant, second step activation energy, heat absorption coefficient and wall temperature. The computational indies $m = 0.5$ is used which represents bimolecular chemical kinetics that determine the energy of the reactants and their orientation.

The following dimensionless parameters are introduced

$$\begin{aligned}
 G &= -\frac{\partial p}{\partial x}, P = \frac{a\bar{p}}{\mu U}, x = \frac{\bar{x}}{a}, y = \frac{\bar{y}}{a}, \theta = \frac{E_1(\bar{T}-T_w)}{RT_w^2}, \varepsilon = \frac{RT_w}{E_1}, H^2 = \frac{\sigma B_0^2 a^2}{\mu}, r = \frac{E_2}{E_1}, \\
 \beta &= \frac{QRT_w^2}{Q_1 c_1 A_1 E_1} \left(\frac{v_l}{kT_w}\right)^m e^{-\frac{1}{\varepsilon}}, \lambda = \frac{Q_1 c_1 A_1 E_1 a^2}{kRT_w^2} \left(\frac{kT_w}{v_l}\right)^m e^{\frac{1}{\varepsilon}}, Br = \frac{\mu U^2 E_1}{kRT_w^2}, \\
 Gr &= \frac{\rho g \beta T_w^2 a^2}{\mu U E_1}, \omega = \frac{Q_2 c_2 A_2}{Q_1 c_1 A_1}, Pr = \frac{\mu c_p}{k}, u = \frac{\bar{u}}{U}, t = \frac{\mu t}{\rho a^2}, Bi = \frac{ah}{k}.
 \end{aligned}
 \tag{4}$$

Substitute the dimensionless quantities (4) in equations (1)-(3) to get

$$\frac{\partial u}{\partial t} = G + \frac{\partial^2 u}{\partial y^2} - H^2 u + Gr\theta, \tag{5}$$

$$Pr \frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial y^2} + Br \left[\left(\frac{\partial u}{\partial y}\right)^2 + H^2 u^2 \right] + \lambda \left[(1 + \varepsilon\theta)^m \left(e^{\frac{\theta}{1+\varepsilon\theta}} + \omega e^{\frac{r\theta}{1+\varepsilon\omega}} \right) - \beta\theta \right], \tag{6}$$

with the corresponding initial and boundary conditions

$$u(y, 0) = 0, u(1, t) = 0, u(0, t) = 0, T(y, 0) = 0, \frac{\partial \theta}{\partial y}(0, t) = -Bi(0, t), \frac{\partial \theta}{\partial y}(1, t) = Bi(1, t). \tag{7}$$

where $u, T, G, Gr, H, Br, \lambda, \omega, Bi, Pr, \varepsilon, r$ and β are respectively the fluid velocity, fluid temperature, pressure gradient, thermal Grashof, Hartmann number, Brinkman number, Frank-Kamenetskii parameter, two-step exothermic reaction parameter, Biot number, Prandtl number, activation energy, activation energy ratio, heat absorption parameter.

Method of solution

The computational system engaged with the momentum and energy equations is finite difference of semi-implicit scheme [24,25], the approach takes implicit terms between the time level $(N + \xi)$ for $0 \leq \xi \leq 1$. So as to make huge time steps, ξ is thought to be 1. Indeed, being totally implicit, the implemented computational method presented in this work is conjectured to be appropriate for any estimation of time steps. The dimensionless equations are discretized on a Cartesian uniform grid with linear mesh on which the finite differences are taken. Approximating the first and second spatial derivatives with second order central differences, the resulting equations of the first and last grid points are modified to incorporate the boundary conditions. The velocity module in semi-implicit technique can be written as follows:

$$\frac{(u^{(N+1)} - u^{(N)})}{\Delta t} = u_{yy}^{(N+\xi)} - H^2 u^{(N+\xi)} + G + Gr\theta^{(N)}, \tag{8}$$

the equation for $u^{(N+1)}$ becomes:

$$-c_1 u_{i-1}^{N+1} + [1 + 2c_1 + H^2 \Delta t] u_i^{N+1} - c_1 u_{i+1}^{N+1} = u^{(N)} + \Delta t(1 - \xi) u_{yy}^{(N)} + \Delta t Gr \theta^{(N)} + \Delta t G - \Delta t H^2 (1 - \xi) u^{(N)}. \tag{9}$$

where $c_1 = \xi \Delta t / \Delta y^2$ and the forward difference procedures are adopted for all derivatives of time. The solution technique for $u^{(N+1)}$ reduces to tri-diagonal inversion matrices.

The semi-implicit method for the temperature component takes after that of momentum equation. The unchanged second derivatives of the energy equation can be written as follows:

$$Pr \frac{\theta^{(N+1)} - \theta^{(N)}}{\Delta t} = \frac{\partial^2 \theta^{(N+\xi)}}{\partial y^2} + Br [u_y^2 + H^2 u^2]^{(N)} + \lambda \left[(1 + \varepsilon\theta)^m \left(e^{\frac{\theta}{1+\varepsilon\theta}} + \omega e^{\frac{r\theta}{1+\varepsilon\omega}} \right) - \beta\theta \right]^{(N)}, \tag{10}$$

the equation for $\theta^{(N+1)}$ becomes:

$$-c_2 \theta_{i-1}^{(N+1)} + (Pr + 2c_2) \theta_i^{(N+1)} - c_2 \theta_{i+1}^{(N+1)} = \theta^{(N)} + \Delta t(1 - \xi) \theta_{yy}^{(N)} + Br \Delta t [u_y^2 + H^2 u^2]^{(N)} + \lambda \Delta t \left[(1 + \varepsilon\theta)^m \left(e^{\frac{\theta}{1+\varepsilon\theta}} + \omega e^{\frac{r\theta}{1+\varepsilon\omega}} \right) - \beta\theta \right]^{(N)}. \tag{11}$$

where $c_2 = \xi \Delta t / \Delta y^2$. The solution technique for $\theta^{(N+1)}$ also decreases to the tri-diagonal inversion matrices. The schemes (9) and (11) were confirmed for regularity. When $\xi = 1$ enable us to take large time steps that is of order two in space but order one in time. As formerly taken, the method gratifies any time step values! The Maple 2016 code was used to carried out the analysis.

Entropy generation analysis

The fluid physical properties can change significantly with temperature when the effects of variable viscosity are taken into consideration. The overall entropy generation equation for the flow per unit volume is define as follows [4].

$$E_G = \frac{k}{T_0^2} (\nabla \bar{T})^2 + \frac{\mu}{T_0} \Phi \tag{12}$$

The heat transfer irreversibility is the first term of equation (12) while the second term is the viscous dissipation entropy generation. By equation (12), the dimensionless entropy generation number is obtained as follows:

$$N_S = \frac{E^2 a^2 E_G}{R^2 T_0^2 k} = \left(\frac{d\theta}{dy}\right)^2 + \frac{Br}{\varepsilon} \left[\left(\frac{du}{dy}\right)^2 + H^2 u^2 \right] \tag{13}$$

Following equation (13), the first term is assigned N_1 and the second term is assigned N_2 , i.e.,

$$N_1 = \left(\frac{d\theta}{dy}\right)^2, N_2 = \frac{Br}{\varepsilon} \left[\left(\frac{du}{dy}\right)^2 + H^2 u^2 \right] \tag{14}$$

The Bejan number (Be) is define mathematically as follows:

$$Be = \frac{N_1}{N_S} = \frac{N_1}{N_1 + N_2} = \frac{1}{1 + \Phi}, \Phi = \frac{N_2}{N_1} \tag{15}$$

The N_S and Be are illustrated in Figures 7-12.

RESULTS AND DISCUSSION

The following parameters default values are adopted for the computation based on existing theoretical results $H = 2$, $G = 0.5$, $Gr = 3$, $Pr = 3$, $Br = 0.2$, $\beta = 0.5$, $\omega = 1$, $\lambda = 1$, $r = 1$, $Bi = 0.5$, $t = 2m = 0.5$ and $\varepsilon = 1$ except otherwise stated on the graph.

The effect of pressure gradient G on the fluid momentum is presented in Figure 2. An enhancement in the pressure gradient values increases the fluid flow velocity within the channel i.e. the highest flow velocity is observed as the parameter values G is rises which means that the more pressure is applied on the fluid in the system, the faster the flow as a result of warmth in the fluid as the pressure is magnifies. Figure 3 illustrates the response of the fluid velocity to diverse values of Hartmann number H . It is noticed that as the parameter values H is increasing, there is a rise in the damping magnetic properties due to the present of Lorentz force that amplifies the flow resistance and thereby slow down the fluid flow convective motion. Thus, the electrically conducting fluid is influenced by the magnetic force by prompting an electrically conducting fluid in the micro scale system. Hence, the velocity distribution decreases.

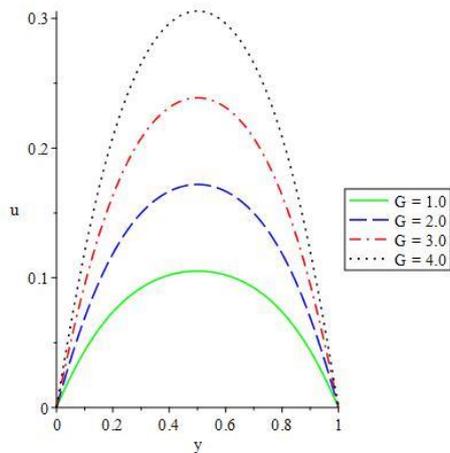


Figure 2. Effects of (G) on velocity

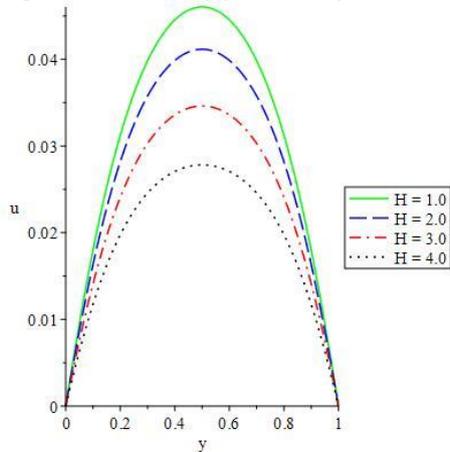


Figure 3. Effects of (H) on velocity

Figure 4 depicts the effect of thermal Grashof number Gr on the velocity field. It is seen that an increase in the parameter number Gr boosted the fluid flow distribution within the system. This is due to the fact that the fluid gets warmer as it moves along the boundary layer surface. The flow resistance forces diminished which then causes a rise in the fluid flow rate. For small buoyancy effects, the maximum flow rate is experienced in the channel. The consequence of Prandtl number Pr on the temperature profile is shown in Figure 5. Huge values of the parameter Pr congruently reduce the source terms strength in energy equation and therefore in turn decrease the overall fluid temperature and viscosity as evidenced in the illustrated data.

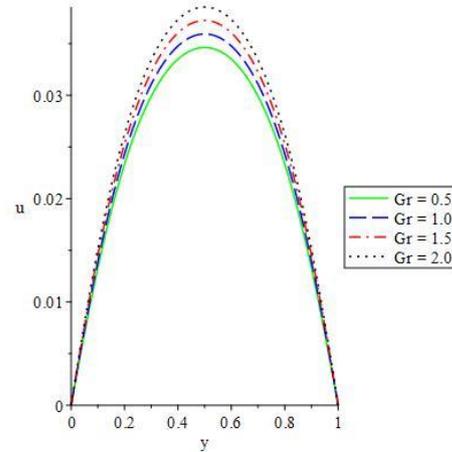


Figure 4. Effects of (Gr) on velocity

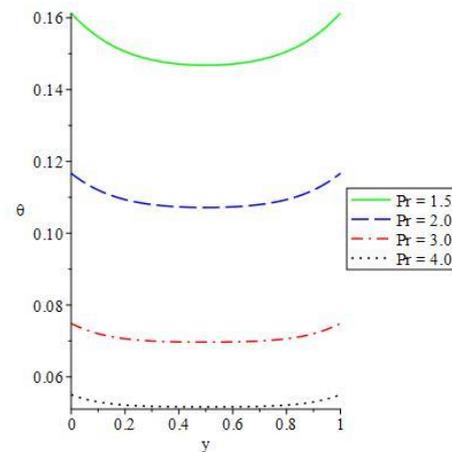


Figure 5. Effects of (Pr) on temperature

Figure 6 portrays the reaction of temperature distribution in the system to varying in the heat absorption rate β . As it is clearly seen from this figure that an increase in the parameter values β decreases the heat content in the system. The behaviour is due to thinner in the thermal boundary layer that causes more heat to leave the system and then reduces the temperature profile. The response of the rate of entropy generation to

variational rise in Brinkman number Br is illustrated in Figure 7. For a proportionally cooled channel with values of both the thermal Grashof number and the pressure gradient remain unchanged. As expected, the smallest rate of entropy generation is experienced when Brinkman number is small. The rate of entropy production gradually increases as Brinkman number is enhanced.

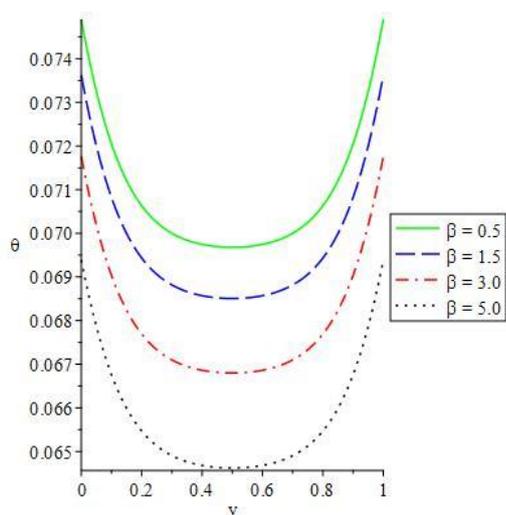


Figure 6. Effects of (β) on temperature

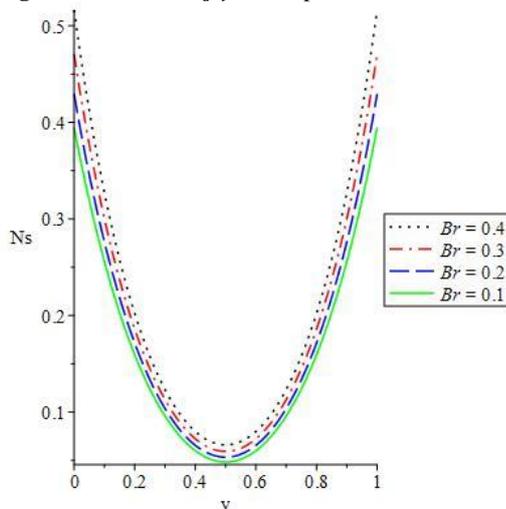


Figure 7. Effects of (Br) on entropy generation

Figure 8 shows the rate of entropy generation for different values of the Frank-Kamenetskii parameter λ . As observed from the graph, increasing the parameter λ enhances the generation of entropy within the flow system. This is substantially right since more heat is internally generated as the concentration reagents is rises. The exothermic chemical reactions stimulate the rate of combustive heat transfer to the cooling wall. Also, the heat is distributed throughout the fluid which melted the fluid bonding force, and encourages collision of inter-particle; hence, more heat is generated due to the fluid

particles interaction. Therefore, the entropy generation profile increases. Figure 9 displays the influence of the energy activation parameter ϵ on the rate of entropy generation. As noticed from the diagram, a rise in the parameter ϵ is seen to decrease the entropy production rate of the system. This happens because an increase in activation energy of the fluid corresponds to diminish in fluid energy activation. Therefore, the more activation energy, the smaller the temperature within the system. The declined in heat content discourage entropy production within the system.

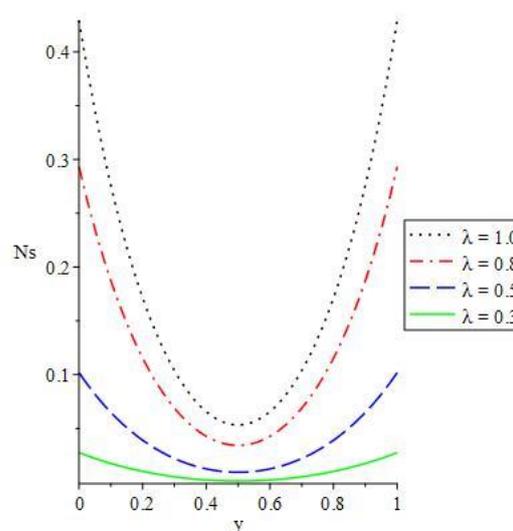


Figure 8. Effects of (λ) on entropy generation

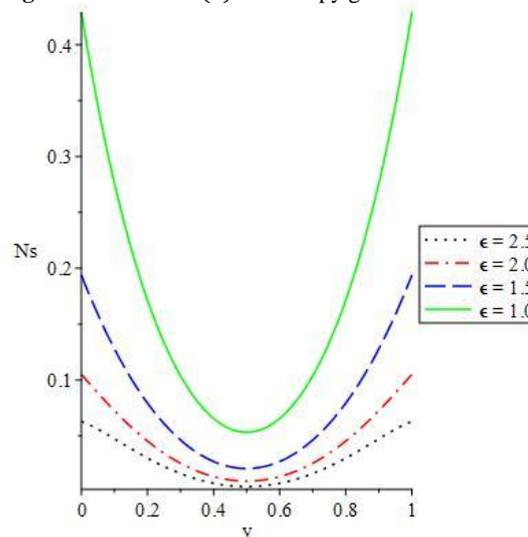


Figure 9. Effects of (ϵ) on entropy generation

Figure 10 represents the influence of Brinkman number on Bejan number distribution. As Brinkman number increases there is decline in Bejan number profile. That is, there is decrease in the irreversibility process within the fluid flow channel due to high fluid friction within the channel principal area of the flow.

Therefore, a diminish Bejan number at the walls is experienced.

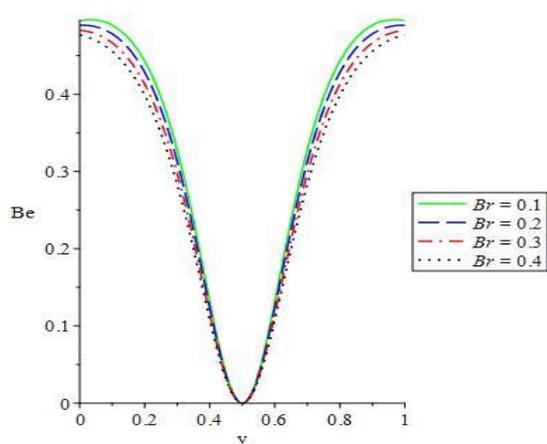


Figure 10. Effects of (Br) on Bejan number

Figure 11 shows the reaction of Bejan number to variational increase in the values of Frank-Kamenetskii parameter λ . It is observed from the plot that an enhancement in Frank-Kamenetskii parameter causes to strong decline in irreversibility heat transfer within the channel as a result of exothermic chemical reaction nature of the fluid flow. Hence, heat is loss of to the surrounding which leads to rises in the irreversibility of the fluid friction as the parameter λ increases, that is as the chemical kinetic influence strengthens.

Figure 12 represents response of Bejan number to an increase in the activation energy parameter ϵ , Bejan number is steadily encouraged past the channel path. Obviously, as the fluid friction irreversibility remains reduced, Bejan number is highly noticeable. This is because a rise in the parameter ϵ reduces the fluid friction which in turn enhances the flow irreversibility profile. When this occurs, it implies that the fluid friction irreversibility is governed by heat transfer.

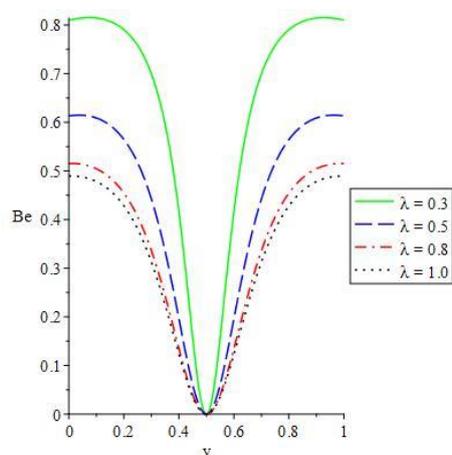


Figure 11. Effects of (λ) on Bejan number

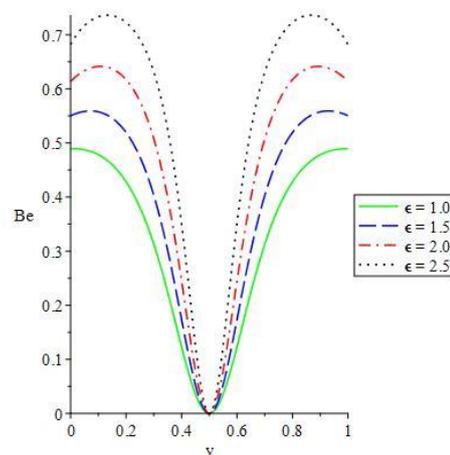


Figure 12. Effects of (ϵ) on Bejan number

CONCLUSION

The analysis thermodynamic second law for hydromagnetic two-step exothermic chemical reaction flow through fixed channel with asymmetry convective cooling under the influence of gravity and constant pressure were examined. The governing equations was solved using convergent, stable and unconditional semi-implicit finite difference method. From the studied, it was noticed that the magnetic field reduces the flow and unwanted changes in the fluid viscosity due to rise in temperature. Also, electrical conductivity and high thermal is credited to hydromagnetic lubricants with smaller viscosity than the conventional lubricant oils. Irreversibility fluid friction governs at the channel main region while at both upper and lower plate surfaces, irreversibility of heat transfer rules. More also, a rise in both Frank-Kamenetskii and heat viscosity parameter needs to be watched as they contribute meaningfully to damage the thermo-fluid system while activation energy dampens entropy distribution encourage irreversibility of heat transfer over fluid friction.

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چکیده

در این مطالعه، قانون دوم حرارتی مایع قابل احتراق گرانی گرانروی گرما دهی واکنش شیمیایی دو مرحله ای با جذب گرما و خنک کنهای تحت سینتیک بیوموکلئیک بررسی شده است. جریان بر اساس تغییرات دوره ای در شیب فشار محوری و زمان در امتداد محور کانال با وجود میدان مغناطیسی عمل می کند. انتقال گرما در سطوح کانال با محیط زیست یکسان است و قانون خنک کننده نیوتون را رعایت می کند. معادلات اصلی بی معنی جریان با استفاده از یک روش تقسیم محدود و نیمه ضمنی با روش همگرا و پایدار حل می شود. اثر برخی از پارامترهای مایع مربوط به مشکل بر روی سرعت و رانندگی بدست می آید. بیان نسبت برگشت ناپذیری، تولید آنتروپی حجمی و تعداد بژان همراه با نتایج گرافیکی ارائه شده و کمی مورد بحث قرار می گیرد.
