### MHD Flow of a Kinetic theory of Liquids Originated Fluid with Heat Generation ascendancy

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MHD Flow of a Kinetic theory of Liquids Originated Fluid with Heat Generation ascendancy

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Abstract: In the present article, the heat generation impact on magnetohydrodynamic (MHD) flow of an Eyring-Powell fluid along a permeable plate has been explored. Heat generation/absorption influence on a steady flow of non-Newtonian fluid over a surface is investigated. The governing equations obtained from Eyring-Powell fluid model are transubstantiated into ordinary differential equations using suitable transformations. Along with Runge Kutta method, we attained numerical solution of the present problem by explicating the shooting technique. Also with the assistance of graphs as well as tables, influences of distinct parameters on temperature and the velocity field profiles are highlighted. The acceleration in the value of $\gamma$, velocity profile shows decreasing behavior but recovery occurs with an enlargement in M. The stream lines as well as three dimensional results has been shown graphically for the selection of different parameters. Numerical results of the present work has been discussed with the support of tables.

Keywords: Effects of heat generation; MHD flow; Eyring-Powell fluid model; Porous medium.

Introduction

Heat generation or absorption is of very much significance in fluids where exothermic and chemical reactions are occurring. Chemical reactions are happening in a lot of chemical procedures. When temperature distribution changes, it affects the particle's velocity. We may observe such kind of changings in nuclear reactors, electronic chips and semi-conductor wafers. In our practical life, the problems in which heat generation or absorption occurs are of much importance. For example, we observe in our daily life geographical flows, underground cables cooling, recovery of petroleum resources, storage of nuclear waste materials and environmental impacts of heat generation in buried waste. Many authors \cite{1,2} have studied about the behavior of heat generation and absorption in fluids. M. Salem et al. \cite{3} studied about heat generation effects in chemical reactions on hydromagnetic flow of a surface. Ali J. chamkha included the results that fluid velocity will be increased, whenever heat generation effects are present there and it will be decreased, when heat generation effects are absent but absorption effects are there. M. Khan et al. \cite{4} analyzed about heat transfer squeezed flow of fluid over a sensor surface. Md. Abdul Alim et al. \cite{5} discussed the results of MHD natural convection flow with heat generation impacts.

In many problems related to geophysics and astrophysics, Magnetohydrodynamic flow of electrically conducting fluids is happening in presence of magnetic field. In many geometrical studies, Magneto Hydrodynamics (MHD) is of high significance. Its study is of great interest

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because flow control is affected by magnetic fields and its importance on many systems using electrically conducting fluids. For example, liquid metals and little acid which is mixed in water. Sidra Aman et al. [6] observed about nanoparticles influences on MHD poiseuille flow of nanofluid in the presence of chemical reaction. A. zeshan et al. [7] studied magnetic effects on viscous ferro-fluid and Arif Hussain et al. [8] have also interpreted the computational analysis of MHD sisko fluid flow in his research work.

Pavlov (1974), Chakrabarti and Gupta (1979), Vajravelu (1986) Takhar, Raptis and Pardikis (1987), Anderson (1992, 1995) had taken in context of research Newtonian fluids based on MHD flow. For the very first time, MHD flow of non-Newtonian fluids was investigated by Sarpkaya (1961). After his research work, Djukic (1973, 1974), Anderson, Bech and Dandopat (1992) followed him and studied its different aspects. MHD flows have many real life applications in metallurgy Industry. We may observe its applications as cooling of continuous strips, filaments drawn through a quiescent fluids and purification of molten metals from non-metalic inclusions. Non-Newtonian is the subject of interest for many researchers because it is by nature interdisciplinary and its real life applications are of greater importance. Its behavior is considered under investigation in all chemical and allied processing industries. Its area of applications is wide and diverse. In industrial and many other practical problems complete facts are not obtained about processes which are happening, if we consider fluid as Newtonian fluid. Therefore it is preferred to study models of non-Newtonian fluids. For example, Viscoelastic fluids. The study of Magneto-hydrodynamic non-Newtonian fluid flow in a porous medium has stimulated attention of many researchers due to wide applications in physical areas from liquid metals to cosmic plasmas. For example, MHD power generation, electrostatic precipitation, MHD pumps, aerodynamic heating plasma physics, geophysics and sprays. MHD casson fluid properties past a linearly stretched sheet with porosity was discussed by Nadeem et al. [9]. Recently, Malik et al. [10] surveyed boundary layer stragnation point flow of a MHD Williamson fluid through hyperpolarizing cylinder. Khalil-Ur-Rehman et al. [11] examined mixed convection of Eyring-Powell fluid flow over a stretching cylinder with the consequences of heat absorption/generation.

S. Nadeem et al. [12] studied about mixed convention of Eyring-Powell fluid. The Eyring-Powell fluid model is no doubt mathematically very complex but it attracts the attention of researchers due to the various advantages over the power law model. For the very first reason, we can say that rather than empirical relationship, it is deducted from theory of kinetics for liquids, when we consider the case of power law model. Secondly, for low and high shear stress rates. It converts its behavior to Newtonian behavior for low and high shear rates. Rizwan Ul Haq et al. [13] studied the effects of thermal radiations on MHD flow of nanofluids passed over the stretching sheet. They stuied flow qualities of MHD Sisko fluid through hyperpolarizing cylinder and provided numerical solution with the help of shooting method. T. Hayat et al. [14] interpreted the effects of MHD on the flow of an Eyring-Powell nanofluid. Many authors have made efforts to analyzed the non-Newtonian nanofluid flow and acquired many informative results. [15-19]

Porous medium is a material volume, consists of solid matrix which is interconnected with holes. Kambiz Vafai [20] discussed about the real life applications of porous media. This channel is characterized by porosity, which can be calculated by taking ratio of void space to the total volume of the channel. Darcy Law states that through porous channel flow velocity is linearly related to the pressure gradient. Porous medium is also characterized by calculating flow conductivity. Due to important applications in engineering field, porous medium gained attention in the era of research like insulation process and manufacturing. The flow of carreau fluid by a
porous medium was investigated by R. Ellahi et al. [21]. In recent years, there have been various studies [22-23] on the flows through porous media.

In the present investigation, we elaborated heat generation effects on Magnetohydrodynamic flow of an Eyring-Powell fluid model past a porous medium. We have explained applications of Magnetohydrodynamics flow. To the best of author's knowledge, this problem has not been explained before. Two distinct heat transfer problems are studied. The plate is assumed to be at higher temperature than the fluid in the first case and it is taken as insulated in the second case. The suitable similarity transformations are employed to transform the governing equations of the problem into simple differential equations. Equations are depicted in non-dimensional form. Numerical solutions are acquired by implying shooting technique of the under study problem. Graphs are plotted to present influences of distinct parameters on the momentum and energy profiles. Numerical results are obtained by calculating Nusselt numbers and skin friction coefficient.

**Mathematical Equations**

The Cauchy stress tensor of Eyring-Powell model fluid is expressed as

\[ S = \mu \nabla \mathbf{v} + \frac{1}{\beta} \sinh^{-1}\left( \frac{1}{C} \nabla \mathbf{v} \right), \tag{1} \]

where \( S \) denotes Cauchy stress tensor, \( \mu \) illustrates shear viscosity, \( \mathbf{v} \) indicates the velocity and \( C \) describes the material constant such that

\[ \sinh^{-1}\left( \frac{1}{C} \nabla \mathbf{v} \right) \approx \frac{1}{C} \nabla \mathbf{v} - \frac{1}{6} \left( \frac{1}{C} \nabla \mathbf{v} \right)^3, \quad \left| \frac{1}{C} \nabla \mathbf{v} \right| < 1. \tag{2} \]

**Mathematical modeling of the problem**

Past an infinite penetrable plate, we have talked over the heat generation impacts on magnetohydrodynamic (MHD) Eyring-Powell model fluid flow.
The governing equations may be expressed as

\[ \rho v_0 \frac{d^2 w}{dy^2} + \mu \frac{d^2 w}{dy^2} + \frac{1}{\beta C} \frac{d^2 w}{dy^2} - \frac{1}{2 \beta C^2} \left( \frac{d w}{dy} \right)^2 \frac{d^2 w}{dy^2} = \frac{\partial p}{\partial z}, \]

\[ \frac{\partial p}{\partial y} = 0, \]  \hspace{1cm} (4)

\[ \frac{\partial p}{\partial x} = 0. \]  \hspace{1cm} (5)

Eq. (3) can be written as

\[ \rho v_0 \frac{d^2 w}{dy^2} + \mu \frac{d^2 w}{dy^2} + \frac{1}{\beta C} \frac{d^2 w}{dy^2} - \frac{1}{2 \beta C^2} \left( \frac{d w}{dy} \right)^2 \frac{d^2 w}{dy^2} = L_1, \]

where

\[ \frac{\partial p}{\partial z} = \text{constant} = L_1. \]  \hspace{1cm} (7)

The appropriate boundary conditions for eq. (6) are

\[ w(0) = 0, \]  \hspace{1cm} (8)

\[ w(y) \rightarrow W_\infty \text{ as } y \rightarrow \infty. \]  \hspace{1cm} (9)

Heat flux \( q \) is expressed as

\[ q = -k \text{ grad } \theta. \]  \hspace{1cm} (10)

After simplifications, we get
\[ k \frac{d^2 \theta}{dy^2} + \rho c_p v_0 \frac{d \theta}{dy} + \mu \left( \frac{d w}{dy} \right)^2 + \frac{1}{\beta C} \left( \frac{d w}{dy} \right)^2 - \frac{1}{6 \beta C^3} \left( \frac{d w}{dy} \right)^4 + \frac{Q_0}{\rho c_p} (\theta - \theta_\infty) = 0, \]  

(11)

where \( c_p \) is the specific heat of fluid.

The suitable boundary condition for constant wall temperature may be expressed as:

\[ \theta(0) = 0, \]

\[ \theta(y) \to \theta_\infty \text{ as } y \to \infty. \]  

(12)

The boundary condition for the insulated wall are given by

\[ \frac{d \theta}{dy} \bigg|_{y=0} = 0, \]

\[ \theta(\infty) \to \theta_\infty. \]  

(13)

Non-dimensional equations for constant wall temperature

The non-dimensional parameters are introduced as,

\[ \tilde{y} = \frac{y}{L}, \quad \tilde{w} = \frac{w}{W_\infty}, Q = \frac{Q_0}{\rho c_p}, \quad \tilde{\theta} = \frac{\theta - \theta_\infty}{\theta_0 - \theta_\infty}, \]

(15)

\[ L = \frac{\beta V_0}{\mu}, \quad \gamma = \frac{\rho \beta W_\infty^2}{w^2} \cdot u^2, \quad u = \frac{v_0}{W_\infty}, \]

(16)

\[ \lambda = \frac{W_\infty^2 w}{k(\theta_0 - \theta_\infty)}, \quad E = \frac{W_\infty}{c_p (\theta_0 - \theta_\infty)}, \]

(17)

\[ M = \frac{1}{\beta c \mu}, \quad \varepsilon = \frac{\mu}{6 \beta C^3}, \quad \frac{1}{u^2}, \quad \text{Pr} = \frac{\mu c_p}{k}. \]

(18)

Momentum and energy equations take the form

\[ \frac{d^2 \tilde{w}}{d \tilde{y}^2} + M \frac{d^2 \tilde{w}}{d \tilde{y}^2} + \gamma \frac{d \tilde{w}}{d \tilde{y}} - 3 \varepsilon \left( \frac{d \tilde{w}}{d \tilde{y}} \right)^2 \frac{d^2 \tilde{w}}{d \tilde{y}^2} - \gamma E \tilde{w} = L_1, \]

(19)

\[ \frac{d^2 \tilde{\theta}}{d \tilde{y}^2} + \gamma \text{Pr} \frac{d \tilde{\theta}}{d \tilde{y}} + \lambda \left( \frac{d \tilde{w}}{d \tilde{y}} \right)^2 + M \lambda \left( \frac{d \tilde{w}}{d \tilde{y}} \right)^2 - \lambda E \left( \frac{d \tilde{w}}{d \tilde{y}} \right)^4 - Q \gamma \text{Pr} \tilde{\theta} = 0. \]

(20)

For simplicity, removing the bars in the eqs. (19-20) and we get

\[ \frac{d^2 w}{dy^2} + M \frac{d^2 w}{dy^2} + \gamma \frac{d w}{dy} - 3 \varepsilon \left( \frac{d w}{dy} \right)^2 \frac{d^2 w}{dy^2} - \gamma E w = L_2, \]

(21)

\[ \frac{d^2 \theta}{dy^2} + \gamma \text{Pr} \frac{d \theta}{dy} + \lambda \left( \frac{d w}{dy} \right)^2 + M \lambda \left( \frac{d w}{dy} \right)^2 - \lambda E \left( \frac{d w}{dy} \right)^4 - Q \gamma \text{Pr} \theta = 0. \]

(22)

Here \( L_1 \) and \( L_2 \) are constants. The dimensionless quantity \( \gamma \) described as the product of the Reynold's number and square of ratio between the suction velocity to free stream velocity i. e., \( u^2 \). Dimensionless quantity \( \varepsilon \) is written as the product of the non-dimensionless shear
thickening parameter \( \left( \frac{\mu_{\beta\mu}}{\rho C} \right) \) and \( \frac{1}{\nu} \). At the last, the dimensionless quantity i.e., \( \lambda \) represents the combination of Eckert number and prandtl number. The non-dimensional boundary conditions are

\[
\begin{align*}
\psi(0) &= 0, \\
\psi &\rightarrow 1 \text{ as } y \rightarrow \infty, \\
\text{and} \\
\theta(0) &= 1, \\
\theta &\rightarrow 0 \text{ as } y \rightarrow \infty.
\end{align*}
\] (23)

Non-dimensional equations for Insulated plate

We define non-dimensional forms below

\[
\theta^* = \frac{\theta - \theta_w}{\theta_b - \theta_w},
\] (25)

where \( \theta_b \) represents the bulk temperature and the remaining parameters are same. Also the equations of motion are remain same as the eqs. (20 – 21). We define the Eckert number that is

\[
E^* = \frac{W^2}{c_p(\theta_b - \theta_w)}.
\] (26)

Now, the suitable boundary conditions are

\[
\frac{d\theta}{dy} \bigg|_{y \to 0} = 0,
\] (27)

\[
\theta \to 0 \text{ as } y \to \infty.
\]

Where again for our simplicity stars and bars are removed and all other quantities are dimensionless.

The practically monumental physical objects i.e., skin friction and Nusselt number of flow field are expressed as

\[
C_f = \frac{\tau_w}{\frac{1}{2}\rho W^2} \text{ and } Nu_z = \frac{zq_w}{k(T_u - T_w)}.
\] (28)

In above equation skin friction is denoted with \( C_f \) and Nusselt number is shown as \( Nu_z \). Here, \( \tau_w \) represents wall shear stress and \( q_w \) indicates wall heat flux that are explained as

\[
\tau_w = \left[ \mu \frac{dw}{dy} + \frac{1}{\beta C} \frac{dw}{dy} - \frac{1}{6\beta C^3} \left( \frac{dw}{dy} \right)^3 \right]_{y \to 0}, \quad \text{and} \quad q_w = -k \left( \frac{\partial T}{\partial y} \right)_{y \to 0},
\] (29)

after applying suitable similarity transformation in the above relation, we get interesting monumental quantities in the form

\[
\frac{1}{2} C_f \text{ Re} = w'(0) + Mw'(0) - \varepsilon (w'(0))^3, \quad Nu_z = -\theta'(0).
\] (30)
Here, $Re$ represents Reynold number.

**Numerical Solution**

To get ordinary differential equations from the flow arising governing equations, the suitable similarity transformation is used which are highly nonlinear in nature. The influence of different dimensionless quantities are interpreted with the cooperation of graphs on velocity and temperature fields. Runge-Kutta method is used to solve the initial value problems. First of all we transform momentum and energy equations in first order form i.e.,

$$w' = \frac{-\gamma w'}{1 + M - 3\varepsilon (w')^2}, \quad (31)$$

$$\theta'' = -\gamma \Pr \theta' - \lambda (w')^2 - M \lambda (w')^2 + \lambda \varepsilon (w')^4 + Q \gamma \Pr \theta. \quad (32)$$

Now, defining new variables that are applied to reduce the higher order ordinary differential equations into first order i.e.,

$$w = z_1, \quad w' = z_2, \quad w'' = z_2', \quad \theta = z_3, \quad \theta' = z_4, \quad \theta'' = z_4'. \quad (33)$$

After putting the new variables, the new system of ordinary differential equations is obtained i.e.,

$$z_1 = z_2, \quad z_3' = z_4, \quad (34)$$

$$z_2' = \frac{-\gamma w'}{1 + M - 3\varepsilon (w')^2}, \quad (35)$$

$$z_4' = -\gamma \Pr \theta' - \lambda (w')^2 - M \lambda (w')^2 + \lambda \varepsilon (w')^4 + Q \gamma \Pr \theta, \quad (36)$$

along with the boundary conditions

$$x_1(0) = 0, \quad x_1(\infty) = 1, \quad x_3(0) = 1, \quad x_3(\infty) = 0. \quad (37)$$

**Graphical Results and Discussions**

To demonstrate the nature of above systematic inquiry, influence of emerging parameters upon velocity and temperature distributions are indicated with the cooperation of graphs and tables. **Fig. 1** illuminates the geometry of the problem. **Fig. 2** depicts the influence of $\gamma$ on velocity field. There is direct relationship between velocity distribution and the value of $\gamma$. The velocity distribution goes up due to increment in the value of $\gamma$. **Fig. 3** explores the impact of $M$ upon velocity profile. There is inverse type of relation between them. When $M$ increases, the velocity profile goes down. Due to increasing $\gamma$, **Fig. 4** illustrate the instance of variation in temperature profile. Temperature profile shows decline behavior due to rise in $\gamma$. **Fig. 5** explores the influence of $M$ on temperature field. Temperature distribution is growing by accelerating $M$. **Fig. 6** demonstrates the consequence of $\Pr$ on temperature profile. Owing to escalating $\Pr$, temperature profile points out lowering behavior. **Fig. 7** explores the relation of $\lambda$ with temperature field as same as of parameter $M$. **Fig. 8** elaborates the deductions of $M$ and $A$ on skin friction coefficient. The skin friction coefficient curve proliferates owing to increasing value of $M$. **Fig. 9** forecasts the impacts of $\lambda$ and $A$ on Nusselt number. The curve of Nusselt number has behavior of bending down when value of $\lambda$ increases. **Figs. 10-12** explores the nature about stream lines for different values of $\gamma$. Stream lines compress towards the root when the value of $\gamma$ accelerates. **Figs. 13-15** elaborates the three dimensional graphs of $w(y)$ for
different values of $\gamma$. The three dimensional graphs explain the bending nature of curve because of increasing $\gamma$. Table 1 explains the values of $\frac{d\theta}{dy}$ at the wall for distinct parameters. In first and fourth case, values of table elucidates that rate of change of temperature decreases, whenever the values of $\gamma$ and $Pr$ rise up. In second, third and fifth case, slope of temperature curve grows up as well as increment in the values of $M$, $\lambda$ and $Q$. Table 2 clarify the impact of different parameters on skin friction coefficient. The values of skin friction coefficient are enlarging because of expansion in the values of $A$, $M$ and $\varepsilon$, but it depicts constant behavior when we put different values of $Pr$ number. Table 3 clarifies the consequences of $Pr$, $\varepsilon$ and $\lambda$ on Nusselt number. The values of Nusselt number are increasing due to decreasing value of $\lambda$ but in case of $Pr$ and $\varepsilon$, there is positive variation in values.

![fig 2. eps, Impact of $\gamma$ on the velocity profile](image)

![fig 3. eps, Effect of E on the velocity profile](image)
fig 4. eps, Impact of $\gamma$ on temperature field

$Pr = 7.1$, $\lambda = 1.0$, $\kappa = 0.5$, $A = 0.1$, $M = 0.1$

fig 5. eps, Influence of $M$ on temperature distribution

$Pr = 7.1$, $\lambda = 1.2$, $\kappa = 0.8$, $Q = 0.1$, $M = 0.2$
**fig 6.** eps, Effect of Pr on temperature profile

**fig 7.** eps, Effect of $\lambda$ on temperature profile
fig 8. eps, Effect of M and A on skin friction

fig 9. eps, Impact of $\lambda$ and $\gamma$ on Nusselt number
fig 10. cps, Stream lines for $\gamma=0.1$
fig 11. eps, Stream lines for $\gamma=0.4$

fig 12. eps, Stream lines for $\gamma=1.5$
fig 13. eps, Three dimensional graph for w(x)

fig 14. eps, Three dimensional graph for w(x)
Table 1. Values of $\frac{d\theta}{dx}$ at the wall.

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<td></td>
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Table 2. Values of skin friction coefficient with respect to $A$, $\varepsilon$, $M$.

<table>
<thead>
<tr>
<th>$A$</th>
<th>$\varepsilon$</th>
<th>$M$</th>
<th>$\frac{1}{2}C_f$ Re</th>
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Table 3. Values of Nusselt number with respect to Pr, $\lambda$, $\varepsilon$.

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Concluding Remarks
In this problem, an elaboration has been contended to explore the nature of Eyring-Powell fluid model with the cooperation of conservation laws mathematical modeling of the problem is developed. Runge Kutta method along with shooting technique is implemented to attain numerical solution of the problem. To depict the flow problem, resultant of different parameters upon velocity and temperature fields are demonstrated. Graphical representation and tabulation is used to explain the phenomenon. Attractive corollaries are obtained which are redefined below:

1) Because of acceleration in the value of $\gamma$, velocity profile shows decreasing behavior but recovery occurs within enlargement in $M$.
2) By accelerating value of $\gamma$ and Pr temperature profile decreases but increases due to increment in the value of $\lambda$.
3) Stream lines illustrates the shrinking behavior and three dimensional graphs are showing bending behavior owing to accretion in $\gamma$.
4) Skin friction curve is going upward whenever we boost up the values of pertinent parameters.
5) Rate of change in temperature is mostly rising upward because of accretion in distinct parameters.
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