Research Article

MHD Flow of Thermally Radiative Maxwell Fluid Past a Heated Stretching Sheet with Cattaneo–Christov Dual Diffusion

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This study explains the impression of MHD Maxwell fluid with the presence of thermal radiation on a heated surface. The heat and mass transmission analysis is carried out with the available of Cattaneo–Christov dual diffusion. The derived PDE equations are renovated into ODE equations with the use of similarity variables. HAM technique is implemented for finding the solution. The importance of physical parameters of fluid velocity, temperature, concentration, skin friction, and heat and mass transfer rates are illustrated in graphs. We found that the fluid velocity declines with the presence of the magnetic field parameter. On the contrary, the liquid temperature enhances by increasing the radiation parameter. In addition, the fluid velocity is low, and temperature and concentration are high in Maxwell fluid compared to the viscous liquid.

1. Introduction

Many industrial processes depend on fluids especially, non-Newtonian fluids. Few examples are plastic sheet extrusion, paper production, spinning of metals, glass fiber, etc. Maxwell is one of the non-Newtonian models, and he predicts the stress relaxation. The primary principle of MHD is that forces are produced in the fluid when the magnetic field induces a current through a moving conducting fluid. Magnetohydrodynamics has diverse engineering applications. Sandeep et al. [1] examined the stretching surface flows of Oldroyd-B, Jeffrey, and Maxwell fluids with non-uniform heat source/sink impacts along with radiation effects. They found that Oldroyd-B and Maxwell fluids have lesser effects compared to the Jeffrey fluid. Farooq et al. [2] analyzed the exponentially stretching sheet flow of a Maxwell-type nanomaterial. The Buongiorno model was used in this study to construct the physical model. Fetecau et al. [3] discussed the porous channel flow of the upper-convected Maxwell (UCM). Also, steady-state transient components have an appearance of oscillatory motion. Wang et al. [4] and Sun et al. [5] established the incompressible Maxwell fluid passed through a tube through a triangular cross section (rectangular or isosceles). Analytical approaches are implemented for steady-state solutions of two oscillatory motions. Few other studies about the Maxwell fluid types have been implemented by Qi and Xu [6], Wenchang et al. [7], and Qi and Liu [8].

Heat transfer is a natural phenomenon of heat owing between the object or within the object in the order of the temperature difference. This phenomenon has a wide application in enormous fields such as semiconductors, cooling devices, and power generation. In earlier days, heat transfer is characterized by the Fourier law of heat conduction [9]. However, this law fails to explain the heat transfer effect, and in nature, no material will satisfy this law. So, Cattaneo [10]
extended the work of Fourier by including the thermal relaxation time. Later, Christov [11] upgraded Catteneo's work with the help of Oldroyd’s upper-convected derivatives and thermal relaxation time for efficient performance. Saleem et al. [12] investigated the 3D combined convective Maxwell fluid with mass and heat Catteneo–Christov heat flux models with heat generation. Loganathan et al. [13] presented the second-order slip phenomenon of Oldroyd-B fluid with cross diffusion, radiation, and Catteneo–Christov heat flux impacts. Mango-free convection of nanoliquid presented the second-order slip phenomenon of Oldroyd-B.

Saleem et al. [12] investigated the 3D combined convective and thermal relaxation time for efficient performance. Later, Christov [11] upgraded Catteneo’s work with the help of Oldroyd’s upper-convected derivatives and thermal relaxation time for efficient performance. Saleem et al. [12] investigated the 3D combined convective and thermal relaxation time for efficient performance. Loganathan et al. [13] presented the second-order slip phenomenon of Oldroyd-B fluid with cross diffusion, radiation, and Catteneo–Christov heat flux impacts. Mango-free convection of nanoliquid presented the second-order slip phenomenon of Oldroyd-B.

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\[\psi = \sqrt{\alpha x f}(\eta), u_1 = \frac{\partial \psi}{\partial y}, v_1 = -\frac{\partial \psi}{\partial x}. \]

\[u_1 = ax^n f'(\eta), v_1 = -\sqrt{\alpha x} f'(\eta), \quad (6)\]

\[\theta(\eta) = \frac{T-T_\infty}{T_f-T_\infty}, \quad \phi(\eta) = \frac{C-C_\infty}{C_w-C_\infty} \]

Apply the above transformations:

\[f'''' + ff''' - f'' + \lambda (2ff'' + f'f) - Mf' = 0, \quad (7)\]

\[\left(1 + \frac{4}{3}R\right)\theta'' + Prf \theta' - Pr\gamma^2 \eta \left(f''^2 + f'f\right) + Pr Hg \theta = 0, \quad (8)\]

\[\frac{1}{Sc} \phi'' + f \phi' - \gamma_5 \eta \left(f'' \phi + f' \phi\right) = 0, \quad (9)\]

The engineering quantities are stated as

\[\frac{1}{2} C_f \sqrt{\text{Re}} = (1 + \lambda) f''(0) \quad \text{("Local skin friction")}, \]

\[\frac{Nu}{\sqrt{\text{Re}}} = -\frac{1 + 4R}{3} \theta'(0) \quad \text{("Local Nusselt number")}, \]

\[\frac{Sh}{\sqrt{\text{Re}}} = -\phi'(0) \quad \text{("Local Sherwood number")}. \quad (12)\]

### 3. HAM Solution

Several numerical schemes are available for solute the nonlinearity problems. The efficient semianalytic process HAM was employed to solve these current nonlinearity problems. This method presents the independence to select the primary assumptions of the solutions.

The initial guesses are

\[f_0 = f \omega + 1 - e^{-\eta}, \quad (13)\]

\[\theta_0 = \frac{B_i \eta}{1 + Bi} \]

\[\phi_0 = e^{-\eta}. \quad \text{Linear operators are} \]

\[L_f = f''''(\eta) - f'(\eta), L_\theta = \theta''(\eta) - \theta(\eta) \text{ and } L_\phi = \phi''(\eta) - \phi(\eta), \quad (14)\]

\[L_f [\Delta_1 + \Delta_2 e^{\eta} + \Delta_3 e^{-\eta}] = 0, \quad L_\theta [\Delta_4 e^{\eta} + \Delta_5 e^{-\eta}] = 0, \text{ and } L_\phi [\Delta_6 e^{\eta} + \Delta_7 e^{-\eta}] = 0, \quad \text{where } \Delta_j(j = 1 - 7). \]
Generally, the HAM solution depends on the auxiliary parameters $h_f$, $h_\theta$, and $h_\phi$, and these parameters control the convergence. The range value of $h_f$ is $-1.4 \leq h_f \leq -0.2$, $-0.2 \leq h_\theta \leq 0$, and $-1.8 \leq h_\phi \leq -0.2$. We fix $h_f = -0.8$ and $h_\theta = h_\phi = -1$ for better convergence (see Figure 2). Table 1 provides the order of HAM, and we found that 15th order is adequate for all profiles. Table 2 indicates the code validation of $f''(0)$ for various values of $\lambda$ with the limiting value of $M = 0$.

### 4. Result and Discussion

In this section, we focus on the importance of physical parameters of fluid velocity, fluid temperature, fluid concentration, skin friction coefficient, local Nusselt number, and local Sherwood number for viscous fluid ($\lambda = 0.0$) and Maxwell fluid ($\lambda = 0.4$). Figures 3(a)–3(d) show the impact of $\lambda$, $M$, $f w^+$, and $f w^-$ on velocity profile for both viscous and Maxwell fluids. Figure 3(a) provides the impact of Deborah number ($\lambda$) on the velocity of the fluid. The fluid velocity improves while boosting up the values of $\lambda$. For Newtonian fluids, the opposite effect is produced by $\lambda$, for these type of fluids, the boundary layer thickness rises for higher $\lambda$. Figure 3 elucidates the magnetic field ($M$) influence on velocity of the fluid. The higher range of $M$ produces a reduction in velocity of the fluid because the Lorentz force is created against the fluid flow by magnetic field. The maximum Lorentz force is produced while the magnetic field is applied at perpendicular to the fluid flow. For this reason, momentum boundary layer thickness reduces. The fluid velocity suppresses with more availability of suction, and it enhances in the injection case (see Figures 3(c) and 3(d)).

The significance of $\gamma$, $R$, $Bi$, and $f w^+$ on fluid temperature profile for both fluids was illustrated in Figures 4(a)–4(f) and seen that the fluid temperature becomes high with enhancing the values of $R$, $Bi > 0.0$ and $f w^+ > 0.0$ for both fluids. However, it decreases for $f w^- = 0.0$ and $Bi < 0.0$. In addition, the thickness of the thermal boundary layer is high in Maxwell fluid compared to viscous fluid. Figures 5(a)–5(d) provide the variance of fluid...
concentration for “$\gamma_c$, $fw$, and $Sc$” for both fluids. It is noted that the fluid concentration is a nondecreasing function of injection, and the reverse trends were obtained in “$\gamma_c > 0$, $fw$, and $Sc$” for both fluids. It is also noted that the concentration boundary layer is high in Maxwell fluid compared to viscous fluid.

The skin friction coefficient for different combination of “$fw$, $M$, and $\lambda$” was shown in Figures 6(a) and 6(b). It is concluded that the surface shear stress declines with increasing values of “$fw$, $M$, and $\lambda$”. Figures 7(a) and 7(b) explain the local Nusselt number for different combinations of “$Bi$, lambda, $R$, and $\gamma$.” It is found that the heat transfer gradient raises with escalating the values of “$Bi$, $\gamma$, and $R$,” and it decreases with heightening the values of “$\lambda$.” The local Sherwood number for different combinations of “$\gamma_c$, $M$, $\lambda$, and $Sc$” are presented in Figures 8(a) and 8(b). We noted that the mass transfer gradient becomes small with rising the values of “$M$ and $\lambda$” and it is high for the presence of “$\gamma_c$ and $Sc$.”

| $\lambda$ | Mukhopadhyay [37] | Sadghey et al. [38] | Present |
|-----------|-------------------|---------------------|---------|
| 0.0       | 0.9999963         | 1.000               | 1.00000 |
| 0.2       | 1.051949          | 1.0549              | 1.05189 |
| 0.4       | 1.101851          | 1.10084             | 1.10190 |
| 0.6       | 1.150162          | 1.0015016           | 1.15014 |
| 0.8       | 1.196693          | 1.19872             | 1.19671 |

Table 2: Code validation results with $f''(0)$ obtained by Mukhopadhyay [37] and Sadghey et al. [38] in the limiting condition for various $\lambda$ by fixing $M = 0$. 

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Figure 3: Impact of velocity on the different values of parameters. (a) $\lambda = 0.0, 0.4, 0.8, 1.2$, (b) $M = 0.0, 0.4, 0.8, 1.2$, (c) $fw = 0.0, 0.2, 0.4, 0.6$, and (d) $fw = -0.0, -0.2, -0.4, -0.6$. 
Figure 4: Impact of temperature on the different values of parameters. (a) $y = 0.0, 0.2, 0.4, 0.6$, (b) $R = 0.0, 0.5, 1.0, 1.5$, (c) $Bi = 0.0, 0.3, 1.0, 2.0$, (d) $Bi = 0.0, -0.2, -0.4, -0.6$, (e) $fw = 0.0, 0.2, 0.4, 0.6$, and (f) $fw = 0.0, -0.2, -0.4, -0.6$. 
Figure 5: Impact of concentration on the different values of parameters. (a) $\gamma_c = 0.0, 0.2, 0.4, 0.6$, (b) $f_w = 0.0, 0.2, 0.4, 0.6$, (c) $f_w = 0.0, -0.2, -0.4, -0.6$, and (d) $S_c = 0.5, 1.0, 1.5, 2.0$.

Figure 6: Impact of skin friction on combined parameters. (a) $\lambda$ and $f_w$ and (b) $M$ and $f_w$. 
5. Conclusions

In our analysis, we found the following key points:

(i) The fluid velocity declines with escalating the value of magnetic field parameter (M) and Maxwell fluid parameter (λ).

(ii) Rising values of thermal relaxation time and Biot number leads to the higher heat transfer rate.

(iii) The fluid concentration suppresses by enhancing the values solutal relaxation time.

(iv) The surface shear stress is suppressing function of M and f_w.

(v) The mass transfer gradient enhances with improving the solutal relaxation time parameter.

Abbreviations

\begin{align*}
& a: \quad \text{Stretching rate (s}^{-1}\text{)} \\
& Bi: \quad \text{Biot number} \\
& B_0: \quad \text{Constant magnetic field (kgs}^{-2}\text{A}^{-1}) \\
& C: \quad \text{Concentration (kgm}^{-3}\text{)} \\
& c_p: \quad \text{Specific heat (J kg}^{-1}\text{K}^{-1}) \\
& C_{\infty}: \quad \text{Ambient concentration (kgm}^{-3}\text{)} \\
& C_w: \quad \text{Fluid wall concentration (kgm}^{-3}\text{)} \\
& f (\eta): \quad \text{Velocity similarity function} \\
& f_w: \quad \text{Suction / injection parameter} \\
& H_g: \quad \text{Heat generation parameter} \\
& h_f: \quad \text{Convective heat transfer coefficient (W m}^{-1}\text{K}^{-1}) \\
& k_f: \quad \text{Thermal conductivity (W m}^{-1}\text{K}^{-1}) \\
& M: \quad \text{Hartmann number} \\
& Nu: \quad \text{Nusselt number} \\
& Pr: \quad \text{Prandtl number} \\
& Q: \quad \text{Dimensional heat generation/absorption coefficient} \\
& R: \quad \text{Radiation parameter} \\
& Sc: \quad \text{Schmidt number} \\
& Sh: \quad \text{Sherwood number} \\
& T: \quad \text{Temperature (K)} \\
& T_{\infty}: \quad \text{Ambient temperature (K)} \\
& T_f: \quad \text{Convective surface temperature (K)} \\
& u_{1x}: \quad \text{Velocity of the sheet (ms}^{-1}\text{)} \\
& u_x, v_y: \quad \text{Velocity components in (x, y) directions (ms}^{-1}\text{)}
\end{align*}
\( v_1 > 0 \): Suction velocity
\( v_1 < 0 \): Injection velocity
\( x, y \): Cartesian coordinates (m)
\( \beta \): Relaxation time of the fluid
\( \phi(\eta) \): Concentration similarity function
\( \gamma \): Dimensionless thermal relaxation time
\( \gamma_c \): Dimensionless mass relaxation time
\( \eta \): Similarity parameter
\( \lambda_T \): Thermal relaxation time
\( \lambda_m \): Mass relaxation time
\( \lambda \): Maxwell fluid parameter
\( \nu \): Kinematic viscosity (m\(^2\) s\(^{-1}\))
\( \theta(\eta) \): Temperature similarity function
\( \rho \): Density (kg m\(^{-3}\))
\( \sigma \): Electrical conductivity (Sm\(^{-1}\))
\( \psi \): Stream function (ms\(^{-1}\)).

**Data Availability**

The raw data supporting the conclusions of this article will be made available by the authors without undue reservation.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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