Three-Dimensional Rotating Flow of MHD Jeffrey Fluid Flow between Two Parallel Plates with Impact of Hall Current

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This article deals with three-dimensional non-Newtonian Jeffrey fluid in rotating frame in the presence of magnetic field. The flow is studied in the application of Hall current, where the flow is assumed in steady states. The upper plate is considered fixed, and the lower is kept stretched. The fundamental equations are transformed into a set of ordinary differential equations (ODEs). A homotopy technique is practiced for a solution. The variation in the skin friction and its effects on the velocity fields have been examined numerically. The effects of physical parameters are discussed in various plots.

1. Introduction

The rotation of fluid exists in nature due to the fact that the fluid particles rotate internally and rises with fluid movement. Due to engineering and industrial applications, the scientist considers the rotational fluid coupled with various features. Rotational fluids have many applications in engineering. Taylor and Geoffery introduced the motion of viscous fluid in the rotating system [1]. The detailed study of fluid in rotating system is done by Greenspan [2] and Goodman [3]. The effects of MHD in a rotating system and stretched and porous mediums have been studied by Attila and Kotb [4], Borkakoti and Bharali [5], and Vajravelu and Kumar [6]. This work has been magnified along with the temperature effects by Mehmood and Ali [7], Das et al. [8], and Tauseef et al. [9].

The non-Newtonian fluid is used in many industry and technology appliances. Hayat et al. studied the non-Newtonian fluid in a rotating frame, considering the effects of MHD for micropolar nanofluids [11, 12]. Jeffrey’s model was presented by Jeffrey as a subclass of non-Newtonian fluid and studied with convection term [13, 14].

Most of the physical problems are nonlinear and have rare exact solutions. The numerical methods (NMs) and analytical methods (AMs) are used to get the results. The NMs required discretization techniques which can affect the results. Among the AMs, HAM proposed by Liao is the most powerful and fast convergent [15–19]. Hall introduced Hall current and proves that, in case of strong magnetic field, the Hall current effects cannot be ignored [20]. Similar other interesting studies are provided in [21–32] for different fluid models. This article aims to elaborate the non-Newtonian nanofluid in the rotating frame with Hall effect. Hall effect is produced due to the potential difference across an electrical conductor when a magnetic field is acting in a direction vertical to that of the flow of current. So, for this aim, Jeffrey fluid flow is considered. For the proposed model, HAM is used.
2. Problem Formulation

Assume the Jeffrey fluid between two parallel plates having d separation. The plate and fluid rotate about y axis with \( \Omega \). The lower plate is stretched by two opposite and equal forces. A uniform magnetic field \( B_0 \) is applied perpendicularly with a steady-state condition (Figure 1).

The fundamental identities are

\[
\begin{align*}
\rho (u \tilde{x} + v \tilde{y} + \tilde{w}) &= 0, \\
\rho \left( u \tilde{x} + v \tilde{y} + 2w \Omega \right) &= -p + \frac{\mu}{1 + \gamma_1} \left( \tilde{u}_{xx} + \tilde{u}_{yy} \right) - \frac{\sigma B_0^2}{1} \left( \tilde{u} + 2 \tilde{w} \right) + \frac{\mu y_2}{1 + \gamma_1} \left( \tilde{u}_{xxx} + \tilde{u}_{xyy} \right) + \tilde{v} \left( \tilde{u}_{xx} + \tilde{u}_{xxy} \right) + \tilde{w} \left( \tilde{u}_{xy} + \tilde{u}_{xxy} \right) + \tilde{u} \left( \tilde{v}_{xx} + \tilde{v}_{xyy} \right) + \tilde{v} \left( \tilde{v}_{xy} + \tilde{v}_{xxy} \right) + \tilde{w} \left( \tilde{v}_{xy} + \tilde{v}_{xxy} \right) + \tilde{v} \left( \tilde{w}_{xx} + \tilde{w}_{xyy} \right) + \tilde{w} \left( \tilde{w}_{xy} + \tilde{w}_{xxy} \right), \\
\rho \left( u \tilde{x} + v \tilde{y} - 2 \Omega u \right) &= -p + \frac{\mu}{1 + \gamma_1} \left( \tilde{v}_{xx} + \tilde{v}_{yy} \right) + \frac{\mu y_2}{1 + \gamma_1} \left( \tilde{v}_{xxx} + \tilde{v}_{xyy} \right) \tilde{u} + \tilde{v} \left( \tilde{v}_{xx} + \tilde{v}_{xyy} \right) \tilde{u} + \tilde{w} \left( \tilde{v}_{xy} + \tilde{v}_{xxy} \right) \tilde{u} + \tilde{u} \left( \tilde{w}_{xx} + \tilde{w}_{xyy} \right) \tilde{u} + \tilde{v} \left( \tilde{w}_{xy} + \tilde{w}_{xxy} \right) \tilde{u} + \tilde{w} \left( \tilde{w}_{xy} + \tilde{w}_{xxy} \right) \tilde{u} + \tilde{v} \left( \tilde{w}_{xy} + \tilde{w}_{xxy} \right) \tilde{u} + \tilde{w} \left( \tilde{w}_{xy} + \tilde{w}_{xxy} \right) \tilde{u}.
\end{align*}
\]

The BCs are

\[
\begin{align*}
\tilde{u}(0) &= ax, \\
\tilde{v}(0) &= 0 = \tilde{w}(0), \\
\tilde{u}(d) &= \tilde{v}(d) = \tilde{w}(d) = 0.
\end{align*}
\]

The similarity transformation used is

\[
\begin{align*}
\tilde{u} &= ax f'(\eta), \\
\tilde{v} &= -a df(\eta), \\
\tilde{w} &= ax g(\eta), \\
\eta &= \frac{y}{d}.
\end{align*}
\]

Using equation (6) in (1)–(4), we get

\[
\begin{align*}
f'''' + (1 + \gamma_1) \left( R \left( f f'' - f' f'' \right) \right) - 2Krf' &= \left( \frac{M}{1 + m^2} \right) \left( f'''' + m g' \right) + \beta \left( 2 f'' f'' - f f'''' - f' f'''' \right), \\
g'' + (1 + \gamma_1) R (fg' - g f') + 2Krf'' &= \left( \frac{M}{1 + m^2} \right) \left( g - m f' \right) + \beta \left( f g' - g f' \right).
\end{align*}
\]

Substituting equation (8) in (7), we get
\[ f(0) = 0, \quad f'(0) = 1, \quad g(0) = 0, \quad f(1) = 0, \quad f'(1) = 0, \quad g(1) = 0, \]

where

\[ Kr = \frac{2\Omega d^2}{\nu}, \]
\[ R = \frac{ad^2}{\nu}, \quad (10) \]
\[ M = \frac{\sigma B_0 d^2}{\rho \nu}, \]
\[ \beta = a \gamma_2. \]

\[ c_f = \frac{(\mu(1 + \gamma_1)) \left[ (\frac{\partial^2 v}{\partial x^2}) + (\frac{\partial^2 v}{\partial y^2}) + \gamma_2 (\frac{\partial^2 u}{\partial x \partial y}) + \nu (\frac{\partial^2 v}{\partial x \partial y}) + u (\frac{\partial^2 v}{\partial x^2}) + v (\frac{\partial^2 u}{\partial y^2}) \right]_{y=0}}{\rho u_w^2} \]
functions defined on topological spaces \( \mathbb{X}, \mathbb{Y} \), then

\[
\psi: \mathbb{X} \times [0,1] \longrightarrow \mathbb{Y},
\]

such that \( \bar{x} \in \mathbb{X} \):

\[
\psi(0) = \Psi_1,
\psi(1) = \Psi_2.
\] (13)

The initial guesses are

\[
\bar{f}(\xi). = \bar{g}(\xi). = \bar{f}'(\xi). = 0,
\]

\[
\bar{f}(1.\xi). = \bar{g}(1.\xi). = \bar{f}'(1.\xi). = 0,
\]

\[
N_l = \bar{f}_\eta + \beta(2\beta\bar{f}_\eta\bar{f}_\eta - \bar{f}\bar{f}_\eta\bar{f}_\eta),
\]

\[
N_{ll} = \bar{g}_\eta + (1 + \gamma_1)R(\bar{f}\bar{g}_\eta + \bar{g}\bar{f}_\eta) + 2k\bar{r}\bar{g}_\eta + \beta(\bar{g}\bar{f}_\eta - \bar{g}_\eta\bar{f}_\eta).
\] (19)

Table 1: Convergence table of HAM up to the 25th-order approximations when \( R = \beta = \gamma_1 = m = M = 0.01 \).

| Order of approximation | \( f''(0) \) | \( g'(0) \) |
|------------------------|--------------|--------------|
| 1                      | 3.18886      | 0.2207921    |
| 3                      | 3.17650      | 0.2387064    |
| 6                      | 3.17584      | 0.2396453    |
| 11                     | 3.17583      | 0.2396677    |
| 15                     | 3.17583      | 0.2396682    |
| 20                     | 3.17583      | 0.2396682    |

The linear terms are

\[
L_l(f) = f_{\eta\eta\eta},
\]

\[
L_l(g) = g_{\eta},
\] (16)

with differential operator

\[
L_l(D_1 + D_2\eta + D_3\eta^2 + D_4\eta^3) = 0,
\]

\[
L_{ll}(D_3 + D_4\eta) = 0,
\] (17)

where \( D_n \) represents arbitrary constants, where \( n = 1, 2, 3, \ldots, 6 \).

3.1. Zeroth-Order Problem. Express \( q \in [0,1] \) as an embedding parameter with \( h_f \) and \( h_g \), where \( h \neq 0 \). Then,

\[
(1 - q)L_l(\bar{f}(\eta, q) - \bar{f}_0(\eta)) = ph_fN_l(\bar{f}, \bar{g}),
\]

\[
(1 - q)L_g(\bar{g}(\eta, q) - \bar{g}_0(\eta)) = ph_gN_g(\bar{f}, \bar{g}).
\] (18)

The BCs are

\[
f_0 = \eta^3 - 2\eta^3 + \eta,
g_0 = 0.
\] (15)
Figure 3: Effect of $R$ on $f(\eta)$ when $m = 0.5, \gamma_1 = 0.7, M = 1, \beta = 0.4$, and $kr = 0.6$.

Figure 4: Effect of $R$ on $g(\eta)$ when $m = 0.5, \gamma_1 = 0.7, M = 1, \beta = 0.4$, and $kr = 0.6$.

Figure 5: Effect of $kr$ on $f(\eta)$ when $m = \gamma_1 = 0.8, M = 0.4, R = 1$, and $\beta = 0.4$.

Figure 6: Effect of $kr$ on $g(\eta)$ when $m = \gamma_1 = 0.8, M = 0.4, R = 1$, and $\beta = 0.4$.

Figure 7: Effect of $m$ on $f(\eta)$ when $R = 1, \gamma_1 = 0.7, \beta = 0.4, M = 1$, and $kr = 0.6$.

Figure 8: Effect of $m$ on $g(\eta)$ when $R = 1, \gamma_1 = 0.7, \beta = 0.4, M = 1$, and $kr = 0.6$. 
Figure 9: Effect of $\gamma_1$ on $f(\eta)$ when $R = 0.1, m = 0.8, \beta = 0.4$, and $M = kr = 1$.

Figure 10: Effect of $\gamma_1$ on $g(\eta)$ when $R = 0.1, m = 0.8, \beta = 0.4$, and $M = kr = 1$.

Figure 11: Effect of $\beta$ on $f(\eta)$ when $R = 1, m = \gamma_1 = 0.8, M = 1$, and $kr = 0.6$.

Figure 12: Effect of $\beta$ on $g(\eta)$ when $R = 1, m = \gamma_1 = 0.8, M = 1$, and $kr = 0.6$.

Figure 13: Effect of $M$ on $f(\eta)$ and $g(\eta)$ when $R = 1, m = \gamma_1 = 0.8, \beta = 1$, and $kr = 0.6$.

Figure 14: Effect of $M$ on $f(\eta)$ and $g(\eta)$ when $R = 1, m = \gamma_1 = 0.8, \beta = 1$, and $kr = 0.6$. 
3.2. \( l \)th-Order Deformation Problem.

\[
\begin{align*}
  f_1(\eta) &= \frac{1}{P} (\tilde{f}_1)_{q=0}, \\
  g_1(\eta) &= \frac{1}{P} (\tilde{g}_1)_{q=0}.
\end{align*}
\]

(20)

\[
L_l \left( f_1(\eta) - \prod_l f_{l-1}(\eta) \right) = h_f \mathfrak{R}_l^f (\eta),
\]

\[
L_l \left( g_1(\eta) - \prod_l g_{l-1}(\eta) \right) = h_g \mathfrak{R}_l^g (\eta),
\]

where

\[
\mathfrak{R}_l^f (\eta) = f_{l-1}^{(v)} + 2 k r g_{l-1} + (1 + \gamma_1) \left[ R \sum_{j=0}^{l-1} \left( f_{l-1-j} f_j^{(v)} - f_{l-1-j} f_j^{(v)} - f_{l-1-j} f_j^{(v)} \right) - \left( \frac{M}{1 + m^2} \right) (f_{l-1}^{(v)} + m g_{l-1}^{(v)}) \right]
\]

\[
+ \beta \sum_{j=0}^{l-1} \left( 2 f_{l-1-j} f_j^{(v)} - f_{l-1-j} f_j^{(v)} - f_{l-1-j} f_j^{(v)} \right),
\]

\[
\mathfrak{R}_l^g (\eta) = g_{l-1}^{(v)} - (1 + \gamma_1) R \sum_{j=0}^{l-1} \left( f_{l-1-j} g_j^{(v)} - g_{l-1-j} f_j^{(v)} \right) + Kr \cdot f_{l-1}^{(v)} - \left( \frac{M}{1 + m^2} \right) (m f_{l-1}^{(v)} - g_{l-1}^{(v)}),
\]

\]

Table 2: Variation in skin friction coefficient for dissimilar values of \( R, Kr, \beta, \) and \( \gamma_1 \) when \( m = 0.1 \) and \( M = 0.5. \)

| \( R \) | \( Kr \) | \( \gamma_1 \) | \( \beta \) | \( \zeta \) | Shehzad et al. [15] results | Present results |
|---|---|---|---|---|---|---|
| 0.01 | 0.5 | 1.0 | 0.5 | 0.0 | 2.6312 | 3.86416 |
| 0.1 | 0.5 | 1.0 | 0.5 | 0.0 | 2.65133 | 2.94882 |
| 0.5 | 0.5 | 0.9 | 0.5 | 0.0 | 2.63995 | 2.64208 |
| 1.0 | 0.5 | 0.9 | 0.5 | 0.0 | 1.31217 | 4.33999 |
| 0.01 | 0.5 | 1.0 | 0.5 | 0.0 | 1.25917 | 4.34157 |
| 0.1 | 0.5 | 1.0 | 0.5 | 0.0 | 1.21694 | 4.36897 |
| 0.5 | 0.5 | 0.9 | 0.5 | 0.0 | 2.38508 | 5.64227 |
| 1.0 | 0.5 | 0.9 | 0.5 | 0.0 | 1.25917 | 5.44576 |
| 0.01 | 0.5 | 1.0 | 0.5 | 0.0 | 1.03399 | 4.89911 |
| 0.1 | 0.5 | 1.0 | 0.5 | 0.0 | 0.61911 | 2.22743 |

4. Convergence of HAM

With the help of assisting constraints \( h_f \) and \( h_g \), the convergence region is achieved. The possible region of convergence for the proposed model is given in Figure 2 and Table 1.
5. Results and Discussion

The effect of $R$ on $f (\eta)$ and $g (\eta)$ is given in Figures 3 and 4. An increase in $R$ decreases $f (\eta)$ and $g (\eta)$. The large amounts of viscous energy reduction produce large inertial forces, which decreases $f (\eta)$ and $g (\eta)$. The effect of $k\tau$ on the $f (\eta)$ and $g (\eta)$ is shown in Figures 5 and 6. It is evident that an increase in $k\tau$ increases fluid flow due to increase in Coriolis force. This fluid rotation increases kinetic energy which also increases the flow rate. The influence of $m$ and $\gamma_1$ on $f (\eta)$ and $g (\eta)$ is given in Figures 7–10, respectively. Both reduce velocity profile. The effect $\beta$ is given in Figures 11 and 12, showing that the velocity profile increases by increasing $\beta$. The relaxation time gets smaller by enhancing $\gamma_1$. The effects of $M$ on $f (\eta)$ and $g (\eta)$ are presented in Figures 13 and 14, respectively, $\beta$ and $M$ oppose the flow due to large relaxation time and magnetic effects. The magnetic field opposes the flow in the $y$ direction and enhances in the $z$ direction.

The numerical values of $R, \gamma_1, \beta$, and $k\tau$ on $C_f$ are presented in Table 2. We see that $C_f$ has inverse relations with $R, \gamma_1, \beta$ and decreases $C_f$ while on direct relation with $k\tau$.

6. Conclusion

The following conclusion is observed:

(i) A rise in $R$ causes to decline $c_f$.

(ii) The mass flux decreases at a lower plate and increases at upper plate.

(iii) $R, \gamma_1, m$ resist the velocity profile.

(iv) $\beta, k\tau$ assist the velocity profile.

(v) $M$ resists the flow along the $y$ direction and assists the flow along the $z$ direction.

Nomenclature

Gravitational acceleration: $g$ (m/S$^2$)

Density: $\rho$ (kg/m$^3$)

Distance between two plates: $d$ (m)

Angular velocity: $\Omega$ (m$^2$/s)

Magnetic field: $B_0$

Ratio of time relaxation to time retardation: $\gamma_1$

Shear stress: $\tau$ (kg/ms$^2$)

Electrical conductivity: $\sigma$ (Siemens per meter (S/m))

Time: $t$ (S)

Velocity: $V$ (m/s)

$x$-component: $u$ (m/s)

$y$-component: $v$ (m/s)

$z$-component: $w$ (m/s)

Dynamic viscosity: $\mu$ (kg/ms)

Kinematic viscosity: $\nu$ (m$^2$/s)

Volume: $V$ (m$^3$)

Pressure: $P$ (N/m$^2$).

Data Availability

The data used to support the findings of this study are available in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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