Research Article

Buoyancy Effect on a Micropolar Fluid Flow Past a Vertical Riga Surface Comprising Water-Based SWCNT–MWCNT Hybrid Nanofluid Subject to Partially Slipped and Thermal Stratification: Cattaneo–Christov Model

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This paper provides a comprehensive analysis of the mixed convective flow that comprises SWCNT-MWCNT/water hybrid nanofluid containing micropolar fluid through a partially slipped vertical Riga surface. A Cattaneo–Christov heat flux model is used to examine the heat transport rate. The energy equation is gaining more significance with the effect of viscous dissipation and thermal stratification. The flow model is transformed by convenient transformation into nondimensionless form. The numerical results of nonlinear complex equations are collected using the bvp4c built-in function from MATLAB which is based on the finite difference method. The graphical results are obtained for both hybrid nanofluid and simple nanofluid. The temperature distribution for hybrid nanofluid is higher than that for simple nanofluid when the solid volume fraction increases. The axial friction factor increases with solid volume fraction, porosity parameter, and mixed convection parameter. The velocity graph varies inversely with nanofluid volume fraction and micropolar parameter.

1. Introduction

Because of heat transfer enhancement application, nanofluids are still very interesting to study. Many previous studies have shown that the performance of nanofluid heat transfer is higher than usual fluids. So, it is better to discuss the nanofluid instead of regular fluid. Nanoliquids have a significantly higher thermal conductivity than other liquids, which is one of their most important properties. In industries such as nuclear reactors, transportation, food, electronics, and biomedicine, nanofluids play a significant role. Nanoparticles are very small (1 nm–100 nm) particles that increase the conductivity of normal fluids when applied to them. The shape of nanoparticles is made of metal oxide, carbon tubes (SWCNT and MWCNT), carbide, silicon, and nitride, etc. Choi [1] initially presented nanofluids and used a large range of nanofluids in production processes in the industries. Nadeem et al. [2] evaluated the flow towards a moving wedge with three different nanoparticles and induced magnetic field. Dianchen et al. [3] deliberated the mass and heat transport in the occurrence of carbon nanotubes with the influence of the heat generation...
coefficient. The convection boundary layer that flows across a vertical cone with carbon nanotubes in the existence of magnetohydrodynamics is scrutinized by Rahmat et al. [4]. Shafiq et al. [5] addressed the significance of SWCNTs and MWCNTs through a static wedge under the magnetohydrodynamics (MHD) impact. In the involvement of a uniform magnetic field, Sheikholeslami and Bhatti [6] explored the nanofluid forced convective heat transfer in a porous semiannulus. Saleem et al. [7] numerically investigated the heat transfer enhancement utilizing nanoparticles past a flat surface. Recent studies of nanofluids are scrutinized through attempts [8–20].

Hybrid nanofluids are new nanofluid categories that produced a small particle of metal. Hybrid nanofluids are of remarkable use in modern areas including applied science, engineering, biology, and agriculture. Heat and cooling storage performance can be improved with hybrid nanofluids at a low cost. As a result, nanofluids are more advantageous because they can be used in hybrid fuel turbines, diesel engine oil, and chillers enhancement. MWCNT nanoparticles affect engine oil preparation, as they increase CNT to oil ratios and thermal conductivity. In [21–24], some recent research on hybrid nanoliquid has been noted. Mehryan et al. [25] investigated the effects of the combined convection Cu-Al2O3/water hybrid nanoliquid and Al2O3/water nanoliquid within a square cavity induced by a warm cylinder oscillation. Sundar et al. [26] tested the MWCNT-Fe2O4/water hybrid nanofluid thermal conductivity within the temperature range of 30°C and 60°C. Baghbanzadeh et al. [27] found out the viscosity and thermal conductivity of the MWCNT/SiO2 hybrid nanofluids. Mackolil and Mahanthesh [28] scrutinized the radiated Casson and nanofluids’ flow with numerical computations of exact and statistical under mass and heat flux boundary conditions. Hussain and Muhammad [29] discussed the convective carbon/water flow of wall and hall characteristics in peristaltic with the influence of Soret and Dufour.

Nadeem et al. [30] investigated the interaction of MWNCT and SWNCT across the oscillatory state with the heat transfer. Mahanthesh et al. [31] studied heat transport of hybrid MoS 2-Ag nanoliquid flowing over an isothermal wedge with the importance of viscous dissipation and Joule heating. Temperature and volume concentration on dynamics viscosity of hybrid nanofluids in the presence of ethylene glycol and MWCNT [32]. Mackolil and Mahanthesh [33] discussed the analysis of TiO 2-EG nanoliquid in Marangoni convection including temperature-dependent surface tension and nanoparticle aggregation.

Impacts of EMHD (Electro-magnetohydrodynamic) by fluid flows perform an elementary role in the production of momentum and the importance found in thermal reactor, microcoolers, liquid chromatography, and managing the flow in a network of fluidic. According to early research, Gailitis [34] invented the Riga plate flow control method. This system is an electromagnetic actuator, and it retains magnets permanently; a continuous separation of the boundary layer helps decline the pressure drag. Zaib et al. [35] considered the entropy generation effects on the combined convection micropolar nanofluid flow past a vertical Riga surface. Abbas et al. [36] investigated the entropy production on viscous nanoliquid towards a Riga sheet. Ahmad et al. [37] examined the combined convective flow including nanofluid out of a Riga plate and obtained the analytical solution by a perturbation method. The Riga plate was considered by Magyari and Pantokratoras [38] to examine the influence of Lorentz force on a Blasius electrically conducting fluid flow.

The micropolar liquid is a unique form of non-Newtonian liquid and the most well-known. Liquids with microstructure are called micropolar liquids. Non-Newtonian liquids in our everyday lives include oils, fruit, juice, mud, emulsions, toothpaste, butter, and ointments. Anandha Kumar et al. [39–41] studied the micropolar fluid under different effects. This exploration inspired to examine the influence of mixed convection on the micropolar SWCNT-MWCNT/water hybrid nanofluid via a vertical Riga sheet with Cattaneo–Christov heat flux, variable viscosity, viscous dissipation, and thermal stratification. To the best of the reviewer’s awareness, no work has been conducted so far on hybrid nanofluids with combined buoyancy effect across a Riga sheet in the existence of micropolar fluid, thermal stratification, and variable viscosity. The transformed equations are explained numerically by applied the MATLAB well-known bvp4c technique. The effect of distinct characteristics on heat and velocity profile is shown graphically and displayed in the table.

2. Problem Formation

Consider the two-dimensional micropolar hybrid nanofluid flow with variable viscosity embedded in the porous vertical Riga surface with viscous dissipation. In the existence of thermal stratification and the Cattaneo–Christov heat flux model, the heat equation is further performed. The physical justification of the considered model is explained in Figure 1 where \( \vec{v} \) and \( \vec{r} \) are velocity components in the directions \( y \) and \( x \), respectively.

Mathematically, viscosity in the variable form is determined by Shafiq and Nadeem [13]:

![Microscopic view of hybrid nanofluid](image-url)
Applying the boundary layer approximation, the basic governing equations take the form as [35, 42, 44, 45]

\[
\frac{\partial \mu}{\partial y} + \frac{\partial \mu}{\partial x} = 0,
\]

\[
\frac{\partial \mu}{\partial x} + \frac{\partial \mu}{\partial y} = u_{nsf} \frac{\partial \mu_{nsf}}{\partial x} + \frac{1}{\rho_{nsf}} \frac{\partial}{\partial y} \left( \left( \mu_{nsf} (T) + \kappa \right) \frac{\partial \mu}{\partial y} \right) + \frac{(\rho \beta)_{nsf}}{\rho_{nsf}} g(T - T_{nsf}) + \frac{\pi J_{0} M_{0} e^{-\pi(i) y}}{8 \rho_{nsf}}
\]

\[
\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} = \rho_{nsf} \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial x} \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) + \frac{\partial T}{\partial y} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) - \frac{\mu_{nsf} (T)}{(\rho C_{p})_{nsf}} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^{2}
\]

\[
= \alpha_{nsf} \frac{\partial^{2} T}{\partial y^{2}} + \frac{\mu_{nsf} (T)}{(\rho C_{p})_{nsf}} \left( \frac{\partial u}{\partial y} \right)^{2}.
\]

The subjected boundary conditions are

\[
\begin{align*}
\bar{u} |_{y=0} &= \mu_{nsf} (T) \frac{\partial \mu}{\partial y} |_{y=0}, \\
\bar{v} |_{y=0} &= 0, \\
\bar{T} |_{y=0} &= \bar{T}_{w} (x) = T_{0} + Bx, \\
\bar{N}_{1} |_{y=0} &= -n \frac{\partial \eta}{\partial y} |_{y=0}, \\
\bar{n} |_{y \to -\infty} &\to \bar{n}_{\infty} (x), \\
\bar{T} |_{y \to -\infty} &\to \bar{T}_{\infty} = T_{0} + B_{1} x, \\
\bar{N}_{1} |_{y \to -\infty} &\to 0.
\end{align*}
\]

The mathematical symbols in the governing equations are, namely, defined in the nomenclature. From the micropolar model, \( n \) is steady with the given closed interval [0, 1]. The limiting case condition \( n = 0 \) is imposed for the strong concentration where the intense particles near the shrinking/stretching surface do not swivel. The strong concentration and the no-slip condition \( N = 0 \) both are similarly matched at the given limiting case. The microstructure particles have a very small influence near the shrinking surface of the sheet, and this behavior is noted for the condition \( n \neq 0 \). Particularly in the condition, \( n = 0.5 \) indicates weak concentration. Also, the turbulent boundary layer flows are produced due to the pertinent condition, \( n = 1 \).

Further, the thermal conductivity, variable viscosity, specific heat, and density for SWCNT-MWCNT/water (hybrid nanofluid) and SWCNT/water (nanofluid) are defined as follows [42]:

Simple nanofluid:
\[ \alpha_{nf} = \frac{k_{nf}}{(\rho C_P)_{nf}}, \]
\[ \mu_{nf} = \mu_f (1 - \phi)^{-2.5}, \]
\[ (\rho C_P)_{nf} = (\rho C_P)_{SWCNT} \phi + (\rho C_P)_f (1 - \phi), \]
\[ \rho_{nf} = \phi \rho_{SWCNT} + (1 - \phi) \rho_f, \]
\[ (\rho \beta)_{nf} = (\rho \beta)_{SWCNT} \phi + (\rho \beta)_f (1 - \phi), \]
\[ \frac{k_{nf}}{k_f} = \frac{(1 - \phi) + 2\phi (k_{SWCNT}/k_{SWCNT} - k_f) \ln(k_{SWCNT} + k_f/k_f)}{(1 - \phi) + 2\phi (k_f/k_{SWCNT} - k_f) \ln(k_{SWCNT} + k_f/k_f)}. \]

Hybrid nanofluid:

\[ \alpha_{hnf} = \frac{k_{hnf}}{(\rho C_P)_{hnf}}, \]
\[ \mu_{hnf} = \frac{\mu_f (1 - \phi_1)^{-2.5} (1 - \phi_2)^{-2.5}}{1 + \theta \theta_r}, \]
\[ (\rho C_P)_{hnf} = \phi_2 (\rho C_P)_{SWCNT} + (1 - \phi_2) \left\{ (1 - \phi_1) (\rho C_P)_f + \phi_1 (\rho C_P)_{MWCNT} \right\}, \]
\[ \rho_{hnf} = \phi_2 \rho_{SWCNT} + (1 - \phi_2) \left\{ (1 - \phi_1) \rho_f + \phi_1 \rho_{MWCNT} \right\}, \]
\[ (\rho \beta)_{hnf} = (\rho \beta)_{SWCNT} \phi_2 + (1 - \phi_2) \left\{ (1 - \phi_1) (\rho \beta)_f + \phi_1 (\rho \beta)_{MWCNT} \right\}, \]
\[ \frac{k_{hnf}}{k_f} = \frac{(1 - \phi_2) + 2\phi_2 (k_{SWCNT}/k_{SWCNT} - k_{bf}) \ln(k_{SWCNT} + k_{bf}/k_{bf})}{(1 - \phi_2) + 2\phi_2 (k_f/k_{SWCNT} - k_f) \ln(k_{SWCNT} + k_f/k_f)}. \]

where

\[ \frac{k_{bf}}{k_f} = \frac{(1 - \phi_1) + 2\phi_1 (k_{MWCNT}/k_{MWCNT} - k_f) \ln(k_{MWCNT} + k_f/k_f)}{(1 - \phi_1) + 2\phi_1 (k_f/k_{MWCNT} - k_f) \ln(k_{MWCNT} + k_f/k_f)}. \]

Here the solid volume fraction of MWCNT and SWCNT are, respectively, exemplified by \( \phi_1 \), and \( \phi_2 \) and \( k_f \) identify the water-based thermal conductivity of the fluid; specific heat is symbolized by \( C_p \). The deviation amount for thermo-physical properties applied in this examination is categorized in Table 1.
2.1. Similarity Transformation Conversion. The following similarity transformation is used [42]:

\[
\eta = \sqrt{\frac{c}{v_f}} y_j
\]

\[
\theta(\eta) = \frac{T - T_{\infty}}{T_w - T_0}
\]

\[
\bar{N}_1 = c x \left( \frac{c}{v_f} \right) g(\eta),
\]

\[
\bar{u} = c x f'(\eta),
\]

\[
\bar{v} = -\sqrt{\bar{v}_f} f(\eta),
\]

where \(v_f\) represents the kinematic viscosity of the carrier-based liquid.

Applying equation (10), equations (2)–(6) transmuted to the following dimensional form of ODEs as follows:

\[
\left( \frac{1}{A_2(1 + \theta_f)} + K \right) f'''' + Hae^{-\lambda_2} + A_1 \left( f f'' + 1 + f'^2 \right)
\]

\[
-\frac{\theta_f' f'''}{A_2(1 + \theta_f)} + Kg_1 + \frac{P_m}{(1 + \theta_f)} f'(1) + \lambda A_1 \theta = 0,
\]

\[
\left( \frac{1 + \theta_f}{A_2} \right) g'' - K2g + Kf'' - A_1 \left( f' g - f g' \right) = 0,
\]

\[
A_6 \theta'' + Pr A_5 \left[ f \theta' - f' \theta - S_1 f' - \gamma \left( \theta f'^2 + S_1 f'^2 - f f' \theta' - S_1 f'' - f f' \theta' + f^2 \theta'' \right) \right]
\]

\[
+ \frac{E_c Pr f'^2}{(1 + \theta_f) A_2} - \frac{2y E_c Pr}{(1 + \theta_f) A_2} \left( f''' f f'' - f'' f' \right) = 0,
\]

while the transform appropriate conditions are

\[
f'(0) = \frac{s f''(0)}{\theta_f(1 + \theta_f)}, g(0) = -nf''(0), f(0) = 0, \text{and } \theta(0) = 1 - S_i,
\]

\[
f'(\eta) = 1, \theta(\eta) = 0 \text{ and } g(\eta) = 0, \quad \text{at } \eta \to \infty.
\]

The dimensionless parameter involved in equations (11)–(14) is identified as follows:

\[
A_1 = \left( 1 - \phi_j \right) \left( 1 - \phi_j + \phi_1 \frac{\rho_{\text{MCNT}}}{\rho_f} \right) + \phi_2 \frac{\rho_{\text{SWCNT}}}{\rho_f}
\]

\[
A_2 = \frac{\rho_{\text{SWCNT}}}{\rho_f} \frac{\rho_{\text{MCNT}}}{\rho_f} \frac{\phi_2}{\phi_1}
\]

\[
A_3 = \left( 1 - \phi_j \right) \left( 1 - \phi_j + \phi_1 \frac{\rho C_p}{\rho_{\text{MCNT}}} \right)
\]

\[
+ \phi_2 \left( \frac{\rho C_p}{\rho_{\text{SWCNT}}} \right)
\]

\[
A_5 = \left( 1 - \phi_j \right) \left( 1 - \phi_j + \phi_1 \frac{\rho C_p}{\rho_{\text{MCNT}}} \right)
\]

\[
+ \phi_2 \left( \frac{\rho C_p}{\rho_{\text{SWCNT}}} \right)
\]

\[
\gamma = \frac{\phi_1}{\phi_2}
\]

\[
\beta = \frac{\phi_3}{\phi_1}
\]

\[
\lambda = \frac{\rho c^2}{\rho_{\text{MCNT}}}
\]

\[
Pr = \frac{\gamma_j}{\alpha_f}
\]

\[
s = \frac{\mu_f}{\mu_j}
\]
2.2. Engineering Physical Quantities of Interest. The local skin friction is stated as
\[ C_f = \frac{\tau_w}{\rho_f u_\infty^2} \]  (16)
where \( \tau_w = ((\kappa + \mu_n) (T)) (\partial u/\partial y) + \kappa N \) \( \nu \) is the wall shear stress for the micropolar hybrid nanofluid. Using (10) into equation (16), the following reduced dimensionless form of the skin friction takes place as
\[ \text{Re}_{x} C_{f} = \frac{1}{A_1} \left[ K(1 - n) + \frac{1 + \theta, \theta(0)}{A_2} \right] f''(0), \]  (17)
whereas the local Reynolds number is indicated as \( \text{Re}_x = (x \bar{u}_\infty / y_f) \).

3. Methodology of the Numerical Solution
The system of equations (11)–(13) is obtained in the form of dimensionless ODEs along with appropriate boundary stipulations (14), after using self-similarity transformations (10). The system of equations is highly nonlinear and difficult to solve exactly. Therefore, the solution to the current investigation is achieved numerically by the MATLAB bvp4c technique. It is a built-in function from MATLAB and is based on the finite differences scheme which is generally known as Lobatto IIIA formula. This method is working only when the dimensionless ODEs are in the first-order ODEs. For the working process of the considered method, we need to transform our equations from the higher third and second order into a first order by implementing the new variables. Let the new variables are as follows:
\[ f = y_1, \]
\[ f' = y_2, \]
\[ f'' = y_3, \]
\[ y_1 = \left( \frac{1}{A_2} + K \right)^{-1} \left\{ -A_1 (1 + y_1 y_3 - y_2^2) + \frac{\theta, y_2 y_3}{A_2 (1 + \theta, \theta)^2} - \frac{P_m}{A_2} (1 - y_2) \right\}, \]  (19)
\[ y_2 = \left( \frac{1}{A_2} + K \right)^{-1} \left\{ A_1 (y_2 y_4 - y_1 y_5) + K (2 y_4 + y_3) \right\}, \]  (21)
\[ \theta = y_6, \]
\[ \theta' = y_7, \]
\[ y_3 = \left( \frac{1}{A_6 - \gamma \theta, \theta} \right)^{-1} \left\{ E, \text{Pr} y_3^2 \left( 1 + y_4 \theta, \theta \right) + \text{Pr} A_5 y_3 y_1 y_3 - y_2 y_3 - y_2 S_1 + y_1 y_2 y_3 \right\}, \]  (23)
with the transform initial conditions.
To solve the aforementioned equations, the system required initial early guesses at the mesh point to accomplish our conditions (24). For clearer and better understanding of the current method bvp4c, the detail flow chart has also been added (see Figure 2). A convergence criterion $10^{-8}$ is provided for the solution which has been obtained. We have set appropriate finite values $\eta \rightarrow \infty$, that is, $\eta = \eta_{\infty} = 2.5$ to 4, based on the values of the suggested variables.

### 4. Results and Discussion

This section of the work demonstrates the consequences of the involved sundry parameter in the considered problems on velocity profiles, microrotation profiles, temperature profiles, and shear stress. The impacts of these parameters are shown through various different graphs (see Figures 3–18). For the computation purposes, we have fixed the value of the constraint throughout the simulation as the following $Pr = 6.2$, $s = 0.7$, $n = 0.5$, $\Lambda = 0.5$, $\gamma = 0.3$, $Ha = 0.1$, $\theta = 1.0$, $\lambda = -1.1$, $P_m = 0.7$, and $K = 0.25$. The visual findings are addressed for both SWCNT-MWCNT/water hybrid nanofluid and SWCNT/water nanofluid. The current issue demonstrates strong alignment with the recently published article that is explained in Table 2.

#### 4.1. The Behavior of Different Characteristics on the Velocity Field

The impact on velocity distribution of the $s$ (slip parameter), $Ha$ (modified Hartman number), $P_m$ (porosity parameter), $\theta$ (variable viscosity parameter), $\phi_2$ (solid volume fraction), and $K$ (micropolar parameter) is depicted in Figures 3–8. Figure 3 is considered to capture the influence of $s$ on velocity $f' (\eta)$. On velocity distribution, it displays rising behavior. On both nanofluid and hybrid nanofluid, the thickness of the velocity boundary layer is often observed to be decreasing. Figure 4 explains that as $Ha$ increased, the velocity field increases. Physically, the $Ha$ values result in the enhancement of internal and external forces including electric forces and adhesive. In these forces, the momentum flow increases, as an effective fluid velocity rises. The influence of $P_m$ on $f' (\eta)$ is sketched in Figure 5. With the increasing estimate, $P_m$, the thickness of the momentum boundary layer declines. Figure 6 highlights that
4.2. Impact of Different Characteristics on Microrotation Profiles. The characteristic of the micropolar parameter \( K \) on the microrotation field is exhibited in Figure 9. It is visible from the observation of certain figure that \( g(\eta) \) is reduced by growing \( K \). It is further observed that near the surface, the microrotation profile enhances for both simple and hybrid nanofluids. Figures 10 and 11 are designed to see the variance of the microrotation field for various parameters of flow, including solid volume fraction \( \phi_2 \) and variable viscosity \( \theta_r \). It is seen from these figures that the microrotation profile \( g(\eta) \) enhances both \( \phi_2 \) and \( \theta_r \).

4.3. Effect of Various Parameters on Fluid Temperature. Figures 12–16 justify that how \( \gamma \) (thermal relaxation time), \( \phi_2 \) (solid volume fraction), \( E_c \) (Eckert number), \( S_1 \) (thermal stratification parameter), and \( \lambda \) (mixed convection parameter) affect \( \theta(\eta) \). \( \theta(\eta) \) is plotted in Figure 12 as \( \phi_2 \) varies. Due to an increase in the solid volume fraction, the conductivity of thermal enhances which improves the temperature \( \theta(\eta) \). Figure 13, \( \theta(\eta) \) reduces with improving values of \( \gamma \). Physically, it is because particles express a nonconductive attitude as we escalate \( \gamma \), i.e., it takes longer for particles to disperse heat to their neighboring particles, which is responsible for lowering the distribution of temperature. Figure 14 confirms that \( \theta(\eta) \) decreases with \( \lambda \). \( \theta(\eta) \) improves with improving \( E_c \) (see in Figure 15). The mechanical fluid’s energy is converted to thermal energy for an increase of the Eckert number \( E_c \) from 0 to 1 due to internal molecular friction. As seen from Figure 16, \( \theta(\eta) \) reduces \( S_1 \). Physically, change \( S_1 \) decreases the difference in temperature between the surface and ambient fluid that contributes to the smaller temperature.

4.4. Effect of Several Parameters on Skin Friction. Figures 17 and 18 illustrate the skin friction \( Re_s^{1/2}C_{fx} \) against \( \phi_2 \) (solid volume fraction) with the impact of \( \lambda \) and \( P_m \). Figure 17 scrutinized the increasing behavior when \( \lambda \) and \( \phi_2 \) boost. Figure 18 demonstrated the impact of solid volume fraction and porosity parameter on \( Re_s^{1/2}C_{fx} \). From the figure, it is explained that, for both values of \( P_m \) and \( \phi_2 \), \( Re_s^{1/2}C_{fx} \) boosts.
**Figure 7:** Result of $K$ on $f' (\eta)$.

**Figure 8:** Influence of $K$ on $f' (\eta)$.

**Figure 9:** Impression of $K$ on $g (\eta)$.

**Figure 10:** Upshot of $\phi_2$ on $g (\eta)$.

**Figure 11:** Result of $\theta_\tau$ on $g (\eta)$.

**Figure 12:** Impact of $\phi_2$ on $\theta (\eta)$.
Figure 13: Results of $\gamma$ on $\theta(\eta)$.

Figure 14: Influence of $\lambda$ on temperature $\theta(\eta)$.

Figure 15: Result of $E_x$ on temperature $\theta(\eta)$.

Figure 16: Influence of $S_1$ on $\theta(\eta)$.

Figure 17: $Re_x^{1/2}C_{fx}$ versus $\phi_2$ for $\lambda$.

Figure 18: $Re_x^{1/2}C_{fx}$ versus $\phi_2$ for $P_m$. 

$\theta(\eta)$

$\gamma = 0.5, 1.0, 2.0$

$\lambda = 0.0, 1.0, 2.0$

$E_x = 0.0, 0.5, 1.0$

$P_m = 0.0, 0.5$
5. Concluding Remarks

This article concisely reports on the mixed convective micropolar fluid flow that comprises SWCNT-MWCNT/water hybrid nanofluid towards a partially slipped vertical Riga sheet. The present model is original and new. The problem gains more importance with the effect of thermal stratification, viscous dissipation, and Cattaneo–Christov heat flux. To resolve the transformed ordinary differential equation, the MATLAB bvp4c technique is used to solve the system numerically. The effect of various characteristics on velocity and heat transfer is inspected. Micropolar nanofluids may be used to increase the rate of cooling or heating in all electronic devices. Given below is an important description of such a problem:

(i) Velocity \( f' (\eta) \) varies inversely with the micropolar parameter \( K \) and the nanofluid volume fraction, \( \phi_2 \)

(ii) Improving \( \theta_r \) and \( \phi_2 \) strongly boosts the microrotation profile, but it is a contradictory behavior for \( K \)

(iii) Axial friction factor enhances with mixed convection parameter, porosity parameter, and solid volume fraction

(iv) \( \theta (\eta) \) is an increasing function of \( \phi_2 \) and \( E_c \), while decreasing function of \( S_1, \gamma, \) and \( \lambda \)

(v) Velocity \( f' (\eta) \) enhances with \( s, H_a, \theta_r, \) and \( \rho_m \)

Nomenclature

\[(x, y): \text{Cartesian coordinates}\]
\[(\Pi, \nu): \text{Velocity components in } x \text{ and } y \text{ directions}\]
\[E_c: \text{Eckert number}\]
\[\kappa: \text{Vortex viscosity}\]
\[d: \text{Electrodes and magnets width}\]
\[K^*: \text{Porous medium permeability}\]
\[j: \text{Microinertia density}\]
\[g: \text{Gravitational acceleration}\]
\[J_0: \text{Density of applied current in the electrodes}\]
\[C_p: \text{Specific heat} (\text{J/kg K})\]
\[M_0: \text{The permanent magnets' magnetization}\]
\[\tilde{T}: \text{Temperature of the fluid}\]
\[T_{\infty}: \text{Free-stream temperature} (\text{K})\]
\[H_a: \text{Modified Hartman number}\]
\[s: \text{Slip parameter}\]
\[K^*: \text{Micropolar parameter}\]
\[l: \text{Slip length}\]
\[\bar{v}_{\infty} (x): \text{Free-stream velocity of the fluid}\]
\[N: \text{Component of microrotation}\]
\[f'(\eta): \text{Dimensionless velocity component}\]
\[g(\eta): \text{Dimensionless angular velocity component}\]
\[Pr: \text{Prandtl number}\]
\[Gr: \text{Grashof number}\]
\[Re: \text{Local Reynolds number}\]
\[C_f: \text{Surface drag force}\]

Greek symbols

\[\mu: \text{Dynamic viscosity}\]
\[\nu: \text{Kinematic viscosity}\]
\[\rho: \text{Density}\]
\[\Lambda: \text{Dimensionless parameter}\]
\[\alpha_{nf}: \text{Thermal diffusivity of hybrid nanofluid}\]
\[\beta: \text{Coefficient of thermal expansion}\]
\[\phi: \text{Volume fraction of nanoparticles}\]
\[\lambda: \text{Mixed convection parameter}\]
\[\theta_r: \text{Dimensionless temperature}\]
\[\tau_w: \text{Shear stress}\]
\[\eta: \text{Parameter of thermal relaxation time}\]
\[\eta: \text{Similarity variable}\]

Subscripts

SWCNT: Single Wall Carbon Nanotube
MWCNT: Multiwall Carbon Nanotube
\( f: \text{Condition at free stream}\)
\( w: \text{Wall boundary condition}\)
\( hnf: \text{Hybrid nanofluid}\)
\( nf: \text{Nanofluid}\)
\( \infty: \text{Free-stream condition}\)

Superscripts

\( \text{'}: \text{Derivative with respect to } \eta \)

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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