



Keller box investigation of hybrid nanofluid flow using aluminum alloys over radiative Riga plate surface subjected to variable porous medium

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Abstract

The current study explores the effects of radiative heat and variable porosity on the steady flow of an incompressible hybridised nanomaterial comprising hybrid alloy nanoparticles (AA7072, AA7075) along with water (H₂O) as the conventional fluid. The proposed investigation is performed within the framework of the Riga plate. Because of the complementary benefits of nanoparticles, a hybrid nanofluid is used to improve the efficacy of heat transfer fluids. The flow scenario is characterized by a system of dimensional, nonlinear differential equations reduced to a set of nonlinear dimensionless ordinary differential equations using appropriate similarity substitution. The Keller Box Method (KBM) then solves these transformed equations. Graphs have been used to inspect the effects of changing physical factors on fluid flow, temperature, and other important measurements. This study evaluates the dependability of the results by comparing them to previous research. The results reveal the significant impact of the flow medium inverse porosity on both the boundary layers and the flow resistance and heat transfer characteristics. The Riga plate significantly affects the fluid flow and heat transfer, leading to variations in velocity profiles due to the generated electromagnetic field. The influence of radiative heat becomes more pronounced at higher temperatures, increasing heat transport for high-temperature applications.

1. Introduction

Hybrid nanofluids are a developed class of nanofluids, which are engineered by suspending hybrid nanoparticles in a host liquid. These innovative liquids combine the developed heat transport properties of traditional nanofluids with the added benefits of synergistic impacts arising from the combination of multiple nanoparticles. The hybrid nanoparticles can be made from various mixtures, such as metal-metal oxide, metal-carbon, or carbon-carbon nanotubes, leading to larger thermal performance, stability, and versatility associated with single-component nanofluids. Humnic et al. [1] considered water-based graphene oxide nanofluid and water-ethylene glycol in 1:1 ration base liquid with silver

to evaluate the thermal properties of nanofluids under several conditions. Mahboobtosi et al. [2] explored the impact of a tri-hybrid nanofluid and compared their results with a water-based copper nanofluid. In particular, the trihybrid nanofluid comprised MoS₂, Cu, and Ag nanoparticles to evaluate their characteristics over various flow phenomena. The circulation of hybridized nanomaterial around a cylinder, considering the influence of radiating heat under the assumption of the Rosseland approximation, vis-à-vis the role of activation energy explored by Madhu et al. [3]. Moreover, the present study shows the results obtained using the “shooting technique” and the “Runge-Kutta Fehlberg 45”

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numerical approach. Imoro et al. [4] scrutinized the Magnetohydrodynamics (MHD) flow of hybridized nanoliquid through thermal radiation in their study, assuming blood as the base liquid. The governing equations are handled utilizing the “Laplace transform method” associated with modified Bessel functions. Saleem et al. [5] explored a magneto-hydro dynamic hybrid nanofluid flow including a colloidal mixture with the conventional fluid. A standard numerical approach, i.e., the “Keller box method” is used to analyze the proposed model. Hybrid nanofluids have recently gained keen attention for their effective thermal properties and are widely used in applications like solar water heaters, etc. The hybridized nanomaterial movement via an inclined stretching disk was investigated by Alharbi et al. [6]. Moreover, the impact of variations in thin film and inclined disc configurations is taken into account. Ali et al. [7] scrutinized the Darcy-Forchheimer model-based flow features of a double-hybridized nanomaterial via a Riga plate, and the results are depicted by withdrawing the effect of thermal radiation. The nanofluid comprises two different nanoparticles, likely silicon graphite (C) and silicon carbide (SiC), suspended in ethylene glycol. Additionally, they analyzed the “Cattaneo-Christov heat flux model” within the governing equations.

Thermal radiation generally dominates the released electromagnetic radiation from the surface of the substance because of the body temperature. Understanding thermal radiation is crucial in fields such as astronomy, materials science, and engineering, where precise control or utilization of heat transfer processes is necessary. Panda et al. [8] deliberated the control of thermal stratification and radiative heat considering Powell-Eyring non-Newtonian fluid via a Riga plate to evaluate the “Cattaneo-Christov heat flux model”. Moreover, the inclusion of thermal transport phenomena along with radiant heat significantly enhances the scope of the study. The subsequent nonlinear Partial Differential Equations (PDEs) are transformed into Ordinary Differential Equations (ODEs) and solved numerically by deploying the “Runge-Kutta method” in conjunction with a “shooting approach”, a reliable numerical technique. Zehra et al. [9] explored the thermal transference phenomena of nanofluid using the “Casson nanofluid model”, incorporating the “double diffusional Cattaneo-Christov heat flux model”. In their study, the focus was on a curved tube that either shrinks or widens. Concurrently, Salahuddin et al. [10] scrutinized the “Cattaneo-Christov model” in a 2D stagnation point flow of nanoliquids, considering activation energy and the viscosity effects in need of temperature. Shoukat et al. [11] applied the theory of “Cattaneo-Christov double diffusion” to investigate Powell-Eyring fluid flowing over a convective sensor plate, seeing the role of an applied magnetic field and radiation effects. Awan et al. [12] investigated an Eyring–Powell model for nanofluid flow through a Riga plate surface. Shah et al. [13] explored a numerical model for the Carreau–Yasuda nanofluid upon a Riga plate, incorporating a variable thermal conductivity.

Akbar et al. [14] analyzed a Riga plate in motion that was subjected to thermal characteristics employing the Tiwari-Das model. Ali et al. [15] discussed the behavior of H₂O-based Al₂O₃-Cu/ hybrid nanomaterial under the conditions of heat flux and heat dissipation. Ali et al. [16] anticipated the behavior of an H₂O-based Al₂O₃-Cu/ hybrid nanomaterial via a Riga plate under conditions of significant suction, and a numerical approach, i.e., the “Adams-Bashforth technique” is employed to handle the system. Ali et al. [17] studied the impact of Cattaneo-Christov characteristics of hybrid nanofluid. Moreover, the consequences of radiation and Joule heating are also considered by introducing wall properties. Mumraiz et al. [18] addressed heat transport under the application of hybrid nanofluid. This examination portrays the consequences of non-uniform heat flux variations. Furthermore, a detailed analysis is performed to investigate how different dimensionless parameters affect the flow fields graphically. Eswaramoorthi et al. [19] analyzed the characteristics of inertial drag for the Darcy–Forchheimer flow model in silver–water nanofluid flowing over a Riga plate, considering dissipation and the effect of radiation. A hybrid methodology is employed for the revised flow problems with the help of bvp4c presented in MATLAB and the “Homotopy Analysis Method”. Kumar et al. [20] scrutinized the thermal aspects of radiative third-grade nanomaterial over a sensor plate via a porous medium considering convective conditions. An investigation examines the free convection of a magneto-polar material through an elongating surface considered by Baithalu and Mishra [21], with the diversified role of radiant heat and reacting species. Pattnaik et al. [22] reported a numerical investigation of nanomaterial movement past a radially widening sheet, incorporating radiant heat. Moreover, the study presents and discusses the physical behavior of several parameters. A new mathematical model has been created to study the diffusion of reactive species under forced convection of nanofluid by Pattnaik et al. [23]. Additionally, the validation involves implementing an “Adams-Moulton predictor–corrector” numerical scheme. Panda et al. [24] presented the movement of Williamson liquid within two parallel sheets. They also explored the interplay and combined effect of radiation and Joule heating. Furthermore, they applied the Homotopy Perturbation Method (HPM) to solve the transformed equations analytically. Baithalu et al. [25] investigated the flow behavior of a nanoliquid that combines magneto and polar properties on a flexible surface. Moreover, their work explored a couple of stresses and shear rates that significantly influence the flow dynamics. Raju and Sandeep [26] investigated the Casson-Carreau liquids adjacent to a widening surface. Tlau and Ontela [27] focused on the movement of hybrid nanofluids in a porous medium with varying permeability. Finally, their work examines the role of a hybrid nanofluid, composed of copper vis-a-vis silver solid particles, moving through permeability of the medium. Khan et al. [28] explored a hybrid nanofluid’s

dynamic flow and heat transfer characteristics incorporating both Single Walled Carbon Nano-Tube (SWCNT) and Multi-Walled Carbon Nano-Tube (MWCNT). Hussain et al. [29] focused on investigating hybrid nanofluids composed of engine oil and mineral oil infused with carbon nanotubes (SWCNTs and MWCNTs). These nanofluids were studied in the context of their interaction with a revolving cone within a convectively heated permeable environment. Haider et al. [30] studied a “single-walled carbon nanotube” (SWCNT) nanomaterial and hybrid nanomaterials containing Carbon Nano-Tubes (CNTs) (SWCNT-MWCNT) across an enlarging sheet. The resulting set of ODEs is then solved via the “Runge–Kutta fourth-order method” combined with the “shooting technique”. Madhukesh et al. [31] examined the impact of a hybrid nanomaterial comprised of water-based aluminum alloy through a bent elongating sheet by a non-Fourier heat flux model. Furthermore, the governing PDEs were transformed into ODEs utilizing the appropriate similarity rule. Additionally, the flow phenomena are solved utilizing the “Runge-Kutta-Fehlberg fourth-fifth order (RKF-45)” procedure, implementing the “shooting method”. The behavior of numerous factors affecting the flow is presented graphically. Ramesh et al. [32] employed the influence of a temperature-dependent heat generation/sink on the flow of Maxwell nanoliquid on a sensor plate. The model incorporates convective thermal and mass boundary constraints. The “finite difference method”, combined with the “Richardson extrapolation technique” is utilized for the solution. Iqbal et al. [33] considered the movement of a Casson liquid via a variable-thickness Riga plate. Furthermore, a Riga plate is particularly made up of permanent magnets and an aligned array of alternating electrodes over a flat surface. Appropriate transformations are utilized to model the problem with the influence of radiant heat and viscous dissipation. Finally, the solution of the set of equations is obtained by using the “Keller box scheme” in “MATLAB”. On the other hand, a comprehensive review on the hybrid nanofluid experiencing several physical aspects in different geometries such as stretching cylinder [34], stretching sheet [35], rotating disk [36], and oscillating plate [37].

1.1. Focus point of the study

The literature survey finds various research gaps, and this leads to the aim of the proposed investigation to:

- Analyse the effect of radiant heat and variable porosity on the steady flow of hybrid nanofluid containing alloy nanoparticles, i.e., AA7072, AA7075, with water as the host fluid.
- Model the flow problem considering the heat transfer scenario over the Riga plate.
- Transform the basic dimensional, nonlinear differential equations into a set of nonlinear dimensionless ordinary

differential equations using appropriate similarity conversion variables.

- Employ the Keller Box Method (KBM) for the solution of these transformed equations with the inclusion of diversified factors.
- Validate the current outcome with the previously established output in particular as showing a good correlation.

1.2. Novelty of the proposed investigation

The aforesaid description of the research gap and objective leads to the novelty of the study:

- The work introduces the use of water-based alloy nanoparticles for enhanced thermal conductivity and heat transfer performance.
- It examines the combined effects of radiative heat transfer and variable porosity on the flow characteristics of the hybrid nanomaterial over a Riga plate.
- The proposed investigation provides the significant impact of inverse porosity on boundary layer resistance and heat transmission characteristics.
- The influence of the Riga plate on fluid flow and heat transmission emphasizing variations electromagnetic field generated by the plate.
- The detailed comparison with conventional fluids is demonstrated through the hybridization of AA7072 and AA7075 aluminum alloys.

2. Materials formulation

We proposed simultaneous thermal transport via an embedded Riga plate in a porous space, resulting in a steady and incompressible hybrid nanofluid flow. The space is considered variable in order to optimize heat transfer. The hybrid nanofluid is created by injecting nanocomposites composed of AA7072 and AA7075 into water. Furthermore, the surface is continuously subjected to stretching/shrinking with wall velocity $u_w(x) = ax$ and isothermal heating with temperature T_w . The 2D flow occurs towards $y \geq 0$ of xy the Cartesian coordinate system, which is depicted in Figure 1. The vector forms of the fundamental equations in component form are:

$$\nabla \cdot \mathbf{V} = 0, \quad (1)$$

$$\mathbf{V} \cdot \nabla \mathbf{V} = \nu_{hnf} \nabla^2 \mathbf{V} + \mathbf{F} - \frac{\nu_{hnf}}{K(x)} \mathbf{V}, \quad (2)$$

$$\mathbf{V} \cdot \nabla T = \alpha_{hnf} \nabla^2 T + \frac{Q}{(\rho C_p)_{hnf}} (T - T_\infty) - \frac{1}{(\rho C_p)_{hnf}} \nabla \cdot \mathbf{q}_r, \quad (3)$$

where $\mathbf{V} = (u, v)$ is the velocity vector, and $\mathbf{F}$ indicates the external force term.

The dimensional form of the fundamental equations used form Navier-Stokes followed from [38].

$$\partial_x u + \partial_y v = 0, \quad (4)$$

Table 1. The thermal relations for hybrid nanomaterials [28-29].

Property	Hybrid nanomaterial
Absolute viscosity	$\mu_{hnf} = \mu_f \left\{ (1-\phi_1)^{-2.5} (1-\phi_2)^{-2.5} \right\}$
Density	$\rho_{hnf} = \rho_f \left((1-\phi_2) \left[(1-\phi_1) + \phi_1 \frac{\rho_{s1}}{\rho_f} \right] + \phi_2 \frac{\rho_{s2}}{\rho_f} \right)$
Heat capacity	$(\rho c_p)_{hnf} = (\rho c_p)_f \left((1-\phi_2) \left[(1-\phi_1) + \phi_1 \frac{(\rho c_p)_{s1}}{(\rho c_p)_f} \right] + \phi_2 \frac{(\rho c_p)_{s2}}{(\rho c_p)_f} \right)$
Thermal conductivity	$\frac{k_{hnf}}{k_{nf}} = \frac{(1-\phi_2) + 2\phi_2 \left(\frac{k_{s2}}{k_{s2} - k_{nf}} \right) \ln \left(\frac{k_{s2} + k_{nf}}{k_{nf}} \right)}{(1-\phi_2) + 2\phi_2 \left(\frac{k_{nf}}{k_{s2} - k_{nf}} \right) \ln \left(\frac{k_{s2} + k_{nf}}{k_{nf}} \right)}$ $\frac{k_{nf}}{k_f} = \frac{(1-\phi_2) + 2\phi_2 \left(\frac{k_{s2}}{k_{s2} - k_{nf}} \right) \ln \left(\frac{k_{s2} + k_{nf}}{k_{nf}} \right)}{(1-\phi_2) + 2\phi_2 \left(\frac{k_{nf}}{k_{s2} - k_{nf}} \right) \ln \left(\frac{k_{s2} + k_{nf}}{k_{nf}} \right)}$
Electrical conductivity	$\frac{\sigma_{hnf}}{\sigma_{nf}} = \frac{\sigma_{s2} + 2\sigma_{nf} - 2\phi_2 (\sigma_{nf} - \sigma_{s2})}{\sigma_{s2} + 2\sigma_{nf} + \phi_2 (\sigma_{nf} - \sigma_{s2})}$ $\frac{\sigma_{nf}}{\sigma_f} = \frac{\sigma_{s1} + 2\sigma_f - 2\phi_1 (\sigma_f - \sigma_{s1})}{\sigma_{s1} + 2\sigma_f + \phi_1 (\sigma_f - \sigma_{s1})}$

$$u \partial_x u + v \partial_y u = \nu_{hnf} \partial_{yy} u + \frac{\pi j_0 M^*}{8 \rho_{hnf}} \exp \left(-\frac{\pi}{a_1} y \right) - \frac{\nu_{hnf}}{K(x)} u, \quad (5)$$

$$u \partial_x T + v \partial_y T = \alpha_{hnf} \partial_{yy} T + \frac{Q}{(\rho C p)_{hnf}} (T - T_\infty) - \frac{1}{(\rho C p)_{hnf}} \partial_y q_r, \quad (6)$$

$$u = u_w(x) + L \frac{\partial u}{\partial y} = ax + L \frac{\partial u}{\partial y},$$

$$v = 0, \quad T = T_w, \quad \text{at } y = 0$$

$$u \rightarrow 0, \quad T \rightarrow T_\infty, \quad \text{as } y \rightarrow \infty. \quad (7)$$

The variable porous space concept is used from [38].

$$K(x) = \frac{m^2 \gamma(x)^3}{(1 - \gamma(x))^2}, \quad \gamma(x) = \gamma_0 \left(1 + \gamma_1 e^{\frac{x \gamma_2}{m}} \right), \quad (8)$$

while γ_1, γ_2 are the constants with respect to particle diameter, γ_0 suggests the ambient porosity, and m , the particle diameter [27,39]. The properties of hybrid nanomaterial are displayed in Table 1. Introducing the similarity variables [20, 38].

$$\eta = y \sqrt{\frac{a}{\nu_f}}, \quad \theta(\eta) = \frac{T - T_\infty}{T_w - T_\infty}, \quad u = ax f'(\eta), \quad (9)$$

$$v = -\sqrt{a \nu_f} f(\eta).$$

Eqs. (4)-(7) transform as:

$$A_1 f'''(\eta) + f(\eta) f''(\eta) - f'(\eta)^2,$$

$$-A_1 \frac{1}{\lambda} \frac{\left[1 - \gamma_0 \left(1 + \gamma_1 e^{\frac{-\gamma_2 \eta}{\sqrt{\lambda}}} \right) \right]^2}{\left[\gamma_0 \left(1 + \gamma_1 e^{\frac{-\gamma_2 \eta}{\sqrt{\lambda}}} \right) \right]^3} f'(\eta) + A_2 \alpha e^{(-\beta \eta)} = 0, \quad (10)$$

$$\frac{1}{\text{Pr}} \left(A_3 + \frac{4}{3} N r \right) \theta'' + f(\eta) A_4 \theta'(\eta) + \chi \theta(\eta) = 0. \quad (11)$$

With following conditions:

$$f'(0) = 1 + \delta f''(0),$$

$$f(0) = 0, \theta(0) = 1, \quad \text{as } \eta = 0,$$

$$f'(\infty) = 0, \theta(\infty) = 0 \quad \text{at } \eta \rightarrow \infty. \quad (12)$$

Emerging terms in the dimensionless nonlinear system are signified as:

$$\lambda = \frac{am^2}{\nu_f}, \quad \alpha = \frac{j_0 M^* \pi}{8 U_w^2 \rho_f}, \quad \beta = \frac{\pi}{a_1} \sqrt{\frac{\nu_f}{\alpha_f}}, \quad \text{Pr} = \frac{\alpha_f}{\nu_f},$$

$$\chi = \frac{Q}{(\rho C p)_f a}, \quad \lambda = \frac{am^2}{\nu_f}, \quad \alpha = \frac{j_0 M^* \pi}{8 U_w^2 \rho_f}, \quad \beta = \frac{\pi}{a_1} \sqrt{\frac{\nu_f}{\alpha_f}},$$

$$\text{Pr} = \frac{\alpha_f}{\nu_f}, \quad \chi = \frac{Q}{(\rho C p)_f a}. \quad (13)$$

Table 2. Thermal features of the base and nanoparticles.

	ρ (kg/m ³)	C_p (J/kgK)	k (W/mK)	σ (Ω m) ⁻¹
Pure water (H ₂ O)	997.1	4179	0.613	0.05
AA7072	2720	893	222	34.83×10 ⁶
AA7075	2810	960	173	26.77×10 ⁶

Table 2, extracted from Madhukesh et al. [31], presents the actual thermal and physical properties of water (base fluid) and AA7072 and AA7075 nanoparticles.

Furthermore, the physical quantities are combined with various factors, i.e., skin friction coefficient (C_f) and heat transfer rate or Nusselt number (Nu). Implementing Eq. (10), the aforementioned physical quantities are expressed as [32–33].

The Engineering quantities are as follows [19]:

$$C_{fx} = \frac{\tau_w}{\rho_f u_w^2}, \quad Nu_x = \frac{xq_w}{k_f (T_w - T_\infty)}, \quad (14)$$

where,

$$\tau_w = \mu_{hnf} \left. \frac{\partial u}{\partial y} \right|_{y=0},$$

$$q_w = -k_{hnf} \left. \frac{\partial T}{\partial y} - \frac{16\sigma^* T_\infty^3}{3k^*} \frac{\partial T}{\partial y} \right|_{y=0}. \quad (15)$$

Reduced skin friction and Nusselt number (Nu) in dimensionless form are:

$$Re_x^{-1/2} C_f = \frac{\mu_{hnf}}{\mu_f} f''(0),$$

$$Re_x^{-1/2} Nu = - \left(\frac{k_{hnf}}{k_f} + Nr \right) \theta'(0), \quad (16)$$

where $Re_x = xu_w / \nu_f$ is the local Reynolds number (Re).

3. Numerical solution

In this study, the nonlinear ODEs in Eqs. (10) and (11) along with boundary Constraints (12) were numerically computed by employing “the Keller box method”. This method is an unconditionally stable finite difference scheme and possesses the desired accuracy for solving boundary layer problems. The procedure of the “Keller box method” is implemented through the following sequence of steps:

Step 1: Transform into a system of first-order ODEs; A system of coupled nonlinear ordinary differential equations. (10) and (11) are transformed to first order by introducing new independent variables;

Step 2: Finite difference discretization Algebraic equations are obtained from a system of first-order ODEs using central difference approximation at the midpoint,

$$\left(x', \eta_{j-\frac{1}{2}} \right) \text{ for mean average and its derivatives as:}$$

$$\left(\right)_{j-\frac{1}{2}} = \frac{\left(\right)_j + \left(\right)_{j-1}}{2}, \quad \left(\right)'_{j-\frac{1}{2}} = \frac{\left(\right)_j - \left(\right)_{j-1}}{h_j},$$

Table 3. Comparison of present result for varied values of α and χ .

α	χ	Present result $Re_x^{1/2} C_f$	Khan et al. [38] $Re_x^{1/2} C_f$
0.1	0.1	0.224565	0.22432671582
0.3	0.3	0.242737	0.242652782431
0.7	0.7	0.263675	0.263526178920
0.9	0.9	0.287147	0.287325617829

for all involved variables;

Step 3: Quasilinearization technique;

Algebraic equations are linearized based on Newton’s algorithm using the $(i+1)^{th}$ iterate for all included variables as follows:

$$O_j^{i+1} = O_j^i + \delta O_j^i. \quad (17)$$

Step 4: Block-tridiagonal elimination scheme;

Substituting the above Expression (17) and dropping the higher order of δ constitutes a linear tri-diagonal matrix form:

$$[A][\delta] = [r], \quad (18)$$

where $[A]$ is a block tri-diagonal matrix of order 5×5 and $[\delta] = [\delta_1, \delta_2, \delta_3, \dots, \delta_{j-1}, \delta_j]^T$, $[r] = [r_1, r_2, r_3, \dots, r_{(j-1)}, r_j]^T$, are unknown vector matrix and constants for $1 \leq j \leq 5$. Then, after applying the elimination technique to the coefficient matrix A and sweep conditions are used. Finally, the solution is obtained through MATLAB R2023a, where the step length was chosen as $\eta = 0.01$ and the series of iterations is terminated asymptotically at the maximum condition of 10^{-8} .

4. Code validation

In order to validate the MATLAB code for the “Keller box method”, we have compared the results computed by the developed code with earlier published results of Khan et al. [38] and obtainable in Table 3. From the table, it is disclosed that the approximate solutions indicate excellent agreement with the previous result obtained by Khan et al. [38].

5. Analysis of results

Figures 1 to 12 show the graphs of velocity and temperature profiles against different physical parameters for which the values of parameters $\eta = 1$, $Pr = 0.7$, $\lambda = 0.5$, $\alpha = 0.1$, $\beta = Nr = \chi = 0.5$, $\gamma_0 = 0.5$, $\gamma_1 = \gamma_2 = 0.1$, $\phi_1 = \phi_2 = 0.01$ are fixed, but the value $\eta = 0.1$, $\lambda = 0.7$, $\alpha = 0.5$, is only changed for the temperature profile. Next, Figures 13 to 19 indicate the behavior of skin friction, Nusselt number, and different physical parameters. Finally, the present results were evaluated with the related literature, as indicated in Table 2.

5.1. Flow field discussion

In Figure 2, the reaction of the hybridized aluminum alloys “AA7072” and “AA7075” fluid velocity to an increasing porosity

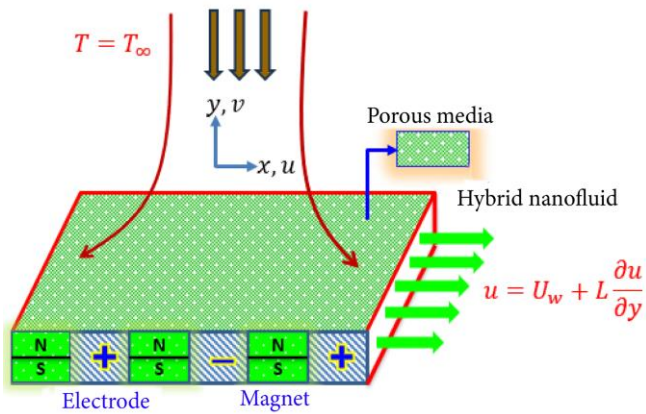


Figure 1. Diagrammatic representation of the hybrid nanofluid over the Riga surface.

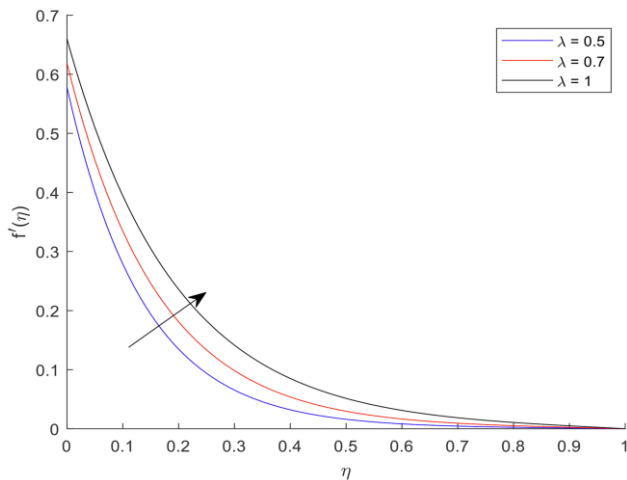


Figure 2. $f'(\eta)$ Profile for different values of λ .

(λ) value is displayed. As obtained, the velocity profile is boosted due to the induced internal heating, which reduces viscosity and shear stress. Under the influence of the Riga plate, the medium pore is enhanced to allow free nanoparticle mobility to raise the flow velocity field; thus, high medium permeability is associated with high porosity. The drag and electromagnetic forces are reduced to promote the interaction and dispersion of nanoparticle thermal properties in the fluid, leading to increasing flow velocity. This effect is applicable in optimizing industrial system designs. Figure 3 exhibits the influence of increasing values of the electromagnetic actuator (α) on the flow dynamics of the hybridized aluminum alloy nanofluids. The Riga plate stimulates an electromagnetic transverse field, which influences the dynamics of the nanofluid flow rate. The Riga plate device is embedded with electrodes and magnets to create a fluid flow perpendicular to the electric and magnetic fields. The nanofluid flow experienced a noteworthy velocity change near the plate because of the electromagnetic force. Thus, the orientation and strength of the applied field are optimized to cause a thinner boundary layer, which induces flow velocity close to the stretchy surface. This correspondingly encourages convective heat transfer that results in the overall enhancement of the flow velocity field.

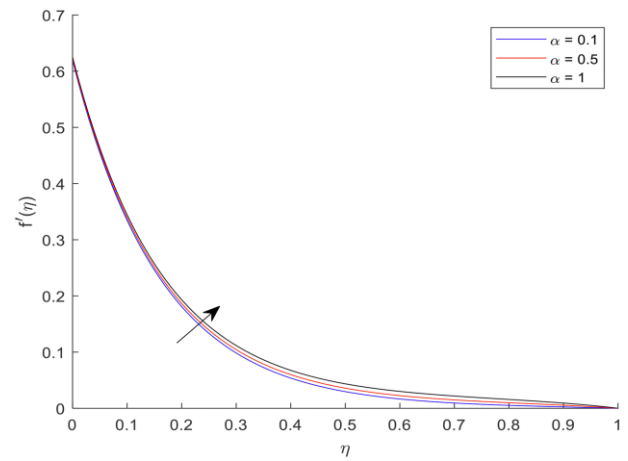


Figure 3. $f'(\eta)$ Profile for different values of α .

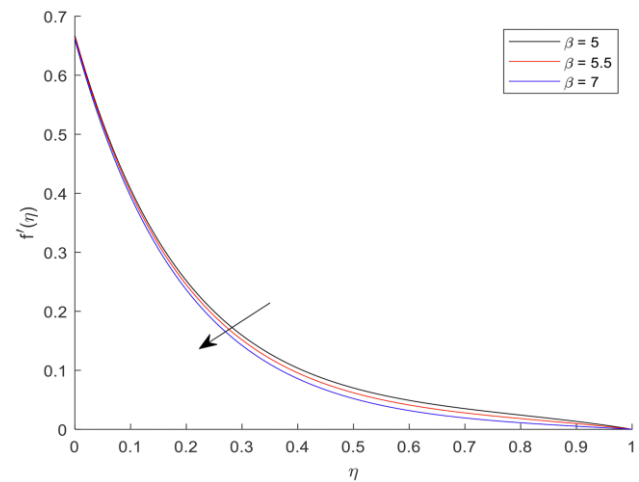


Figure 4. $f'(\eta)$ Profile for different values of β .

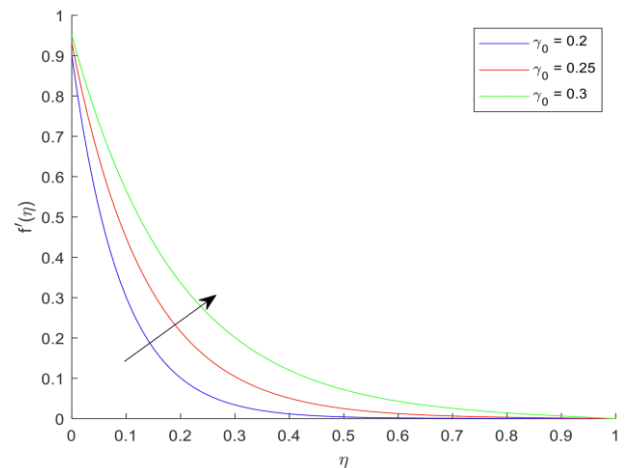


Figure 5. $f'(\eta)$ Profile for different values of γ_0 .

Figure 4 illustrates the impact of the non-dimensional Riga term related to the electrode and magnetic width (β) on the velocity profile. The Lorentz force is prompted to resist the flow, causing a rising value of the term progressive decline in the hybrid nanofluid flow velocity. The electrode and magnet's size and shape strongly affect the nanofluid's electric and magnetic field dispersion. The fluid properties and behavior are affected; thus, the effects must be carefully studied for efficient specific performance. In Figure 5, the

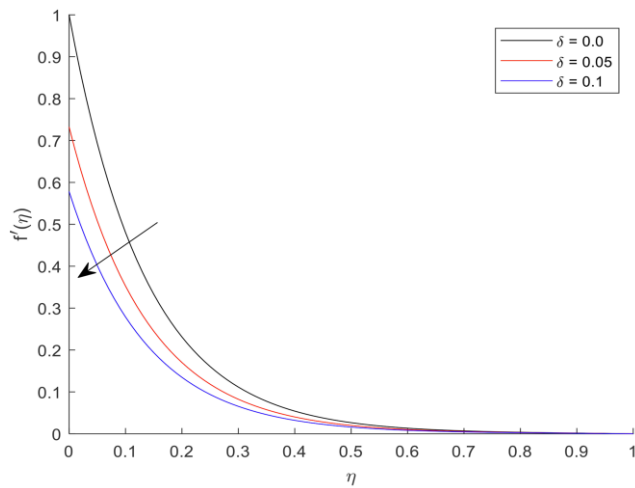


Figure 6. $f'(\eta)$ Profile for different values of δ .

effects of ambient porosity (γ_0) on the hybridized AA7072 and AA7075 aluminum alloy nanofluids velocity profile are investigated. The term describes the pores within the AA7072 and AA7075 aluminum alloy material. The fundamental flow properties and dynamics are used to enhance the velocity profile. A convective thermal distribution is induced, and internal thermal generation is induced to oppose molecular bonding, thus decreasing the boundary layer viscosity, resulting in a higher flow velocity rate. Figure 6 examines the velocity slip impact on the flow velocity of the hybrid nanofluid. This phenomenon is associated with the boundary wall and the fluid motion; it happens when the fluid fails to completely adhere to the boundary, creating a slip. A significant decrease in the velocity field is observed near the wall, which gradually declines far from the nanofluid stream. Therefore, the complexity between velocity slip and nanoparticle thermal properties should be consciously analyzed to optimize the engineering usage. Heat transfer within the system is discouraged, and shear stress is propelled to reduce the AA7072 and AA7075 aluminum alloy nanoparticle motion and interaction; this causes an overall decrease in the dynamics of the flow characteristics.

5.2. Thermal field discussion

Figure 7 shows the response of the hybrid nanofluid thermal distribution to an enhancing inverse porosity term (λ). The term depicts the density of the porous medium to the pore; the heat conductivity effectiveness decreases with boosting inverse porosity values. The fluid resistance is boosted with rising inverse porosity due to a denser solid matrix. This is because the typical thermal conductivity of the solid matrix is higher than that of the aluminum alloy hybrid nanofluid. As such, the system's thermal conductivity is raised to enhance heat transfer; this prompted interaction leads to augmented heat diffusion and dissipation, thereby reducing the fluid temperature profile. Also, the porous medium structure affects the thermal boundary layer to induce solid heat transfer to the

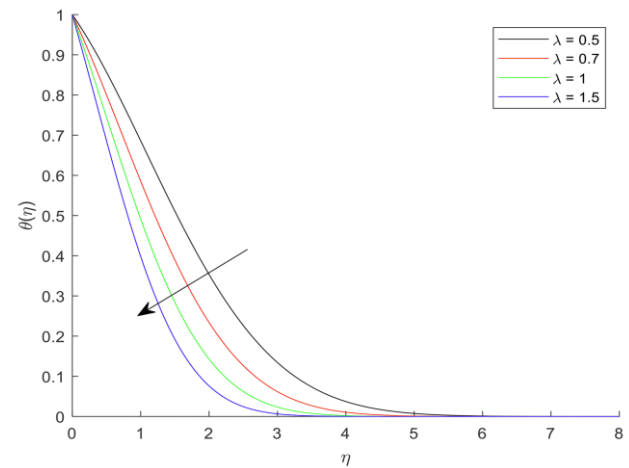


Figure 7. $\theta(\eta)$ Profile for different values of λ .

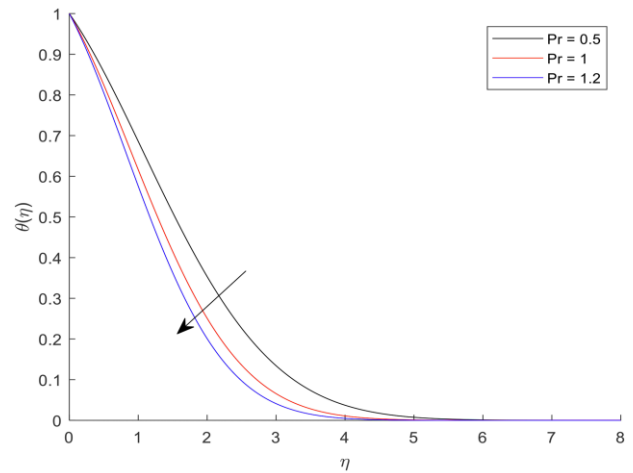


Figure 8. $\theta(\eta)$ Profile for different values of Pr .

fluid, consequently damping the thermal fluid field. Figure 8 displays the temperature profile for variations in the Prandtl number. The fluid temperature reduces with increasing Prandtl numbers, as shown in the plot. The parameter characterizes the momentum boundary layer thickness relative to the temperature boundary layer. As observed, the fluid viscosity is strengthened with heat diffusivity, resulting in a damped ambient thermal diffusion and a thicker thermal boundary film; heat transfer governs the fluid heat conduction. The choice of Prandtl number depends on the material considered and the particular applications. Figure 9 demonstrates the temperature distribution for varying values of thermal radiation (Nr). Radiation is an electromagnetic effect that influences heat transfer at high temperatures, resulting in a rise in thermal conductivity and the distribution of nanoparticles. The hybridized aluminum alloy nanofluid relates with radiation to emit and absorb radiative heat, affecting heat transfer. The thermal conduction of the fluid nanoparticle is efficiently enhanced due to the combined impact of radiation, convection and conduction. The thermal conducting strength of nanoparticles depends on the concentration, size, type, and dispersion as applied in cooling systems and heat exchangers, and others.

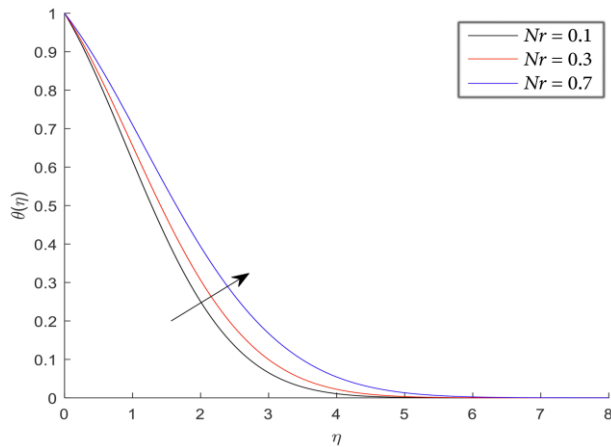


Figure 9. $\theta(\eta)$ Profile for different values of Nr .

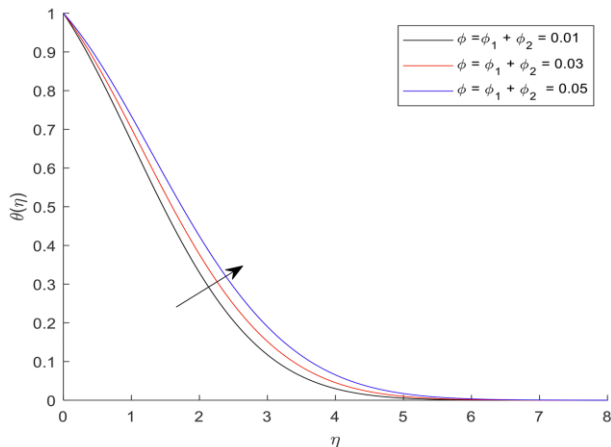


Figure 10. $\theta(\eta)$ Profile for different values of ϕ .

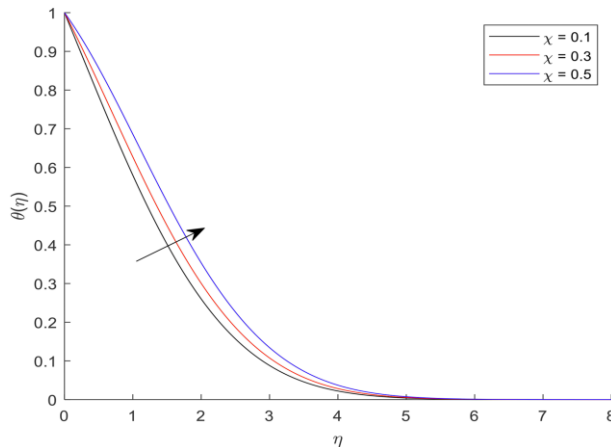


Figure 11. $\theta(\eta)$ Profile for different values of χ .

Figure 10 investigates the impact of volume fraction on the temperature distribution. As plotted, the aluminum alloy hybrid nanofluid's temperature field is influenced by the nanoparticle's rising volume fraction or concentration. Fluid thermal conduction is improved to propel heat transfer from the hot area to the more relaxed area, leading to a decreasing fluid thermal gradient and rising nanofluid viscosity. Thus, high viscosity opposes convective heat transport in areas of the system's high local temperature for higher volume fraction. Meanwhile, the viscosity is lower for small nanoparticle volume fractions to enhance the efficient temperature profile.

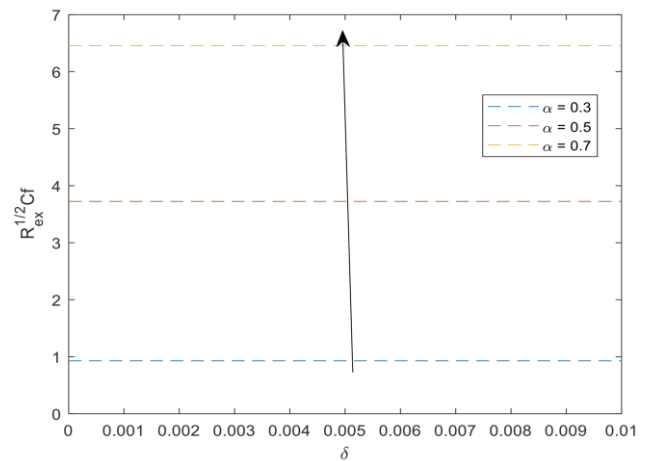


Figure 12. $Re_x^{1/2} C_f$ variations with δ for different values of α .

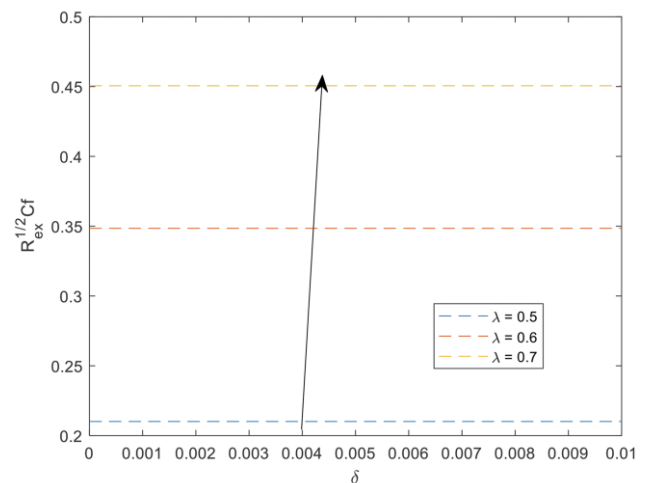


Figure 13. $Re_x^{1/2} C_f$ variations with δ for different values of λ .

Figure 11 shows heat generation's influence on the aluminum alloy hybrid nanoparticle thermal propagation. The fluid internal heating arising from reactant species, an electromagnetic actuator, and electrical resistance directly boosted the temperature of the nanofluid; these heat sources must be effectively managed for system stability and control overheating. Hence, the fluid temperature field is improved due to the propagation of nanoparticles in the hybridized nanofluid. The base fluid thermal conductivity is highly improved to support adequate thermal dissipation and lower viscosity for effective heat convection transport. Therefore, internal heat generation needs an appropriate convective mechanism to guarantee uniform temperature distribution and avoid localized hotspots. Hence, continuous nanoparticle propagation is encouraged to maintain thermal stability despite the thermal source, which requires a surfactant for suspension stability.

5.3. Engineering quantities discussion

Figures 12 to 16 describe the impact of parameter variation on the engineering quantities, specifically the wall friction and thermal gradient. In Figures 12 to 14, with an asymptotic increase in the Velocity slip (δ), a rising value of Hartmann

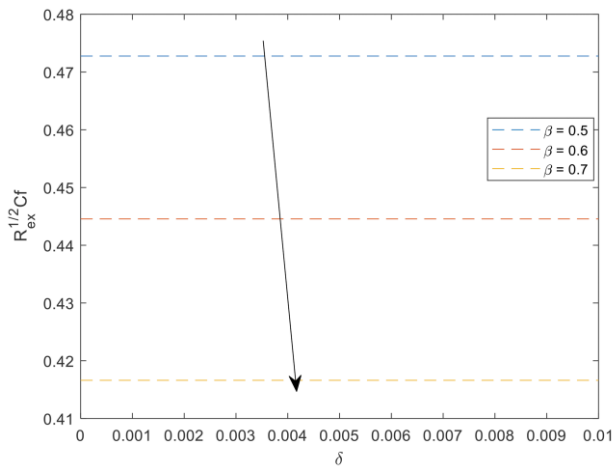


Figure 14. $Re_x^{1/2} C_f$ variations with δ for different values of β .

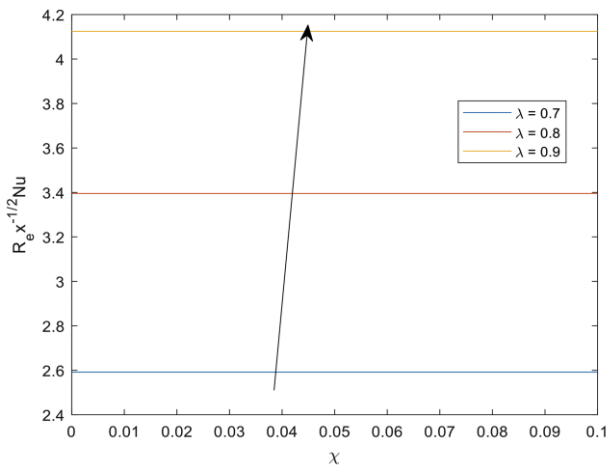


Figure 15. $Re_x^{-1/2} N u_x$ variations with χ for different values of λ .

number (α), Inverse porosity (λ), and electrode and Magnet width (β) are studied on the skin friction. In Figure 12, increasing the values of the Parameter (α) raises the wall friction of the conducting fluid significantly due to magnetic field influence. The velocity gradient is boosted as the internal heating suppresses the Lorentz force strength, causing a reduction in skin friction. Thus, the aluminium alloy nanoparticles' viscosity, thermal conductivity, and thermophysical properties are altered to influence the boundary layer film, thereby raising the fluid skin friction. Likewise, in Figure 13, increasing the values of Inverse porosity (λ) resulted in rising skin friction. The term depicts porous media with increasing solid matrix density within the medium, which resulted in fluid flow resistance and a high-pressure drop. Therefore, a significant flow restriction is provided, prompting enhanced skin friction. Meanwhile, in Figure 14, the impact of electrode and magnet width (β) on the skin friction is shown. As noticed, the skin friction reduces due to the boundary film becoming thinner, which stimulates free fluid flow, which affects the velocity field near the plate surface; the velocity gradient declines directly influencing the skin friction. The term impacted the Lorentz force magnitude for an unvaried velocity field, potentially decreasing

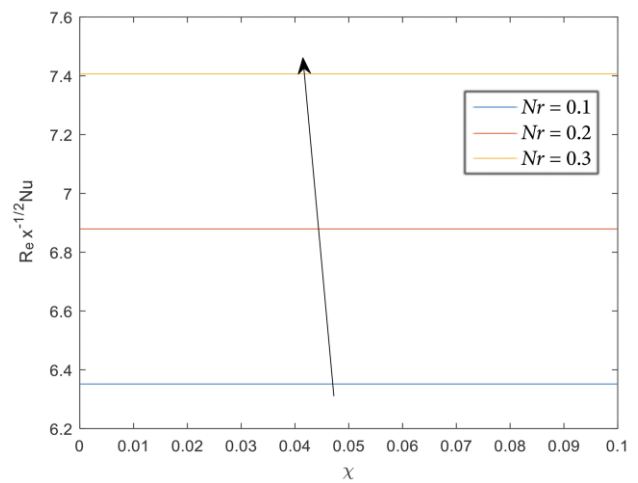


Figure 16. $Re_x^{-1/2} Nu_x$ variations with χ for different values of Nr .

skin friction. The induced electromagnetic force optimizes the thinner boundary layer to discourage the velocity gradient, thereby reducing skin friction. In Figures 15 and 16, with asymptotically rising Heat generation (χ), the increasing values of the Inverse porosity (λ) and Thermal radiation (Nr) raise the Nusselt number profiles. The wall thermal gradient of the aluminum alloy hybrid nanofluids increases for both parameters due to the inspired heat source terms, thermal conductivity, and convective heat distribution. The porosity and radiation terms affect the thermal film viscosity to influence the heat transport coefficient that, in turn, propels the temperature gradient with the nanofluid at the surface, thus enhancing the Nusselt number profile.

6. Conclusion

The investigation of heat transport in hybridized AA7072 and AA7075 aluminum alloy nanomaterial-based radiative nanomaterial flow via a Riga plate embedded in a variable porous medium is carried out. The Keller box technique solves the invariant dimensionless coupled derivative boundary value model. Thus, the study's aim and objectives are achieved. The analysis discloses several vital understandings of the thermal and fluid dynamics behavior of the systems:

- The hybridization of AA7072 and AA7075 aluminum alloys in the nanofluid significantly enhances thermal conductivity, resulting in improved heat transfer rates compared to conventional fluids.
- Radiative effects become more pronounced at higher temperatures, increasing heat transport for high-temperature applications.
- The presence of flow medium inverse porosity influences both the momentum and thermal boundary layers, altering the flow resistance and heat transfer characteristics,
- The electromagnetic field generated by the Riga plate significantly affects the fluid flow and heat transfer,

leading to variations in velocity profiles and thermal gradients.

- The combined effects of the hybrid nanomaterials, radiative heat transfer, porous medium, and electromagnetic field result in complex interactions affecting skin friction and the heat transfer coefficient.

The findings from this study have significant implications for the design and optimization of cooling and heating systems in advanced engineering applications. Combining hybridized nanofluids with magnetic fields and porous media leads to highly efficient thermal management solutions. Future studies can explore optimization techniques to identify the best combinations of nanoparticle concentrations, magnetic field strengths, and porous medium configurations for thermal stability and applications.

Nomenclature

u & v	Components of the velocity
γ_1, γ_2	Empirical constant
λ	Porosity parameter
m	Particle diameter
χ	Heat generation parameter
γ_0	Ambient porosity
α	Hartmann number
Nu	Nusselt number
Pr	Prandtl number
C_f	Skin friction coefficient
δ	Velocity slip
m	Particle diameter
β	Non-dimensional Riga term related to the electrode and magnetic width
Nr	Thermal radiation
ϕ	Nanoparticle volume fraction

Authors' contribution statement

First author: Formal analysis; Writing – original draft; Super vision; Writing - review; and editing;

Second author: Writing - original draft; Resources; Project administration;

Third author: Resources; Conceptualization; Formal analysis; Investigation;

Fourth author: Methodology; Software Validation; Visualization;

Fifth author: Writing - original draft; Writing - review and editing.

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