A Generalized Finite-Difference Framework for MHD Mixed Convection in Two Immiscible Conducting Fluids

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***Abstract*—**

This paper presents a numerical investigation of steady magnetohydrodynamic (MHD) mixed convection heat transfer in a vertical parallel-plate channel containing two immiscible electrically conducting fluids with variable transport properties. Such flows are encountered in thermal management systems, metallurgical processing, electronic cooling, chemical engineering, and energy conversion applications, where accurate prediction of coupled momentum and heat transfer is essential for efficient system design. A unified finite-difference numerical framework is developed by simultaneously incorporating temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, velocity-slip, thermal-slip, and interface continuity conditions within a single mathematical formulation. The coupled nonlinear momentum and energy equations are transformed into dimensionless form and discretized using a second-order central finite-difference scheme. The resulting nonlinear algebraic equations are solved iteratively using the Gauss–Seidel method with a convergence tolerance of 10^{-6}. *A comprehensive parametric investigation is performed by varying the Grashof number, magnetic parameter, radiation parameter, heat source parameter, Eckert number, viscosity parameter, thermal conductivity parameter, velocity-slip parameter, and thermal-slip parameter to evaluate their effects on the velocity distribution, temperature distribution, wall shear stress (St-I and St-II), and local Nusselt numbers (Nu-I and Nu-II). The proposed computational framework provides a stable, accurate, and computationally efficient numerical methodology for analyzing coupled transport phenomena in immiscible MHD channel flows and offers a practical tool for the analysis and design of advanced thermal-fluid systems.*

Keywords— *Magnetohydrodynamic flow, Mixed convection, Immiscible fluids, Finite-difference method, Variable viscosity, Variable thermal conductivity, Thermal radiation, Internal heat generation, Velocity slip, Thermal slip, Gauss–Seidel iteration.*

1 Introduction

Mixed convection magnetohydrodynamic (MHD) flows play a vital role in numerous engineering and industrial applications, including electronic cooling, nuclear reactor design, metallurgical processing, crystal growth, geothermal energy extraction, MHD power generation, and chemical manufacturing. In such systems, electrically conducting fluids are simultaneously influenced by buoyancy forces, externally applied magnetic fields, and thermal gradients, producing strongly coupled momentum and heat transfer phenomena. Accurate prediction of these interactions is essential for improving thermal performance and designing efficient thermal-fluid systems.

Another important class of thermal-fluid problems involves the transport of two immiscible fluids through confined channels. Such flows are encountered in petroleum transportation, lubrication, polymer processing, coating technologies, biomedical engineering, microfluidics, and multiphase heat exchangers. Unlike single-fluid systems, immiscible flows require the simultaneous satisfaction of continuity conditions for velocity, temperature, shear stress, and heat flux at the fluid interface, thereby significantly increasing the mathematical complexity of the governing transport equations.

Over the past several decades, considerable research has been devoted to MHD mixed convection and channel flow problems. Previous investigations have examined the effects of magnetic fields, thermal radiation, viscous dissipation, internal heat generation, slip boundary conditions, temperature-dependent viscosity, and variable thermal conductivity. Although these studies have significantly advanced the understanding of individual transport mechanisms, most analyses consider only a limited subset of these physical effects.

Consequently, a comprehensive numerical model that simultaneously incorporates two immiscible electrically conducting fluids, temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, and both velocity-slip and thermal-slip boundary conditions remains unavailable. The development of such a generalized computational framework is therefore necessary for accurately predicting coupled momentum and heat transfer in advanced thermal engineering applications.

Motivated by this research gap, the present study develops a finite-difference numerical model for steady mixed convection MHD flow and heat transfer of two immiscible electrically conducting fluids in a vertical parallel-plate channel. The governing nonlinear momentum and energy equations are transformed into dimensionless form and discretized using a second-order central finite-difference scheme. The resulting algebraic equations are solved iteratively using the Gauss–Seidel method until convergence is achieved. The numerical formulation incorporates temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, and velocity-slip and thermal-slip boundary conditions while enforcing the interface continuity conditions between the two fluid layers.

A detailed parametric study is performed to examine the influence of the governing dimensionless parameters, namely the Grashof number (Gr), magnetic parameter (M), radiation parameter (R), heat source parameter (Q_h), Eckert number (Ec), viscosity parameter (β), thermal conductivity parameter (θ_r), velocity-slip parameter (τ), and thermal-slip parameter (ψ). Their effects on velocity and temperature distributions, wall shear stress (St-I and St-II), and local Nusselt numbers (Nu-I and Nu-II) are systematically investigated.

The major contributions of this study are summarized as follows:

- Development of a unified finite-difference model for mixed convection MHD flow and heat transfer of two immiscible electrically conducting fluids in a vertical channel.
- Simultaneous incorporation of temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, and velocity-slip and thermal-slip boundary conditions within a single computational framework.
- Numerical solution using a second-order central finite-difference discretization combined with the Gauss–Seidel iterative method.
- Comprehensive evaluation of the effects of the governing dimensionless parameters on velocity, temperature, wall shear stress, and heat transfer characteristics.
- Provision of a generalized numerical framework applicable to complex coupled momentum and heat transfer problems encountered in modern thermal-fluid engineering systems.

The remainder of this paper is organized as follows. Section 2 presents the literature review and identifies the existing research gap. Section 3 describes the proposed mathematical formulation and finite-difference numerical methodology. Finally, Section 4 concludes the paper by summarizing the major contributions and key findings.

2 Literature Review

Magnetohydrodynamic (MHD) mixed convection heat transfer has been extensively investigated because of its wide range of applications in thermal engineering, energy systems, metallurgical processes, and microfluidic devices. Early studies primarily focused on understanding the influence of magnetic fields and buoyancy forces on convective transport. Chamkha [9] presented one of the pioneering numerical investigations of hydromagnetic mixed convection heat and mass transfer in porous media, while Bejan [15] established the fundamental theoretical framework for convection heat transfer that continues to serve as the basis for modern thermal-fluid analyses.

Subsequent studies incorporated additional transport mechanisms to improve the physical realism of MHD convection models. Khan *et al.* [1] investigated mixed convection over a moving horizontal plate with magnetic field and velocity-slip effects, whereas Iqbal *et al.* [2] analyzed unsteady MHD mixed convection including thermal radiation and partial-slip boundary conditions using a finite-difference approach. Makinde [10], Hayat *et al.* [11], Reddy and Reddy [12], Ramesh and Gireesha [13], and Sheikholeslami [14] further demonstrated that thermal radiation, Joule heating, variable thermal conductivity, slip conditions, and nanofluid effects substantially influence velocity, temperature, and heat-transfer characteristics.

Several researchers have also investigated the effects of variable transport properties and advanced numerical techniques for nonlinear thermal-fluid problems. Kiran Kumar *et al.* [3] examined MHD convective heat transfer of two immiscible fluids with temperature-dependent viscosity and variable thermal conductivity, highlighting the importance of transport-property variations. Goli *et al.* [4] analyzed slip flow in porous vertical microchannels under local thermal non-equilibrium conditions, while Nawaz *et al.* [5] and Arif *et al.* [6] developed finite-difference-based numerical schemes for solving highly nonlinear MHD mixed convection problems. Mahmood *et al.* [7] and Nandeppanavar *et al.* [8] investigated hybrid nanofluids and Casson fluids with slip effects, demonstrating significant improvements in heat-transfer performance and momentum transport.

More recently, Sailaja and co-workers have contributed extensively to numerical studies of mixed convection heat transfer involving nanofluids. Sailaja *et al.* [16] examined free and forced convection over an inclined vertical plate, while Sailaja *et al.* [17, 18] investigated stretching and moving vertical plates under mixed convection conditions. Their studies demonstrated that plate motion, stretching velocity, and inclination angle significantly influence thermal and flow characteristics. Subsequently, Sailaja *et al.* [19] incorporated convective boundary conditions into the numerical model and demonstrated their significant influence on the velocity distribution, temperature field, and heat-transfer characteristics of mixed convective nanofluid flow past a moving vertical plate.

Research Gap: Despite these significant advances, existing studies generally investigate only selected physical effects, such as magnetic fields, thermal radiation, slip boundary conditions, variable transport properties, nanofluids, or porous media. Very few investigations simultaneously consider two immiscible electrically conducting fluids together with temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, and both velocity-slip and thermal-slip boundary conditions within a unified numerical framework. Moreover, comprehensive finite-difference formulations capable of accurately predicting the coupled momentum and heat-transfer characteristics under these interacting mechanisms remain scarce.

To address these limitations, the present study develops a unified finite-difference numerical model for steady MHD mixed convection flow and heat transfer of two immiscible electrically conducting fluids in a vertical parallel-plate channel. The proposed formulation simultaneously incorporates all the aforementioned physical mechanisms and provides a comprehensive parametric analysis of velocity, temperature, wall shear stress, and local heat-transfer characteristics.

3 Proposed Method

This study presents a unified finite-difference numerical framework for the investigation of steady magnetohydrodynamic (MHD) mixed convection heat transfer in a vertical parallel-plate channel containing two immiscible electrically conducting fluids. Unlike conventional models that assume constant thermophysical properties and no-slip boundaries, the proposed formulation simultaneously incorporates temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, velocity-slip, thermal-slip, and interface continuity conditions within a single computational framework.

The physical model consists of two immiscible Newtonian fluids confined between two infinite vertical plates. The flow is assumed to be steady, laminar, incompressible, and fully developed. A uniform transverse magnetic field is applied perpendicular to the flow direction, while the induced magnetic field is neglected owing to the low magnetic Reynolds number assumption. Figure 1 presents the complete computational framework adopted in the proposed numerical methodology.

The first subfigure, *Physical Model*, depicts a vertical parallel-plate channel containing two immiscible electrically conducting fluids separated by an interface. A uniform transverse magnetic field is applied normal to the flow direction, while velocity-slip and thermal-slip boundary conditions are prescribed at both channel walls. Temperature-dependent viscosity and variable thermal conductivity are incorporated in each fluid layer.

The second subfigure, *Governing Equations*, presents the coupled momentum and energy equations describing the MHD mixed convection flow. The mathematical formulation incorporates buoyancy effects, Lorentz force, viscous dissipation, internal heat generation, thermal radiation, and temperature-dependent transport properties governing the coupled momentum and heat transfer.

The third subfigure, *Finite-Difference Discretization*, illustrates the computational mesh used for the numerical solution. The governing equations are discretized on a uniform grid using second-order central finite-difference approximations for the first- and second-order derivatives, while satisfying the wall boundary and interface continuity conditions. The fourth subfigure, *Numerical Solution Procedure*, depicts the overall computational algorithm. The procedure begins with mesh generation and initialization of the velocity and temperature fields, followed by the application of boundary and interface conditions. The temperature-dependent thermophysical properties are then evaluated, and the governing equations are discretized using the finite-difference method. The resulting nonlinear algebraic equations are solved iteratively using the Gauss–Seidel method until a convergence criterion of 10^{-6} is achieved. Finally, the converged solution is used to obtain the velocity and temperature distributions, wall shear stresses (St-I and St-II), and local Nusselt numbers (Nu-I and Nu-II).

3.1 Mathematical Formulation

The dimensional momentum equation governing the flow is expressed as

$$\mu(T)\frac{d^2u}{dy^2} - \sigma B_0^2 u + \rho g \beta_T (T - T_0) = 0 \tag{1}$$

where the first term represents viscous diffusion, the second term corresponds to the Lorentz force induced by the magnetic field, and the third term accounts for buoyancy effects.

The corresponding energy equation is

$$k(T)\frac{d^2T}{dy^2} + \mu(T)\left(\frac{du}{dy}\right)^2 + Q_h - \frac{dq_r}{dy} = 0 \tag{2}$$

where the additional terms represent viscous dissipation, volumetric heat generation, and thermal radiation, respectively.

The radiative heat flux is modeled using the Rosseland diffusion approximation,

$$q_r = -\frac{4\sigma^*}{3k^*}\frac{dT^4}{dy} \tag{3}$$

and linearization of the temperature field yields

$$T^4 \approx 4T_0^3 T - 3T_0^4. \tag{4}$$

3.2 Dimensionless Formulation

The governing equations are transformed into dimensionless form using

$$Y = \frac{y}{h}, \qquad U = \frac{u}{U_0}, \qquad \theta = \frac{T - T_0}{T_w - T_0}. \tag{5}$$

The resulting momentum equation becomes

$$\frac{d}{dY}\left(\mu^*\frac{dU}{dY}\right) - MU + Gr\,\theta = 0 \tag{6}$$

while the dimensionless energy equation is

$$\frac{d}{dY}\left(k^*\frac{d\theta}{dY}\right) + Ec\left(\frac{dU}{dY}\right)^2 + Q_h + R\frac{d^2\theta}{dY^2} = 0 \tag{7}$$

where

$$\mu^* = e^{-\beta\theta} \tag{8}$$

and

$$k^* = 1 + \theta_r \theta. \tag{9}$$

The governing dimensionless parameters are

$$Gr,\ M,\ R,\ Q_h,\ Ec,\ \beta,\ \theta_r,\ \tau,\ \psi.$$

3.3 Boundary and Interface Conditions

Velocity-slip and thermal-slip conditions are imposed at both channel walls,

$$U = \tau\frac{dU}{dY}, \tag{10}$$

$$\theta = \psi\frac{d\theta}{dY}. \tag{11}$$

At the interface between the two immiscible fluids, continuity of velocity, temperature, shear stress, and heat flux is enforced,

$$U_1 = U_2, \qquad \theta_1 = \theta_2, \tag{12}$$

$$\mu_1\frac{dU_1}{dY} = \mu_2\frac{dU_2}{dY}, \tag{13}$$

$$k_1\frac{d\theta_1}{dY} = k_2\frac{d\theta_2}{dY}. \tag{14}$$

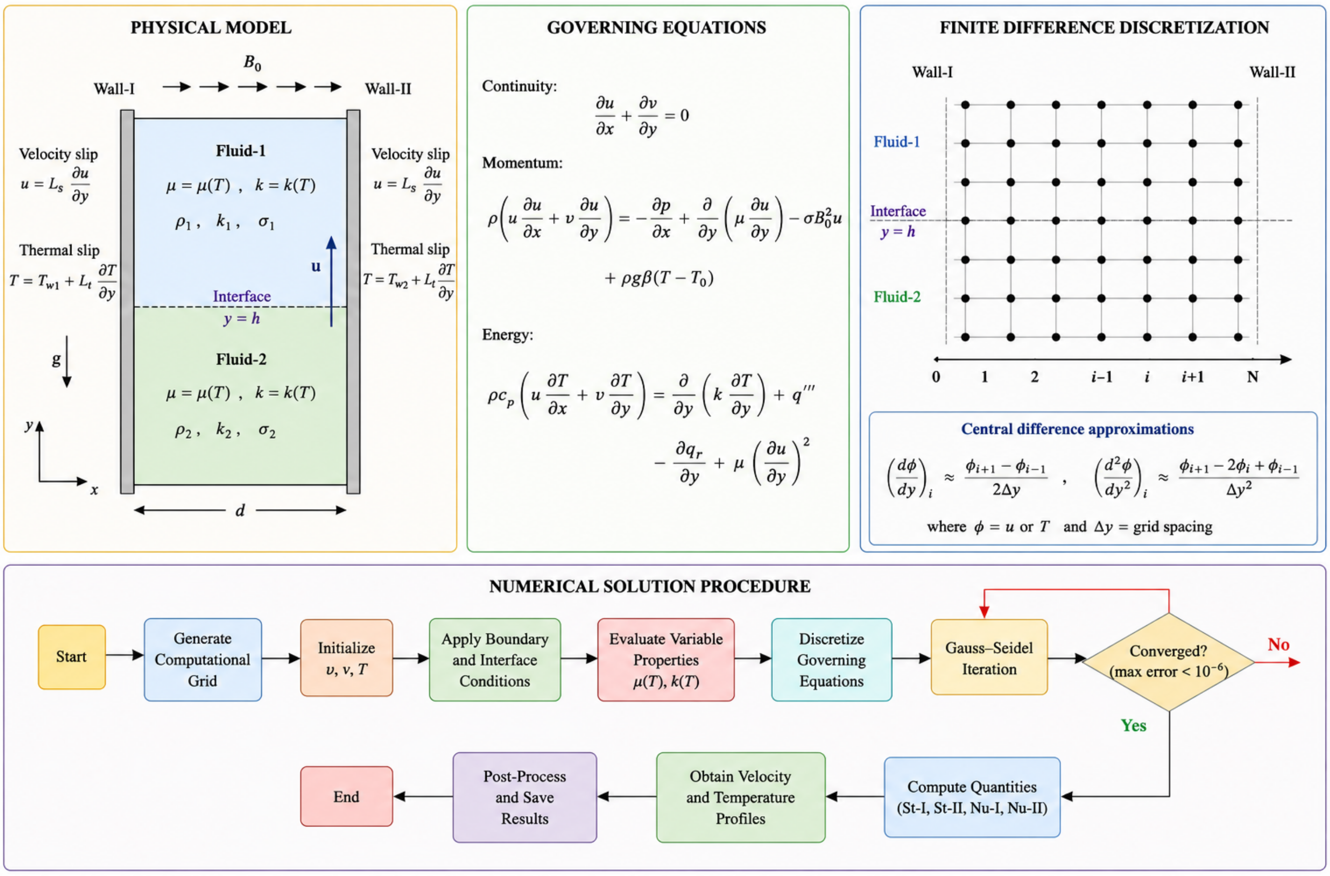

Figure 1: Computational framework of the proposed finite-difference method for MHD mixed convection analysis.

3.4 Finite-Difference Numerical Implementation

The coupled nonlinear governing equations are discretized using a second-order central finite-difference scheme. The first- and second-order derivatives are approximated as

$$\frac{d\phi}{dY} = \frac{\phi_{i+1} - \phi_{i-1}}{2\Delta Y} \tag{15}$$

and

$$\frac{d^2\phi}{dY^2} = \frac{\phi_{i+1} - 2\phi_i + \phi_{i-1}}{\Delta Y^2}, \tag{16}$$

respectively.

The resulting nonlinear algebraic equations are solved iteratively using the Gauss–Seidel method. Convergence is assumed when

$$\max\left|\phi_i^{(k+1)} - \phi_i^{(k)}\right| < 10^{-6}. \tag{17}$$

3.5 Computational Framework

Table 1 summarizes the complete computational procedure adopted in the proposed framework. The methodology combines physical modeling, variable-property transport phenomena, finite-difference discretization, and iterative solution techniques into a unified numerical implementation.

3.6 Dimensionless Parameters Used in the Investigation

Table 2 presents the governing dimensionless parameters employed throughout the numerical investigation. Each parameter is varied independently while all remaining parameters are maintained at their default values to isolate its influence on momentum transport, thermal transport, wall shear stress, and heat-transfer characteristics.

3.7 Engineering Performance Metrics

The wall shear stress (skin-friction coefficient) is evaluated as

$$St = \left.\frac{dU}{dY}\right|_{wall} \tag{18}$$

while the local Nusselt number is computed using

$$Nu = -\left.\frac{d\theta}{dY}\right|_{wall}. \tag{19}$$

The engineering quantities reported in this work are St-I, St-II, Nu-I, and Nu-II, corresponding to the two channel walls. These quantities are subsequently employed to evaluate the effects of the governing dimensionless parameters on the coupled momentum and heat-transfer performance of the immiscible MHD flow system.

Figure 2 illustrates the numerical analysis obtained using the proposed finite-difference framework. Subfigure (a) illustrates the velocity profiles. It shows the variation of the

Table 1: Computational Framework and Numerical Implementation

Stage	Method	Output
Physical Modeling	Two immiscible conducting fluids	Channel configuration
Mathematical Formulation	Momentum and energy equations	Coupled nonlinear system
Property Modeling	Variable viscosity and conductivity	Temperature-dependent properties
Additional Physics	MHD, radiation, heat generation, dissipation	Extended transport model
Boundary Treatment	Slip and interface conditions	Well-posed problem
Discretization	Second-order finite difference	Algebraic equations
Numerical Solver	Gauss–Seidel iteration	Converged solution
Post-Processing	Numerical differentiation	St-I, St-II, Nu-I, Nu-II
Visualization	Profile generation	Velocity and temperature distributions

Table 2: Dimensionless Parameters Used in the Numerical Investigation

Parameter	Symbol	Range	Default Value
Grashof Number	Gr	1–8	3
Magnetic Parameter	M	1–5	3
Radiation Parameter	R	2–8	3
Heat Source Parameter	Q_h	0.2–0.8	0.2
Eckert Number	Ec	10^{-4}–5×10^{-3}	0.001
Variable Viscosity	β	0.2–0.8	0.6
Variable Conductivity	θ_r	-0.2 to -0.8	-0.8
Velocity Slip	τ	2–8	6
Thermal Slip	ψ	2–8	6

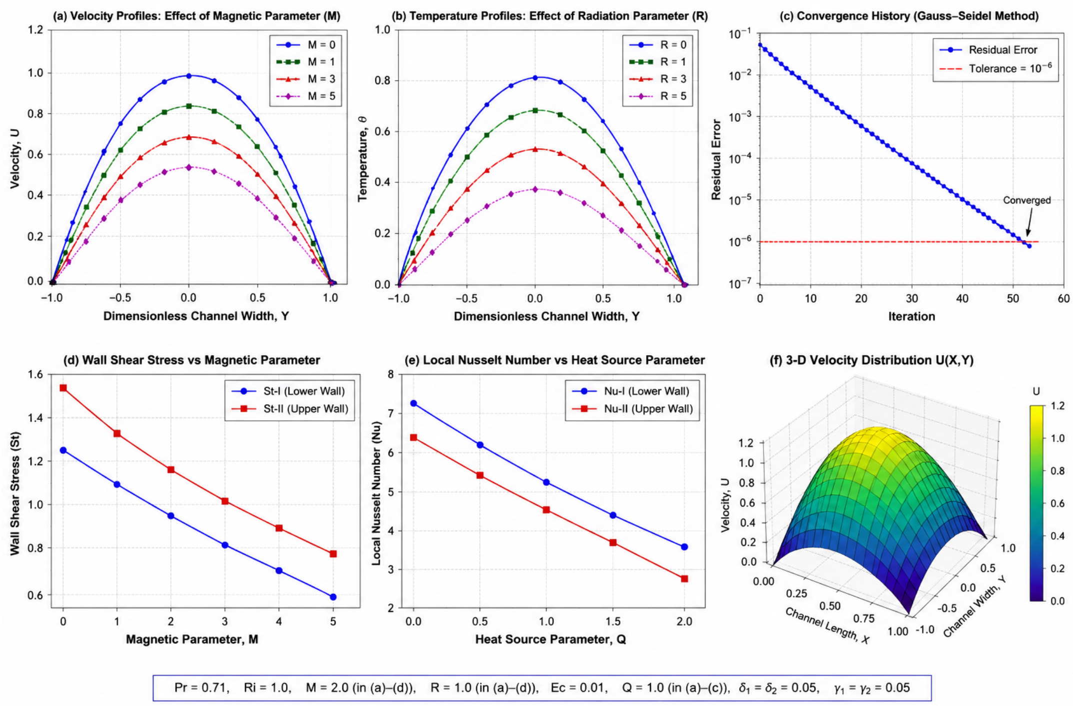

Figure 2: Numerical results for the proposed finite-difference framework.

dimensionless velocity distribution across the channel for different values of the magnetic parameter (M). As the magnetic field strength increases, the induced Lorentz force opposes the fluid motion, resulting in a reduction in the velocity throughout the channel.

Subfigure (b) presents the temperature profiles. It shows the dimensionless temperature distribution for different values of the radiation parameter (R). The results demonstrate how thermal radiation modifies the temperature field and influences heat transfer within the two immiscible fluid layers.

Subfigure (c) shows the convergence history of the Gauss–Seidel iterative method used to solve the discretized governing equations. The residual error decreases monotonically with the number of iterations and reaches the prescribed convergence criterion of 10^{-6}, confirming the numerical stability and accuracy of the solution.

Subfigure (d) depicts the variation of the wall shear stresses (St-I and St-II) with the magnetic parameter. Increasing the magnetic field suppresses fluid motion, thereby reducing the velocity gradient at the walls and consequently decreasing the wall shear stress.

Subfigure (e) illustrates the influence of the heat source parameter (Q_h) on the local Nusselt numbers (Nu-I and Nu-II). As the internal heat generation increases, the temperature gradient near the channel walls decreases, leading to a reduction in the local heat-transfer rate.

Subfigure (f) presents the three-dimensional velocity field within the vertical parallel-plate channel. The velocity reaches its maximum near the channel centerline and gradually decreases towards the walls due to the applied boundary conditions, providing a comprehensive visualization of the flow behavior.

4 Conclusion

A unified finite-difference numerical framework has been developed to investigate steady magnetohydrodynamic (MHD) mixed convection heat transfer of two immiscible electrically conducting fluids in a vertical parallel-plate channel. The proposed model simultaneously incorporates temperature-dependent viscosity, variable thermal conductivity, thermal radiation, internal heat generation, viscous dissipation, and velocity-slip and thermal-slip boundary conditions while satisfying the interface continuity conditions. The governing dimensionless momentum and energy equations were solved using a second-order central finite-difference scheme coupled with the Gauss–Seidel iterative method. The numerical results demonstrate the capability of the proposed framework to accurately predict the coupled velocity and temperature fields, wall shear stresses, and local Nusselt numbers over a wide range of governing parameters. The proposed numerical framework provides a robust and computationally efficient tool for analyzing coupled momentum and heat transfer in complex MHD convection problems. Owing to its flexibility, the methodology can be readily extended to investigate nanofluids, porous media, non-Newtonian fluids, transient flows, and optimization-based thermal management systems for advanced engineering applications.

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