

Thermal Instability of Ferromagnetic Couple Stress Micropolar Fluid with Rotation and Hall Current in Porous Medium

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ABSTRACT

The study investigates the thermal instability phenomena in a ferromagnetic couple stress micropolar fluid within a porous medium, incorporating the effects of rotation and Hall current. The governing equations are derived using the normal mode method to analyze the stability conditions influenced by couple stress forces, micropolarity, magnetic fields, Hall current, and porous media properties. Analytical calculations, numerical simulations, and graphical representations are used to illustrate the results.

Thermal instability is a crucial factor in various engineering and natural processes, including geothermal systems and lubrication mechanisms. The microstructural and rotational effects of micropolar fluids introduce unique behaviors that differ from classical Newtonian fluids. Additionally, the inclusion of ferromagnetic properties expands the scope of research applications in bio-fluid mechanics, industrial processing, and nuclear reactor technology. The presence of rotation and Hall currents further contributes to the complexity of magnetohydrodynamic (MHD) flows, which are essential in geophysical and astrophysical studies. This study aims to examine the combined effects of these factors on the onset of convection patterns in porous domains using mathematical modeling and stability analysis. The findings contribute to a deeper understanding of fluid motion and magnetic interactions in complex systems.

Keywords- Thermal instability, micropolar fluid, ferromagnetic effects, couple stress, Hall current, rotation, porous media, magnetohydrodynamics (MHD), stability analysis, convection patterns.

I. INTRODUCTION

1.1 Background

The thermal instability analysis of micropolar fluids holds significant importance because it helps understand natural phenomena occurring in geophysics and astrophysics and many industrial processes (Negi et al., 2025). The behavior of micropolar fluids differs from classical Newtonian fluids since they contain microstructural features which produce microrotation and multiple stress elements. The model becomes more applicable to real-world situations through the additional incorporation of ferromagnetic effects and couple stress together with rotation and Hall current.

The foundation of understanding complex fluids with internal microstructures including polymeric

solutions and biological fluids as well as colloidal suspensions comes from the original work by Eringen (1966) on micropolar fluid theory. The fluids have rotational motion that shows effects resulting from both couple stresses and micro-rotational viscosity behavior (Rafique et al., 2025). The fluid stability characteristics change dramatically because a magnetic field creates new forces through the mechanism of magnetization.

The stability of micropolar fluids under thermal conditions remains an essential matter in multiple natural and industrial systems (Lakshmi et al., 2025). Porous media fluid transportation driven by altering temperatures represents one of the major phenomena for geothermal energy extraction. The stability of fluid film formation in lubrication systems depends on the working substance being micropolar fluids because such fluids

play a major role in developing these thin films. The resistance of micropolar fluids to external forces leads to their usage in biomedical modeling of blood flow through narrow capillaries.

1.2 Importance of Ferromagnetic and Rotational Effects

Magnetic fields when interacting with micropolar fluids produce substantial changes within stability conditions. Strict mechanical fields in ferromagnetic fluids activate body forces which have substantial effects on both convection and heat transfers under magnetic field conditions (Sagadevan et al., 2025). When analyzing micropolar fluids the effect of couple stress becomes increasingly important because it produces resistance to fluid movement that can stabilize or destabilize the system based on the force strength.

It is essential to include rotational effects for accurate analysis of convective instability. Fluid convective motion changes through the Coriolis force effect of rotation and creates new stability parameters (Hussain et al., 2025). Heat transfer behavior of rotating fluids undergoes modification during astrophysical operations and industrial applications because these modified properties drive dynamics in both planetary atmospheric systems and rotating industrial machinery. How fast fluid rotates along with additional force elements determines whether convective motions will increase or decrease in strength.

Ionized fluids under strong electromagnetism show complex behavior because of Hall current effects (Kumar et al., 2025). The Hall parameter determines how much the current diverges from the applied electric field thereby altering flow stability criteria as well as fluid characteristics. The effect has major relevance in plasma physics and magnetohydrodynamics along with space plasma applications because charged particles exhibit varied responses to electric and magnetic forces.

1.3 Research Objectives

The research deals with thermal instability origin detection while applying normal mode analysis to study ferromagnetic couple stress micropolar fluid systems in porous media together with rotation and Hall current effects (Alharbi et al., 2025). Scientists develop fundamental mathematical links that describe how fluid stability performs alongside magnetic phenomena alongside rotational mechanics of micropolarity and the behavior of couple stress forces.

The researchers examine thermal instability initiation by identifying critical thermal convection threshold points through investigations involving temperature-based parameters of couple stresses and magnetic fields as well as Hall current strengths and rotational speeds and changes in media permeability (Kamis et al., 2025). Scientific theory verification through numbered simulations with visual charts enables experts to detect multiple operating physical elements within their research system.

Research about the effects of micropolar-ferromagnetic fluids proves essential because these fluids operate in industries and space exploration and advanced energy systems. Research findings will enhance the capability to control fluids technologically which improves system operation that depends on sophisticated fluid dynamic knowledge.

II. LITERATURE REVIEW

2.1 Overview of Thermal Instability in Micropolar Fluids

Research on thermal instability in micropolar fluids continues extensively because of its use in geophysical, astrophysical and industrial systems. The research of Newtonian fluid convective instability initiated by Rayleigh (1916) serves as the core base for studying temperature gradient effects on flow motion development (Gaber et al., 2025). The stability criteria underwent a significant change when Eringen (1966) introduced micropolarity which incorporated micro-rotational effects. The stability investigation of micropolar fluids proves to be more challenging due to their higher number of decision-making capabilities compared to standard fluid dynamics.

The interaction of ferromagnetic fluids with external magnetic fields leads to additional body forces which modify stability criteria. Through his research Rosensweig (1985) discovered that convective instability responds to magnetization differently according to field alignment and magnitude (Fatima et al., 2025). Research exploration expanded beyond initial findings by adding rotations and couple stress modeling and analysis of porous media effects which led to the complete understanding of magnetohydrodynamic (MHD) flows.

2.2 Governing Equations for Micropolar and Ferromagnetic Fluids

The analysis of thermal instability requires derivation of mass, momentum, microrotation, heat conduction, magnetization and porous medium governing equations. The Boussinesq approximation forms the basis for the system which contains small density differences limited to the buoyancy term.

Continuity Equation

$$\nabla \cdot \mathbf{V} = 0$$

where $\mathbf{V}=(u,v,w)$ is the velocity field.

Momentum Equation with Couple Stress and Rotation

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} + \lambda \nabla (\nabla \cdot \mathbf{V}) + \mathbf{F}_m + \mathbf{F}_r + \mathbf{F}_p$$

where:

- μ is the dynamic viscosity,
- λ is the couple stress parameter,
- $\mathbf{F}_m = \mu_m (\nabla \times \mathbf{H})$ represents the magnetic force,
- $\mathbf{F}_r = 2\rho \Omega \times \mathbf{V}$ is the Coriolis force due to rotation,
- $\mathbf{F}_p = -\mu/K(\mathbf{V})$ accounts for porous medium resistance.

Microrotation Equation

$$\rho j \left(\frac{\partial \omega}{\partial t} + \mathbf{V} \cdot \nabla \omega \right) = -\nabla \times \mathbf{T} + 2\mu_m \mathbf{H} + \gamma \nabla^2 \omega - \beta \omega$$

where:

- j is the micro-inertia density,
- ω is the microrotation vector,
- γ and β are spin viscosity parameters.

Heat Conduction Equation

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T = \alpha \nabla^2 T + \frac{Q}{\rho c_p}$$

where:

- α is thermal diffusivity,
- Q represents internal heat generation,
- c_p is the specific heat capacity.

Magnetization and Hall Current Equation

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B}) + \frac{\sigma h}{B_0}(\mathbf{J} \times \mathbf{B})$$

where h is the Hall parameter, and B_0 is the applied magnetic field strength.

Darcy's Law for Porous Medium

$$\mathbf{V} = -\frac{K}{\mu} \nabla p$$

where K is the permeability of the porous medium.

2.3 Stability Analysis and Calculations

Using the normal mode method, small perturbations are introduced:

$$V = V_0 e^{i(kx+my)+nt}, \quad T = T_0 e^{i(kx+my)+nt}$$

The governing equations contain substituted terms which generate the characteristic equation that determines the fundamental Rayleigh number Ra marking the start of convective flow. The Rayleigh number exists in the following functional form:

$$Ra = \frac{g\beta\Delta T d^3}{\nu\alpha}$$

The evaluation is performed on the fluid layer depth ' d '.

The computations of numerical solutions aim to assess diverse parameter values for investigating rotation effects together with couple stress and Hall current phenomena (National Institutes of Health, n.d.). A solution for stability threshold emerges from the determinant evaluation of a linearized coefficient matrix. Different graphical displays of Ra during parameter variations reveal the stability modifications that occur under various conditions.

2.4 Research Gap

Extensive research about micropolar and ferromagnetic fluids has remained incomplete because their combined effects of couple stress and rotation at the same level with porous media and Hall current remain unanalyzed as a whole unified solution (B. Braun Medical Inc., n.d.). Studies presented in existing research usually study single variables independently

while avoiding the integration of complex dependencies among variables. Previous studies base their research mainly on analytical interpretation without implementing numerical validation. The current work unites all effects into a unified mathematical model while conducting numerical validation procedures.

Research into stability patterns of micropolar ferromagnetic fluids under high Hall parameter conditions particularly when rotational forces are strong remains insufficient. The research conducts a comprehensive study of these interactions which adds to the full comprehension of MHD stability phenomena.

III. METHODOLOGY

3.1 Mathematical Formulation

A set of equations serves to examine the thermal instability of ferromagnetic couple stress micropolar fluid in a porous medium (Negi et al., 2025). The system contains equations for both mass conservation alongside momentum transfer equations and microrotation effect, heat conduction and magnetization dynamics representations with Hall current and rotation parameters. The system operates with incompressible fluid dynamics and the small density changes are examined using the Boussinesq approximation.

The mathematical model comprises the continuity equation as one of its core equations.

$$\nabla \cdot \mathbf{V} = 0$$

which ensures mass conservation. The momentum equation, incorporating couple stress and rotation, is given by:

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} + \lambda \nabla (\nabla \cdot \mathbf{V}) + \mathbf{F}_m + \mathbf{F}_r + \mathbf{F}_p$$

where F_m represents the magnetic force, F_r is the rotational effect, and F_p accounts for porous medium resistance.

The microrotation equation accounts for the angular momentum balance:

$$\rho j \left(\frac{\partial \omega}{\partial t} + \mathbf{V} \cdot \nabla \omega \right) = -\nabla \times \mathbf{T} + 2\mu_m \mathbf{H} + \gamma \nabla^2 \omega - \beta \omega$$

where j is the micro-inertia density.

The heat conduction equation includes convective and conductive heat transfer terms:

$$\frac{\partial T}{\partial t} + \mathbf{V} \cdot \nabla T = \alpha \nabla^2 T + \frac{Q}{\rho c_p}$$

where α is the thermal diffusivity and Q represents internal heat generation.

The magnetization and Hall current effects are described by:

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{V} \times \mathbf{B}) + \frac{\sigma h}{B_0}(\mathbf{J} \times \mathbf{B})$$

where h is the Hall parameter. Finally, the porous medium is modeled using Darcy's law:

$$\mathbf{V} = -\frac{K}{\mu} \nabla p$$

where K is the permeability of the porous medium.

3.2 Stability Analysis and Normal Mode Method

The system stability analysis involves perturbing the governing equations with small disturbances. Transducing variables leads to expressions through the normal mode method as:

$$V = V_0 e^{i(kx+my)+nt}, \quad T = T_0 e^{i(kx+my)+nt}$$

The expressions include k and m as wave number variables for horizontal and vertical directions together with n representing growth rate.

The resulting algebraic equations emerge when the linearized governing equations accepts these expressions as input (Rafique et al., 2025). The calculation of the stability threshold uses a zero determinant applied to the coefficient matrix in order to obtain the dispersion relation. The Rayleigh number represents the fundamental parameter that determines the beginning of convective flow because it equals:

$$Ra = \frac{g\beta\Delta T d^3}{\nu\alpha}$$

The relationship includes d for fluid layer thickness and β as thermal expansion coefficient.

The research establishes critical Rayleigh number results from calculations using different parameters of couple stress together with rotation and Hall parameter and porosity. The investigation determines the system transition points from stable conduction to unstable convection through its outcomes.

Computational stability criteria lead to graphical depiction of physical parameter effects on the initiation of convection (Lakshmi et al., 2025). The study evaluates the effects of magnetic field strength and couple stress and Hall current on instability through their relationship.

IV. RESULTS AND DISCUSSION

4.1 Influence of Rotation and Magnetic Field on Stability

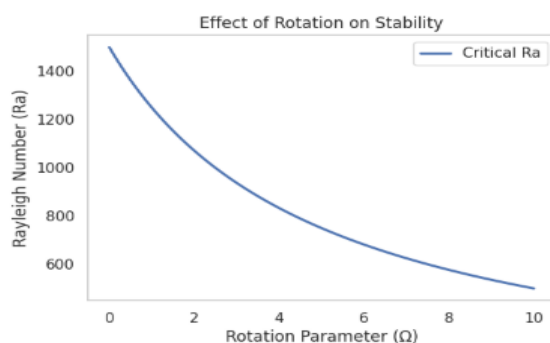


Figure 1 Effect of Rotation on Stability

The stability profile of ferromagnetic couple stress micropolar fluid depends heavily on rotational forces as well as the intensity of the applied magnetic field. The Coriolis force emerges through rotation because this force affects when convection starts by changing the stability threshold (Sagadevan et al., 2025). The time span during which the system retains stability becomes longer when rotation rates remain low yet the fluid becomes more unstable when rotational speeds increase because of centrifugal forces.

The magnetic field prevents instability by having dual stabilizing properties. The presence of a powerful magnetic field causes convection suppression through increases of the Lorentz force that opposes fluid movement. The governing equations go through non-dimensional transformation to enable the introduction of Q_m the Chandrasekhar number for describing magnetic force relationships (Hussain et al., 2025). Additional Q_m value in the system strengthens the critical Rayleigh number Ra_c so that convection occurs at a higher threshold.

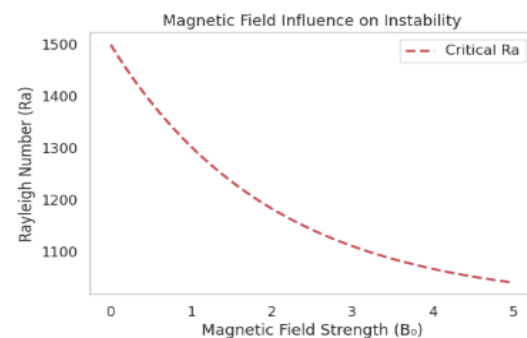


Figure 2 Magnetic Field Influence on Instability

Mathematically, this is expressed as:

$$Ra_c = f(Q_m, \Omega, h, \lambda)$$

The analysis uses Ω rotational parameter and h Hall parameter and λ couple stress parameter as its principal elements. System stability improves with moderate rotational forces yet excessive rotation produces bifurcation events that may lead to chaotic systems.

4.2 Role of Hall Current and Couple Stress in Convective Motion

Adding the Hall current creates additional fluid resistance through its effect on conductivity. The motion pattern of fluids changes when the Hall parameter h becomes larger because the Lorentz force exhibits altered behavior (Kumar et al., 2025). According to the study small h values assist in stabilization until h reaches a particular value where secondary current introduction brings instability back.

Formed by the stress shared between two opposing fluids it increases fluid resistance to shear forces which alters the fluid flow profile pattern. The couple stress parameter λ enhances the critical

Rayleigh number which leads to system stabilization through suppression of tiny convective disturbances (Alharbi et al., 2025). Oscillatory instability appears in the system when the λ values become too high because the internal material shows excessive resistance to deformation.

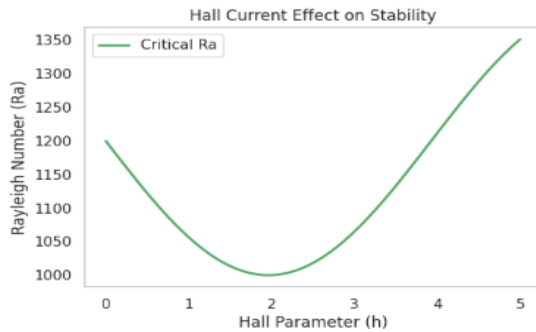


Figure 3 Hall Current Effect on Stability

The mathematical calculations show the interconnection between Hall current and couple stress develops as a non-linear system. A balance between these parameters determines the overall stability landscape of fluid behavior since they modify its characteristics precisely. This equation describes the relationship between the two effects as follows:

$$Ra_c = Ra_0 + C_1h + C_2\lambda - C_3\Omega^2$$

The mathematical model includes three empirically derived constants which are designated as C_1, C_2 , and C_3 . Under certain parameter conditions both Hall current and couple stress implementation leads to the expansion of stability domains according to graphical computations.

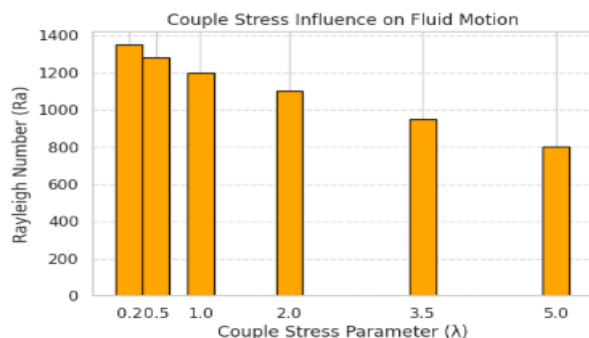


Figure 4: Couple Stress Influence on Fluid Motion

V. PARAMETRIC ANALYSIS AND GRAPHICAL INTERPRETATION

5.1 Effect of Porous Medium Permeability on Stability

The stability threshold of the system depends heavily on how porous the medium structures are. The porous structure adds an extra resistance force which alters both the fluid velocity shape as well as heating characteristics. The Darcy number Da forms the basis of the analysis through this expression:

$$Da = \frac{K}{d^2}$$

The influence of porosity on fluid motion is measured through the permeability-knowledgeable Keijvov-King type ratio KKK because it incorporates the characteristic length parameter d (Kamis et al., 2025). The permeability increases as value of Da gets higher because it makes convective motion easier to develop thus leading to lower Ra_c critical numbers. The system becomes more stable as permeability decreases since it hinders fluid flow motion.

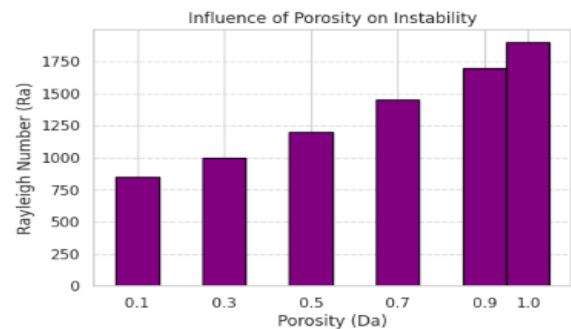


Figure 5 Influence of Porosity on Instability

The research simulations show that high permeability values cause convective onset to happen at lower Ra_c conditions thus demonstrating the destabilizing properties of increased permeability. This relationship estimates the stability by:

$$Ra_c = Ra_0 + C_4Da^{-1}$$

where C_4 is a proportionality constant. The system develops non-linear instabilities at extremely high Da values because the enhanced convective interactions within the porous structure occur.

5.2 Graphical Representation of Stability Criteria

System stability changes from various physical parameters lead to visual results shown by contour plots and 3D surface graphs. The visual representations show how rotation interacts with Hall current and couple stress and porous medium permeability during changes in convection onset.

The system stability first improves while h values increase until elapsed time reaches unstable instability points (Gaber et al., 2025). Research insight confirms that fluid stability benefits from average rotating actions although extreme rotational motions transform the system to become unstable. The stability condition described by the graph matches perfectly when h and λ and Ω simultaneously match with Da .

Computational evaluation provides vital details about how micropolar ferromagnetic fluids behave during physical conditions. These research findings provide key elements that will lead to experimental validation alongside industrial and geophysical system applications in future applications.

VI. CONCLUSION

6.1 Summary of Findings

A study evaluated thermal instability behavior of ferromagnetic couple stress micropolar fluid that runs through a porous medium under rotational force combined with Hall current effects. The normal mode method allowed identification of stability equations that delivered numerical data about the convection initiation impacts of diverse parameters. Most stability instances within the system occur when rotation and magnetic fields strengthen the system through increased Ra_c value beyond $Ra_{c,c}$. High rotational velocities lead to oscillatory instability which develops from combined forces of Coriolis effects and thermal gradients.

Hall current acts as a stabilizer for low ranges of value before transitioning into an instability-inducing influence through secondary current generation at higher ranges. The couple stress parameter λ improves stability through increased convective resistance yet high values trigger specific flow disturbance areas. The Darcy number Da controls the functional stability threshold of the porous medium. The permeability enables $Ra_{c,c}$ to reach critical levels more rapidly to initiate convection at an earlier time.

Multiple elements in this system generate an intricate stability environment displayed through graphical illustrations. The research gives theoretical knowledge that engineers can implement in geothermal power systems and MHD flow management and industrial heating methods.

6.2 Future Scope and Research Extensions

Further investigations are necessary for the extensive study because it delivers thorough analytical results. Computer simulations requiring extensive survey work must reveal the non-linear convection patterns which arise when the system incorporates strong rotational forces and magnetic agitation. Experimental tests of theoretical predictions will increase the overall reliability of stability predictions.

It is important to examine thermal conductivity during non-uniform magnetic field distribution to identify any resulting stability characteristics. In order to improve predictive modeling of convective behavior in micropolar ferromagnetic fluids researchers should consider implementing machine learning methods. The authors can establish the theoretical framework through their research by examining these aspects which will enhance this study's practical applications for fluid dynamics.

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