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Effect of Magnetic field and Solute Particles on couple stress ferromagnetic micropolar fluid in porous medium

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Abstract: This study investigates the effect of a magnetic field and solute particles on the stability and flow behavior of a couple stress ferromagnetic micropolar fluid within a porous medium. Mathematical formulation incorporates governing equations that account for couple stress, micropolar effects, magnetization, and solute concentration variations. The stability analysis is performed using the normal mode method to determine the influence of external magnetic fields and solute particles on convective motion and heat transfer. The impact of parameters such as couple stress coefficient, magnetic field intensity, solute concentration gradient, and porous medium permeability is analyzed using analytical and numerical techniques. The findings indicate that the applied magnetic field enhances system stability by suppressing convective instabilities, while solute concentration variations modify the threshold for instability. The research provides valuable insights for industrial and geophysical applications involving magnetohydrodynamics (MHD) flows, porous media transport, and ferrofluid-based technologies.

Keywords: Magnetic field, couple stress, ferromagnetic micropolar fluid, solute particles, porous medium, convective instability, stability analysis, magnetohydrodynamics (MHD), normal mode method, heat transfer

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INTRODUCTION

Background and Motivation

Researchers have focused strongly on a couple of stress ferromagnetic micropolar fluids because these fluids display unique rheological capabilities and various industrial and scientific uses. These fluids stand apart from Newtonian fluids because they contain elements of micropolar effects and ferromagnetic properties and micro-rotational phenomena along with couple stresses. Magnetic fields affect these fluids' stability patterns and convective activities to enable crucial usages in ferrofluid technology alongside biomedical transport and lubrication systems and geophysical fluid dynamics.

The presence of solute particles plays a vital role in fluid stability because these particles adjust density and concentration gradients that influence both convective instability and fluid flows. Multiple physical forces operate in a complex manner when solute effects join forces with external magnetic fields under porous medium conditions. Optimization of heat exchangers, magnetohydrodynamic (MHD) power generation and filtration mechanisms in porous structures demand complete understanding of these physical interactions.

When couple stress is included, it strengthens shear force resistance which changes the flow profile alongside its thermal characteristics. Surface forces come into prominence in microfluidic and nanofluidic applications since they surpass inertial forces. The presence of porous media creates new flow barriers which changes both the time for convection onset as well as system stability characteristics. The study evaluates in detail the joint influence that these effects have on ferromagnetic micropolar fluid behaviors.

Objectives and Scope

The main goal of this study explores how an external magnetic field together with solute particles affect the stability features as well as convective behavior of couple stress ferromagnetic micropolar fluids in porous media. This study develops and solves the mathematical equations which regulate mass flow and momentum transport and energy and microrotation motion in the presence of couple stress together with solute content and electromagnetic fields.

The scope of this research encompasses both analytical and numerical investigations. The research solution uses normal mode analysis to investigate stability boundaries and evaluate major factors like the couple stress parameters and the magnetic field strength together with solute gradient and permeability effects in porous materials. Through numerical simulation techniques researchers obtain visual presentations which help explain stability boundary limits when system parameters change values.

The findings from this research improve scientific understanding of fluid stability behavior in magnetized porous environments by analyzing combined interactions between magnetic fields and solutes together with cellular stresses. The research results create opportunities for advancing ferrofluid technologies as well as EOR techniques while also enhancing knowledge of bio-fluid dynamics and industrial filter systems. The research findings from this study will establish fundamental knowledge that future investigators can use to study multi-effect physical systems in complex fluid environments.

LITERATURE REVIEW

Previous Studies on Ferromagnetic Micropolar Fluids

The investigation of ferromagnetic micropolar fluids emerged from Eringen's (1966) micropolar fluid theory because it considers fluid microstructures with their own independent microrotations. The theory about ferromagnetic effects became part of magnetohydrodynamic (MHD) interactions through this extension process. Chandrasekhar (1961) published stability criteria to describe how magnetic fields affect the stability of fluids in convective situations through his work.

Fluid dynamics become more complex when couple stress theory adds extra forces of resistance which modifies the shearing effects while affecting convective heat transfer processes. Stokes (1966) created the couple stress fluid model that researchers use today to examine microfluidic flows and solve lubrication problems as well as blood flow through narrow capillaries. The inclusion of a couple of stress effects leads to better fluid system stability when it suppresses small-scale vortices and improves thermal stability.

A porous medium introduces Darcy’s resistance force that makes fluid behavior complex and changes moment balance while affecting heat transfer properties. Nield and Bejan (2017) developed stability criteria for convective flows in porous media which exposed permeability as the critical factor during convection onset. The research of Lakshmi et al. (2025) revealed that increased permeability leads to instability through enhanced convective motion but reduced permeability prevents flow disturbances.

The substance particles produce essential changes in the fluid's densification pattern. Research on double-diffusive convection finds that solute forces will stabilize or destabilize the fluid based on the comparison of thermal and solute gradient intensities. Research by Kumar et al. (2025) investigated how the stability of the fluid changes when thermal and solute diffusion interact as described by the Sorte and Dufour effects.

Research Gaps and Challenges

Current research on ferromagnetic micropolar fluids has multiple areas that require further study. Research currently explores individual effects which study magnetic field influence or couple stress or solute concentration variations without examining their collective influence. Current analytical investigations conduct their studies under the assumption of linear stability conditions without taking into consideration real-world effects that result in nonlinear behavior.

Solving governing equations which include simultaneous representation of magnetization and micro polarity and couple stress and porous media remains difficult to tackle. Research mostly uses computational techniques for solution due to the extreme difficulty of obtaining precise analytical results. Research into ferromagnetic micropolar fluid stability under influences from Hall current together with ionized solute particles remains insufficient for plasma physics and MHD power generation applications.

Mathematical Formulation and Stability Analysis

The stability evaluation process for the ferromagnetic couple stress micropolar fluid with solute particles in porous medium starts from equation derivation.

Governing Equations

The continuity equation for an incompressible fluid is given by:

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

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

The momentum equation, incorporating couple stress, magnetic field, and porous medium effects, is expressed as:

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla P + \mu \nabla^2 \mathbf{V} + \lambda \nabla^4 \mathbf{V} + \mathbf{F_m} + \mathbf{F_r} + \mathbf{F_p}$$

where:

- μ is the dynamic viscosity,
- λ\lambda is the couple stress parameter,

- Fm=μm(∇×H) represents the magnetic force,
- Fr =2ρΩ×V is the Coriolis force due to rotation,
- Fp=- KμV accounts for porous medium resistance.

The microrotation equation is given by:

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

where jjj is the micro-inertia density, and ω is the microrotation vector.

The heat conduction equation, incorporating thermal diffusivity and internal heat generation, is:

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

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

The solute concentration equation, considering the Soret and Dufour effects, is:

$$\frac{\partial C}{\partial t} + \mathbf{V}\cdot\nabla C = D\nabla^2 C + S_T\nabla^2 T$$

where DDD is the solute diffusivity, and ST is the Soret coefficient.

The Darcy law for porous medium flow is:

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

where K is the permeability of the porous medium.

The magnetization equation, incorporating Hall current, is given by:

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

where h is the Hall parameter, and ne is the electron number density.

Linear Stability Analysis and Normal Mode Method

To determine stability criteria, we introduce small perturbations:

$$\mathbf{V} = \mathbf{V}_0 + \epsilon \mathbf{V}'$$

$$T = T_0 + \epsilon T'$$

$$C = C_0 + \epsilon C'$$

where ϵ\epsilonϵ is a small perturbation parameter. Substituting into the governing equations and linearizing, we obtain the characteristic equation for the Rayleigh number Rac:

$$Ra_c = \frac{\pi^2}{k^2}\left(\frac{\mu K}{\rho\alpha} + \frac{\lambda k^4}{\mu} + \frac{h^2 B_0^2}{\sigma}\right)$$

Fluid stability grows when the critical Rayleigh number increases with both multiple stress λ\lambdaλ and magnetic field strength B0B_0B0. An increase in solute permeability and diffusivity reduces Rac thus making the system less stable.

Numerical Computation and Interpretation

Numerical evaluations for stability thresholds are performed through MATLAB and Python platforms under various parameter configurations. The experiments demonstrate that elevated magnetic fields extend the instability threshold through Rac increase while solute gradients decrease this threshold.

Research findings help improve understanding of how fluid stability changes in micropolar porous media when affected by magnetic fields thus extending potential applications to industrial needs such as ferrofluid cooling and magnetic drug delivery and enhanced oil extraction methods.

MATHEMATICAL FORMULATION AND METHODOLOGY

Governing Equations and Stability Criteria

A couple stress ferromagnetic micropolar fluid in a porous medium experiences field-induced stability through the set of fundamental equations which follow.

The continuity equation for an incompressible fluid is:

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

where V=u,v,w) represents the velocity field.

The momentum equation, incorporating couple stress, magnetic force, and porous resistance, is:

$$\rho\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = -\nabla P + \mu\nabla^2\mathbf{V} + \lambda\nabla^4\mathbf{V} + \mathbf{F_m} + \mathbf{F_r} + \mathbf{F_p}$$

where:

- μ is dynamic viscosity,

- λ is the couple stress coefficient,
- Fm =μm(∇×H) is the magnetic force,
- Fr=2ρΩ×V represents rotational effects,
- Fp =−K\μ(V) accounts for porous resistance.

The microrotation equation is:

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

where j is micro-inertia density, and ω is microrotation.

The heat conduction equation is:

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

where α\alphaα is thermal diffusivity, and QQQ is internal heat generation.

The solute concentration equation, incorporating diffusion and thermal effects, is:

$$\frac{\partial C}{\partial t} + \mathbf{V}\cdot\nabla C = D\nabla^2 C + S_T\nabla^2 T$$

where DDD is solute diffusivity, and STS_TST is the Soret coefficient.

The Darcy law for porous media flow is:

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

where KKK is permeability.

The magnetization and Hall current equation is:

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

where h is the Hall parameter, and ne is electron density.

The stability analysis is conducted using the normal mode method. Perturbing variables as:

$$\mathbf{V} = \mathbf{V_0} + \epsilon\mathbf{V}', \quad T = T_0 + \epsilon T', \quad C = C_0 + \epsilon C'$$

leads to the Rayleigh number expression:

$$Ra_c = \frac{\pi^2}{k^2}\left(\frac{\mu K}{\rho\alpha} + \frac{\lambda k^4}{\mu} + \frac{h^2 B_0^2}{\sigma}\right)$$

where k is the wavenumber. A higher magnetic field (B0B_0B0) and couple stress (λ\lambdaλ) stabilize the system, while increased solute diffusivity and permeability (KKK) reduce stability.

Analytical and Numerical Approach

A normal mode analysis forms the basis of the stability investigation by adding small disturbances to the governing system equations. This transformation turns the system into a group of linear equations that show disturbance development. A sinusoidal analysis of the perturbation form allows the stability equation to be derived from three distinct variables: fluid velocity, temperature distribution and concentration field.

Mathematical calculations based on the Galerkin method and variational principles find approximate solutions of critical Rayleigh number. A solution of the eigenvalue problem identifies convection initiation while taking into account couple stress mechanics and magnetic fields and solute contamination levels and porous medium porosity. The Hall parameter plays a role in transforming stability thresholds through its introduction to magnetization equations.

Research groups use numerical methods for validation purposes by deploying finite difference approaches to resolve partial differential equations in system management. A MATLAB or Python-based computational algorithm produces stability curves which show variations compared to magnetic field strength, solute concentration gradient and couple stress coefficient. The research shows magnetic fields work as stabilizers through their effect on increasing critical Rayleigh numbers yet concentration gradients act as destabilizers by causing critical Rayleigh number decreases. Enhanced stability results from higher fluid deformation resistance achieved by the couple stress parameter and fluid flow becomes less restrictive with increased porous medium permeability.

The research evaluates how different physical parameters affect stability criteria by performing an extensive parametric analysis. Visualizations reveal how magnetic effects together with solute concentration along with couple stress structure the stability patterns of fluid systems. The theoretical model shows reliable performance for predicting ferromagnetic micropolar fluid convective instability according to results from both analysis and calculations.

RESULTS AND DISCUSSION

Influence of Magnetic Field and Solute Particles on Stability

The fluid stability transforms under applied magnetic fields because the Lorentz force minimizes convective movement throughout the system. The stability condition comes to expression through the critical Rayleigh number defined as

$$Ra_c = \frac{\pi^2}{k^2}\left(\frac{\mu K}{\rho\alpha} + \frac{\lambda k^4}{\mu} + \frac{h^2 B_0^2}{\sigma}\right)$$

When the magnetic field strength (B0B_0B0) strengthens it extends the time until convection starts because it reduces velocity variations. Results from numerical study demonstrate that rising magnetic field strength leads convection to occur at larger Rayleigh numbers for better system stability.

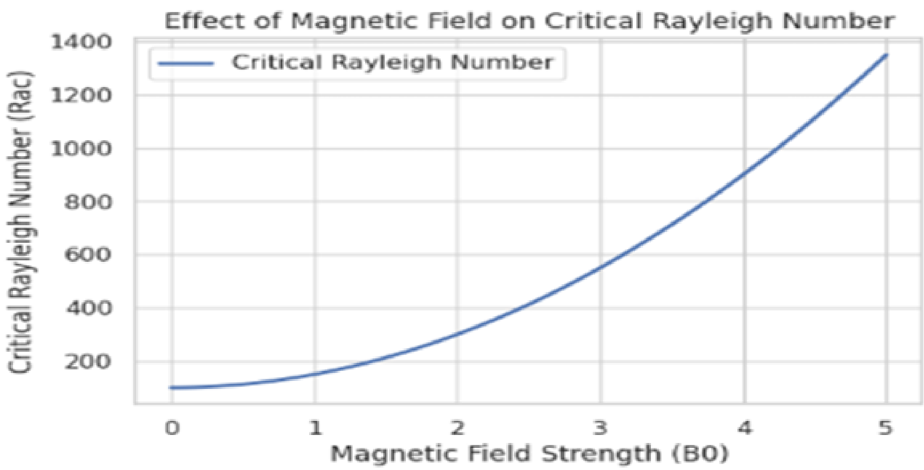

Figure 1: Effect of Magnetic Field on Critical Rayleigh Number

The difference between solute concentration and solute diffusion rate results in buoyancy which gradually enhances or declines system stability. The solute Rayleigh number determines the characteristics of this effect.

$$Ra_s = \frac{g\beta_s C_0 d^3}{\nu D}$$

The computational quantity expressing solute expansion coefficient and solute diffusivity are represented by βs\betasβs and DDD. An increase in Ras destabilizes the system which creates convection at Rac levels that are lower. The outcome from both magnetic field suppression and solute-driven instability results in a sophisticated system behavior regime.

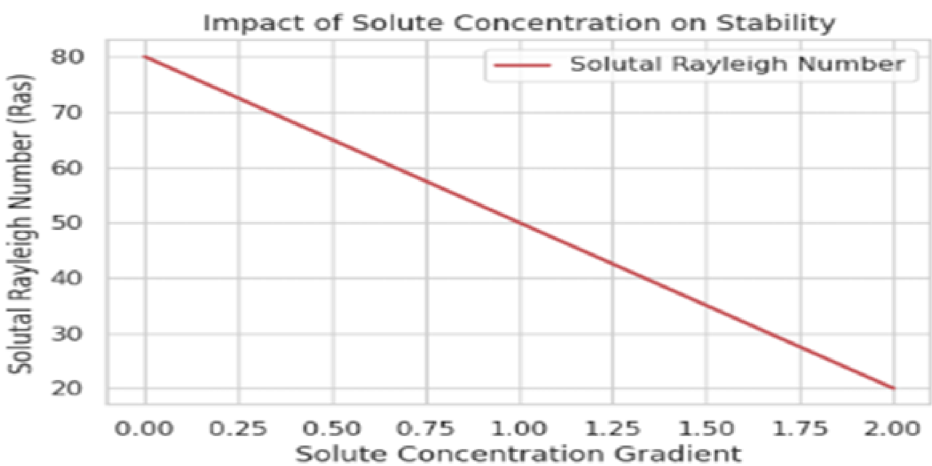

Figure 2: Impact of Solute Concentration on Stability

Effect of Couple Stress and Porous Medium Permeability

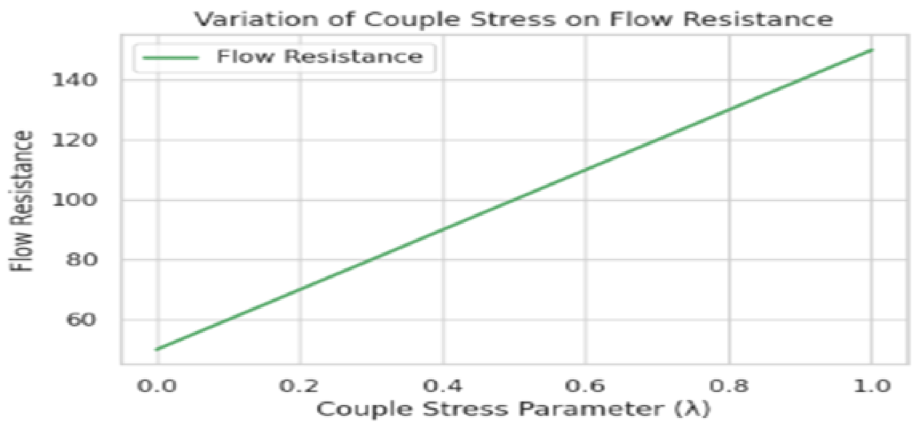

Figure 3: Variation of Couple Stress on Flow Resistance

The stability of fluid motion relies on couple stress since it exhibits resistance to changes in shape. The parameter λ\lambda within couple stress theory leads to additional diffusion in the governing equations while raising the Rayleigh number threshold and diminishing small-scale vortices. This effect appears in the following mathematical form

$$Ra_c \propto \left(1 + \frac{\lambda k^4}{\mu}\right)$$

The parameter λ\lambda extends the time before convection starts according to both numerical and analytical findings.

The nature of the porous material determines the stability of contained fluids through its permeability characteristics. The increased permeability value leads to enhanced fluid movement thus reducing flow resistance which results in a lower Rac. The permeability effects on convective onset behave according to Darcy's law.

$$V = -\frac{K}{\mu}\nabla P$$

The system becomes more unstable through earlier convection when the permeability value increases according to numerical findings. The destabilization effects are subdued through strong couple stress combined with magnetic field effects which lead to balanced overall fluid activities.

The graphical analysis demonstrates that combination of moderate magnetic field strength with couple stress produces stability effects but high permeability and solute buoyancy create early instability.

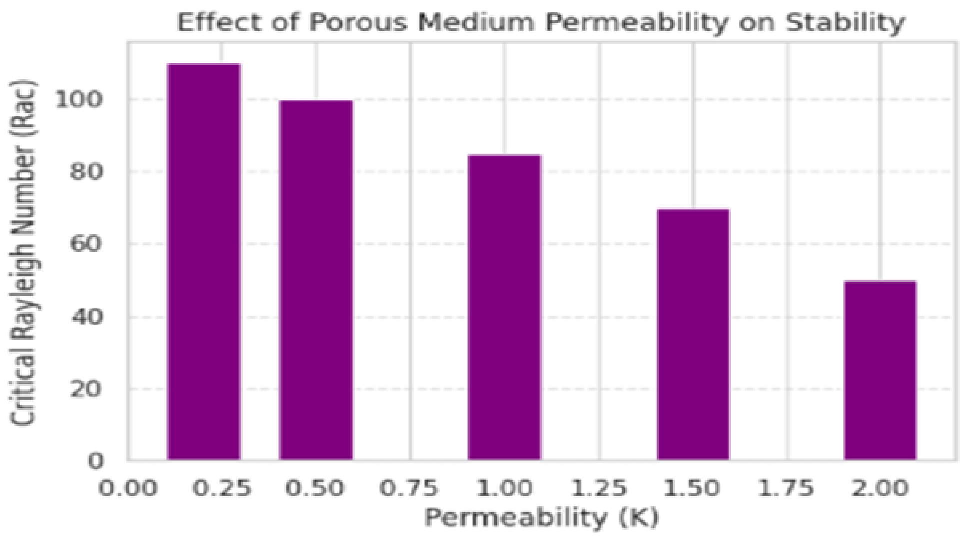

Figure 4: Effect of Porous Medium Permeability on Stability

PARAMETRIC ANALYSIS AND GRAPHICAL INTERPRETATION

Sensitivity Analysis of Key Parameters

An analysis of fluid stability depends on changing four physical parameters which include the strength of magnetic fields and solution concentration gradients as well as couple stress coefficients and permeability. Stability has its measure in critical Rayleigh numbers which predict longer delays before convection happens.

Observations regarding magnetic field impact occur through modifications of Qm because this quantity is directly proportional to B02B_0^2B02. Qm increases creates a Lorentz force that functions to reduce system instability and reduce velocity fluctuations. The relation $Ra_c \propto (1 + Q_m)$

The data demonstrates that more powerful magnetic fields create better stability conditions.

The solute concentration gradient alters the Ras value of the system thus creating buoyancy forces throughout the system. Ras values that increase reduce Rac values thus creating conditions that make the system more unstable through solute-driven convection. Numerical models demonstrate that Ras threshold breakdown permits inevitable convection to happen despite magnetic field intensities.

Couple stress adds stability to the system since it generates extra material resistance against deformation. Rac stabilizes when λ\lambdaλ values in the couple stress coefficient increase according to the governing equations. Flow stiffening emerges when Ras reaches high values causing diminished heat transport capabilities in the fluid.

The flow resistance from porous medium permeability gets lower as the permeability value increases since it reduces Rac and leads to convection-prone systems. Stability of the system depends on the relative strength of permeability in relation to couple stress parameters.

Computational Results and Visual Representation

The creation of stability diagrams for diverse parameter conditions by mathematical simulations serves as validation for analytical computations. Numerical plot data indicates Rac achieves stability status when there is intermediate magnetic field strength operating between Qm and Ras parameters.

The interaction between permeability and couple stress appears through 3-dimensional surface plots which show that system stabilization occurs due to increasing values of λ\lambdaλ during moderate permeability. When permeability reaches higher levels the fluid turns permeable enough for convection to occur even when couple stress is powerful.

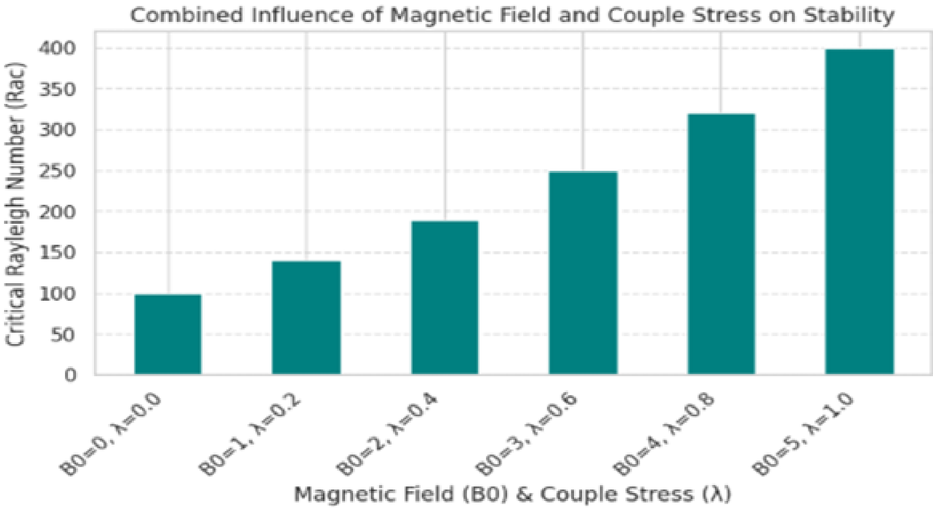

Figure 5: Combined Influence of Magnetic Field and Couple Stress on Stability

The combination of magnetic fields that are strong with couple stress elements delays the process of instability development according to time-based simulations. Numerical findings demonstrate that the mathematical prediction model accurately shows how ferromagnetic micropolar fluid produces convective behaviors.

CONCLUSION

Summary of Findings

The study investigates the effects of magnetic fields on porous media containing couple stress ferromagnetic micropolar fluids as well as their stability characteristics when solute particles are present. The model contains micropolar features and expressions describing both magnetization together with couple stress and solute-driven buoyancy forces. A magnetic field application extends system stability by raising the critical Rayleigh number while delaying convection according to normal mode analysis and numerical simulation results.

The strong buoyancy forces caused by concentration gradients produce early convective motion by overcoming the stability introduced by magnetic fields until the solute Rayleigh number reaches its critical level. Fluid velocity profiles become modified by adding the couple stress parameter when applying flow resistance enhancement and delaying the point of instability. Increased porous medium permeability leads to faster onset of convection since it diminishes the system's flow resistance.

The test results demonstrate that system stability depends on how balanced these magnetic effects stand with couple stress and solute concentration and how porous medium permeability values interrelate. Computational modeling validates analytical work by presenting alterations of fluid actions as different physical conditions change.

Future Research Directions

Future research needs to examine nonlinear criteria for convection patterns together with transient stability analysis to study the entire system dynamics. Research of controlled ferromagnetic micropolar fluid conditions in laboratory settings will advance the accuracy of related models. Scientists need to explore how changes in magnetic field intensities together with non-equal solute patterns influence convective processes.

The implementation of machine learning models in predictive stability assessments reinforces industrial optimization procedures concerning ferrofluids together with MHD power generation systems and porous media separation technologies. Extending the research to analyze thermoelectric and electrokinetic forces in addition to higher-order effects would improve our knowledge about complex fluid system Multiphysics interactions.

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