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Analytical Study of Nonlinear Behavior and Convection Patterns in Darcy-Brinkman Porous Medium with Maxwell-Cattaneo Ferroconvection

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Abstract

This study investigates the onset of ferroconvection in a porous medium, considering the combined effects of second sound and couple stress using classical stability analysis. We assume local thermal equilibrium between the fluid and solid matrix. Employing normal mode analysis with appropriate boundary conditions, we determine critical values for both stationary and oscillatory instabilities. Results indicate that oscillatory instability supersedes the stationary mode. This oscillatory porous media ferroconvection arises from the interplay of magnetization nonlinearity, second sound, and magnetic forces. The analysis further explores the influence of various parameters on the oscillation frequency and convective cell size. This research significantly advances our understanding of ferrofluid applications in coupled stress environments. The findings contribute substantially to technological advancements leveraging the unique rheological properties of ferrofluids under applied stress. A comprehensive understanding of the interplay between magnetic fields and stress-induced behavior in ferrofluids is crucial for optimizing their performance in engineering applications. This study, therefore, provides valuable insights for developing and refining technologies reliant on the controlled manipulation of magnetic fluids under coupled stress fields. The implications are far-reaching, impacting diverse fields such as advanced damping systems, microfluidic devices, and targeted drug delivery.

Major Findings: *The research enhances understanding of ferrofluid applications in coupled stress environments, contributing to technological advancements in engineering applications. It provides insights for developing and refining technologies involving controlled magnetic fluid manipulation under coupled stress fields.*

Keywords: *Couple-stress Fluid, Ferroconvection, Ferrofluids, Oscillatory Convection, Porous Medium, Thermal Relaxation Time, Second Sound*

1.0 Introduction

Ferroconvection, the heat transfer process within ferromagnetic fluids, holds significant promise across diverse applications, as evidenced by extensive research[1-3]. These magnetic fluids, comprising nanoscale ferromagnetic particles suspended in a carrier fluid (*e.g.*, kerosene, water, or hydrocarbons), exhibit pronounced paramagnetic behavior and high susceptibility when exposed to a magnetic field[4]. Their utility spans various sectors, including semiconductor manufacturing (vacuum feed-throughs) and biomedical applications such as targeted drug delivery via magnetic field manipulation, among numerous other uses[5-7]. Early investigations into ferrofluid convective instability under uniform magnetic fields elucidated the complex interplay of

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thermomechanical interactions, while subsequent studies explored stability in the absence of buoyancy effects. More recent research has delved into the intricacies of non-Darcy ferroconvection under gravity modulation, the influence of temperature-dependent viscosity on ferroconvection, and the coupled effects of Marangoni convection and internal heat generation[8-12]. Furthermore, the impact of magnetic field-dependent viscosity on ferroconvection within porous media, considering variable gravity, has also been a subject of considerable investigation[13]. This body of work underscores the ongoing exploration of ferroconvection's fundamental mechanisms and its potential for innovative technological advancements.

Classical heat transport equations assume infinite thermal signal speed, which is unrealistic. Modern theories replace Fourier's law with hyperbolic heat equations, allowing finite heat propagation speeds. This theory treats heat as a wave-like phenomenon, termed second sound (Chandrasekharaiah). Gurtin and Pipkin explored thermal conduction principles with memory effects[14,15]. Straughan and Franchi analyzed Benard advection with Maxwell-Cattaneo heat conduction, replacing Fourier's law[16]. Soya Mathew and Maruthamanikandan demonstrated that oscillatory convection is favoured for high Prandtl numbers and second sound parameters[17,18].

The concept that the distribution of force and momentum inside a material corresponds to mechanical contact between various body components is where couple stress originates. High viscosity and the polar effect are two of these liquids distinctive characteristics. The model for couple-stress liquids developed by Stokes is widely used to explain various suspension-related phenomena. When additives or suspensions are mixed into oil or liquid, the liquids force resists the additives effects. This resistance generates a couple force, causing couple stresses in the liquid. Due to colloidal particles microrotation, these liquids distort and form a spin field. This spin field creates anti-symmetric tension called couple stress, categorizing such liquids as couple-stress fluids. These liquids are useful in industrial processes like crystalline solidification, polymer extrusion, exotic lubricants, metallic plate freezing, and microscopic solutions. Non-Newtonian couple-stress liquids cannot be described using conventional continuum hypotheses. The micro-continuum hypothesis by Stokes allows for body couplings, couple stresses, and non-symmetric tensors[19,20]. Researchers have detailed convective unsteadiness in couple-stress liquids affected by rotation, porous media, chemical reactions, and g-jitter[21-26]. The works cited in the references section had a significant impact on understanding the nature of the reported work[27-49].

Convection control is significant in ferromagnetic fluid applications, despite the complexity of its mathematical modeling. The influence of second sound on Rayleigh-Benard convection within ferromagnetic couple-stress fluids remains relatively unexplored, despite extensive research on Rayleigh-Bénard convection under various constraints. This study addresses this gap in the literature by investigating the onset of Rayleigh-Benard convection in a layer of ferromagnetic couple-stress fluid, explicitly considering the effects of second sound. Our primary objective is to determine how the established stability criteria for ferroconvection are modified by the inclusion of both couple stress and second sound effects. This analysis will provide a more comprehensive understanding of the convective behavior in this complex fluid system, advancing the current theoretical framework.

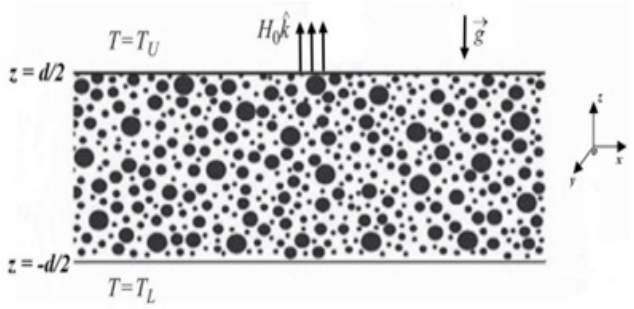


Figure 2. Physical Configuration.

2.0 Formulation of the Problem

In this work, an incompressible Maxwell-Cattaneo couple-stress ferromagnetic fluid in a porous media between infinitely long horizontal surfaces is subjected to a gravity force that is vertically downward and a magnetic field parallel to the z-axis.

The governing equations with the Boussinesq approximation are;

$$\nabla \cdot \vec{q} = 0 \tag{2.1}$$

$$\frac{\rho_0}{\varepsilon}\frac{\partial \vec{q}}{\partial t} + \frac{\rho_0}{\varepsilon^2}\left(\vec{q}\cdot\nabla\right)\vec{q} = -\nabla p + \rho\vec{g} + \nabla\cdot\left(\vec{H}\vec{B}\right) - \frac{\mu_f}{k}\vec{q} + \bar{\mu}_f\nabla^2\vec{q} - \mu_c\nabla^4\vec{q} \tag{2.2}$$

$$\varepsilon\left[\rho_0 C_{V,H} - \mu_0\vec{H}\cdot\left(\frac{\partial \vec{M}}{\partial T}\right)_{V,H}\right]\left[\frac{\partial T}{\partial t} + \vec{q}\cdot\nabla T\right] + (1-\varepsilon)(\rho_0 C)_s\frac{\partial T}{\partial t} + \mu_0 T\left(\frac{\partial \vec{M}}{\partial T}\right)_{V,H}\cdot\left[\frac{\partial \vec{H}}{\partial t} + \left(\vec{q}\cdot\nabla\right)\vec{H}\right] = -\nabla\cdot\vec{Q} \tag{2.3}$$

$$\tau\left[\frac{\partial \vec{Q}}{\partial t} + \left(\vec{q}\cdot\nabla\right)\vec{Q} + \vec{\omega}\times\vec{Q}\right] = -\vec{Q} - k_1\nabla T \tag{2.4}$$

$$\rho = \rho_0\left[1-\alpha\left(T-T_a\right)\right] \tag{2.5}$$

$$M = M_0 + \chi_m\left(H-H_0\right) - K_m\left(T-T_a\right) \tag{2.6}$$

$$\nabla\cdot\vec{B} = 0, \quad \nabla\times\vec{H} = \vec{0}, \quad \vec{B} = \mu_0\left(\vec{H}+\vec{M}\right). \tag{2.7}$$

3.0 Stability Analysis

The following non dimensionl equations can be obtained by doing a stability analysis that include normal modes (Finlayson)[8].

$$\frac{\sigma}{\mathrm{Pr}}\left(D^2-a^2\right)W + \left(R+N\right)a^2\Theta - Na^2D\Phi = \Lambda\left(D^2-a^2\right)^2W - Da^{-1}\left(D^2-a^2\right)W - C\left(D^2-a^2\right)^3W \tag{3.1}$$

$$\left(1+2G\sigma\right)\left(\sigma\Theta - W\right) - \left(D^2-a^2\right)\Theta + G\left(D^2-a^2\right)W = 0 \tag{3.2}$$

$$\left(D^2 - M_3a^2\right)\Phi - D\Theta = 0 \tag{3.3}$$

The appropriate boundary conditions are

re $W = D^2W = D^4W = \Theta = D\Phi = 0$ at $z = \pm 1/2$.

3.1 Stationary Instability

The above mentioned (3.1) - (3.3) turn out to be the following;

$$\Lambda\left(D^2-a^2\right)^2W - Da^{-1}\left(D^2-a^2\right)W - C\left(D^2-a^2\right)^3W - \left(R+N\right)a^2\Theta + Na^2D\Phi = 0 \tag{3.4}$$

$$\left[G\left(D^2-a^2\right)-1\right]W - \left(D^2-a^2\right)\Theta = 0 \tag{3.5}$$

$$\left(D^2 - M_3a^2\right)\Phi - D\Theta = 0 \tag{3.6}$$

Equations (3.4) – (3.6) along with the boundary conditions embrace an eigenvalue problem with R being eigenvalue.

The straightforward solution $W = A_1\cos(\pi z)$, $\Theta = A_2\cos(\pi z)$, $\Phi = \frac{A_2}{\pi}\sin(\pi z)$, we obtain the expression for the stationary Rayleigh number R^{st}.

3.2 Oscillatory Instability

Introducing the frequency of oscillation ω through $\sigma = iw$ and since the Rayleigh number R cannot be imaginary, we obtain R in the form $R = R_1 + iR_2$ with both R_1 and R_2 are computed by *Mathematica software*. The expression for the oscillatory Rayleigh number R_c^{OSC} is arrived at upon substituting the expression for w^2 in R_1.

4.0 Results and Discussion

This study examines ferroconvection in porous materials with couple-stress magnetic fluid, considering non-

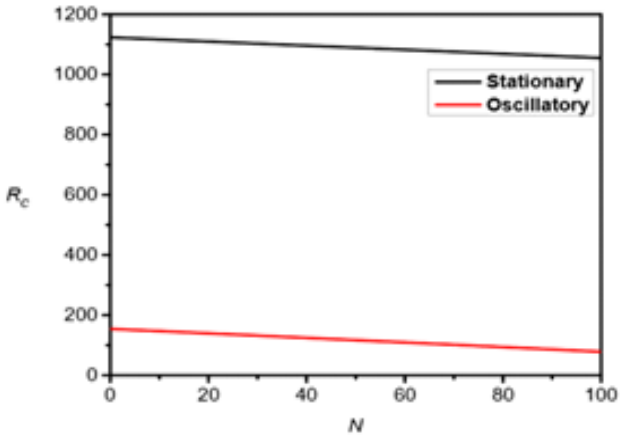


Figure 2. Plot of R_c as a function of N.

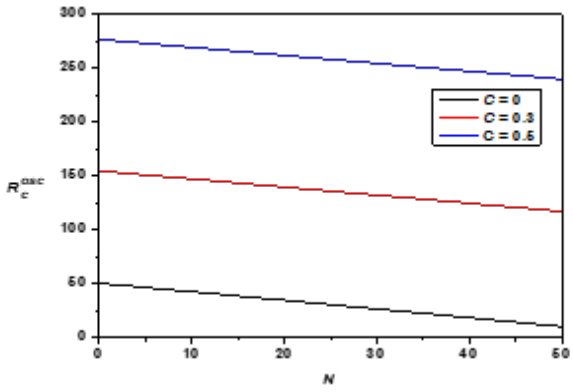


Figure 3. Plot of R_c^{OSC} as a function of N with different values of C.

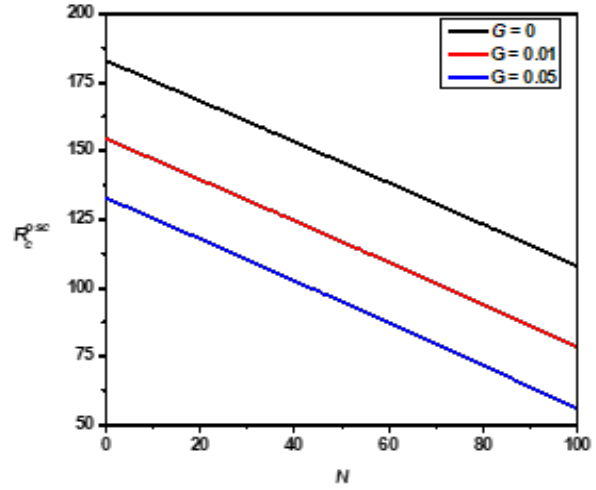


Figure 4. Plot of R_c^{OSC} as a function of N with different values of G.

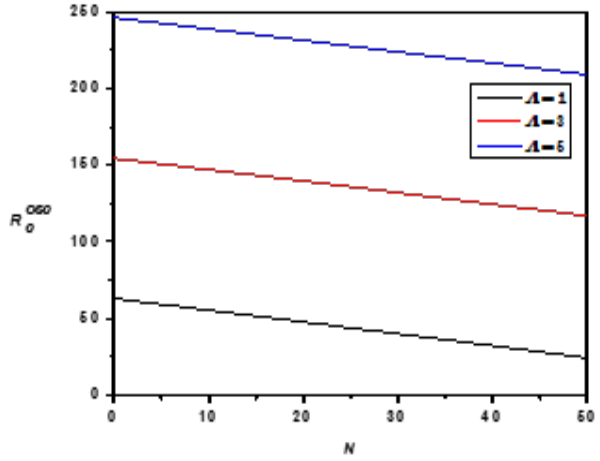


Figure 7. Plot of R_c^{OSC} as a function of N with different values of Λ .

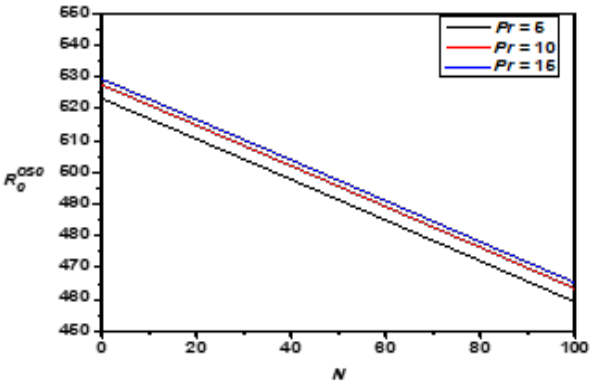


Figure 5. Plot of R_c^{OSC} as a function of N with different values of Pr.

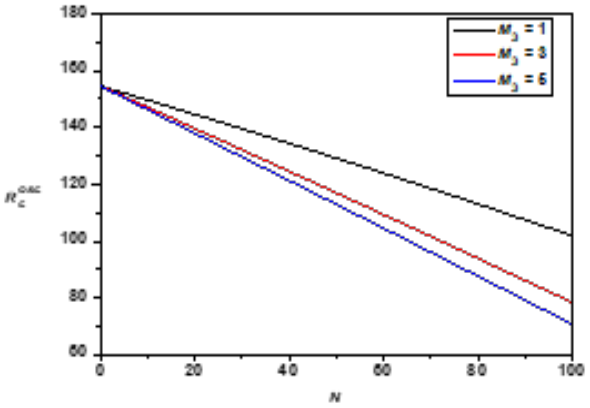


Figure 8. Plot of R_c^{OSC} as a function of N.

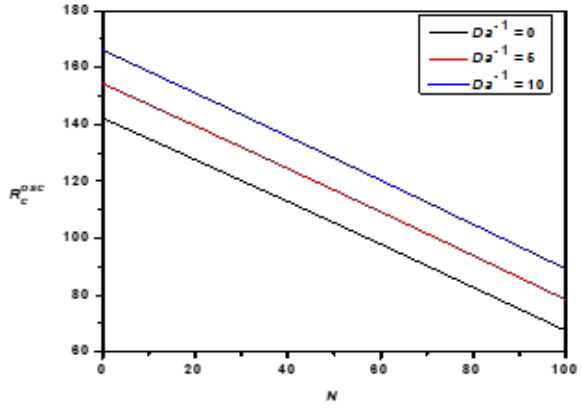


Figure 6. Plot of R_c^{OSC} as a function of N with different values of Da^{-1}.

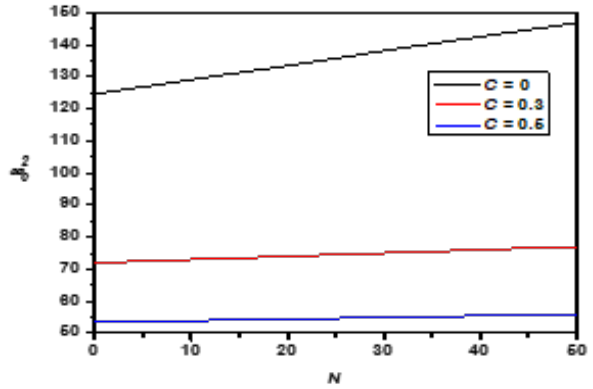


Figure 9. Plot of w_c^2 as a function of N with different values of C

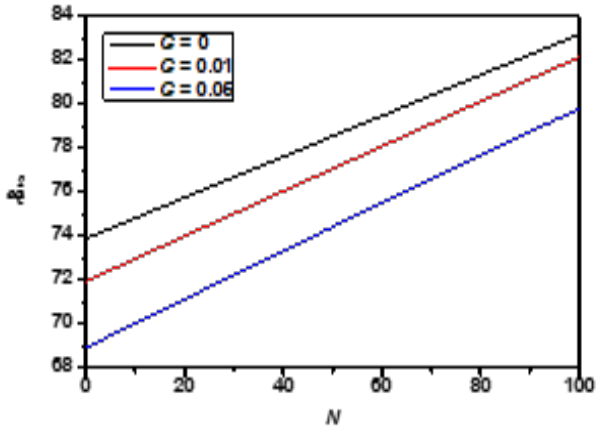


Figure 10. Plot of w_c^2 as a function of N with different values of G

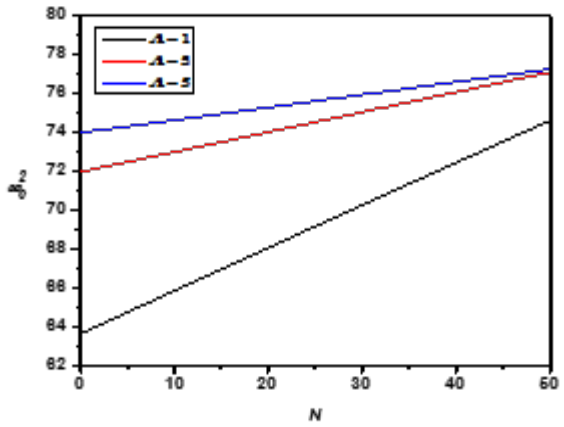


Figure 13. Plot of w_c^2 as a function of N with different values of Λ.

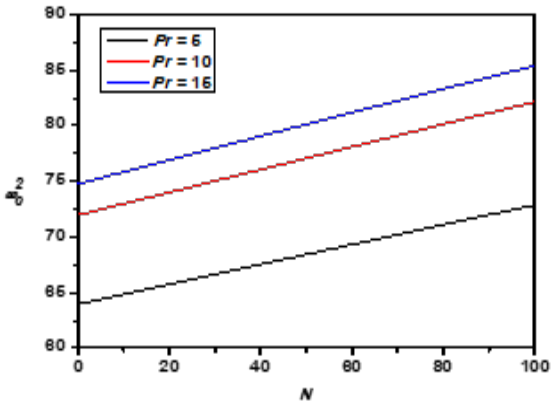


Figure 11. Plot of w_c^2 as a function. of N

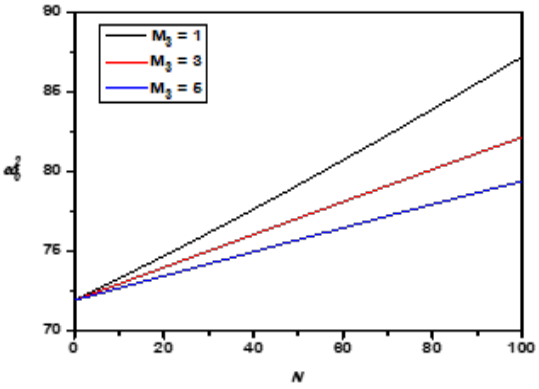


Figure 14. Plot of w_c^2 as a function of N with different values of M_3.

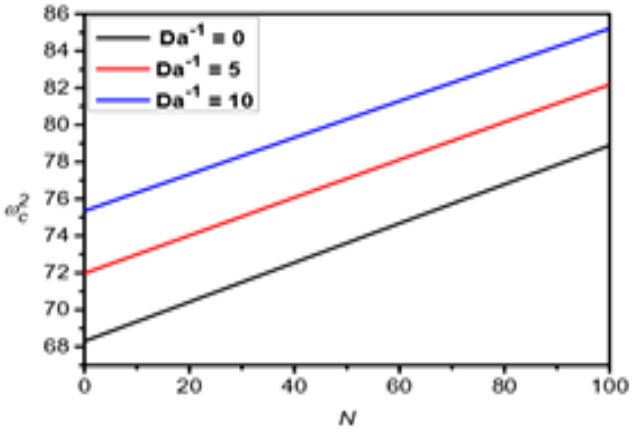


Figure 12. Plot of w_c^2 as a function of N with different values of Da^{-1}.

classical heat conduction effects. It uses the normal mode approach and linear stability theory to determine the start of stationary and oscillatory convection. The thermal Rayleigh number, a crucial metric for system stability, is calculated based on various factors. The study uses Mathematica software to derive the eigenvalue equation and critical values, focusing on the interaction between these characteristics and the ferromagnetic fluids stability.

Figures 2 through 8 illustrate the critical Rayleigh number's dependence on various parameters within the ferroconvective system. In Figure 2, the critical Rayleigh number is presented as a function of the magnetic Rayleigh number, holding all other parameters constant.

Table 1. Critical values of the Rayleigh number and wave number

N	Stationary Case		Oscillatory Case	
	R_c^{st}	α_c^{st}	R_c^{OSC}	α_c^{OSC}
0	1121.54	2.649	153.49	3.056
20	1108.91	2.658	139.60	3.130
40	1095.25	2.667	123.55	3.202
60	1081.56	2.676	108.32	3.272
80	1067.84	2.685	92.949	3.341
100	1054.09	2.694	77.43	3.407

Increasing the magnetic Rayleigh number (N) decreases the critical Rayleigh number, thereby destabilizing the system and favoring oscillatory over stationary convection. This observation contradicts the principle of exchange of stabilities, as the critical Rayleigh number for oscillatory convection is lower. Critical values of the Rayleigh number and wave number was shown in Table 1.

Figure 3 examines the influence of the parameter C on the critical Rayleigh number as a function of N. An increase in C leads to a higher critical Rayleigh number, indicating that the couple-stress mechanism delays the onset of oscillatory ferroconvection. Similarly, Figure 4 shows the effect of the Cattaneo number (G) on the critical Rayleigh number. Increasing G decreases the critical Rayleigh number, demonstrating the destabilizing effect of the second sound mechanism.

The impact of the Prandtl number (Pr) is explored in Figure 5. A higher Pr increases the critical Rayleigh number, thus stabilizing the system. Figure 6 investigates the influence of another parameter (implicitly defined, requiring clarification in the original text) on the critical Rayleigh number. Increasing this parameter also increases the critical Rayleigh number, delaying oscillatory ferroconvection. This effect is attributed to a reduction in porous medium permeability, hindering ferroconvective instability. Figure 7 demonstrates the effect of the Brinkman number on the critical Rayleigh number. An increase in the Brinkman number leads to a higher critical Rayleigh number, delaying oscillatory ferroconvection due to increased viscous effects within the porous medium.

Figure 8 examines the correlation between the critical Rayleigh number and a parameter indicating the shift from linearity in the magnetic equation of state, showing that increasing this parameter decreases the critical Rayleigh number.

Figures 9 through 14 reveal the sensitivity of the oscillatory ferroconvective instability frequency and convection cell size to all parameters under investigation. It is noteworthy that, unlike Newtonian fluids which exhibit only stationary convection, the presence of second sound in this system promotes oscillatory instability, a phenomenon well-documented in the literature.

5.0 Conclusions

The study explores ferroconvection in porous mediums, focusing on second sound and couple stress. Results show oscillatory instability supersedes stationary mode, arising from magnetization nonlinearity, second sound, and magnetic forces. This research contributes to understanding ferrofluid applications in coupled stress environments, optimizing performance in engineering applications and impacting fields like damping systems and drug delivery.

1. The system becomes unstable due to nonlinearity in magnetization and second sound, but stabilizes through couple-stress effect, inverse Darcy number, Prandtl number, and Brinkman number.
2. High magnetization prevents effects from different processes, unlike Darcy porous media. Oscillatory

movements critical wavenumber and frequency are sensitive to issue parameters.

5.1 Industrial Applications of the Present Findings

1. This research significantly advances the understanding of ferrofluid behavior within coupled stress environments, contributing substantially to technological progress by leveraging their unique rheological properties under applied stress.
2. A comprehensive grasp of the interplay between magnetic fields and stress-induced responses in ferrofluids is paramount for optimizing their performance in diverse engineering applications.
3. This study provides valuable insights for the development and refinement of technologies reliant on the precise manipulation of magnetic fluids under complex stress fields.
4. The implications are far-reaching, impacting a broad spectrum of fields, including the design of advanced damping systems, the fabrication of sophisticated microfluidic devices, and the development of targeted drug delivery systems.
5. The findings presented herein offer a foundation for future research and innovation in this rapidly evolving field.

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