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Mathematical Modeling of Heat Transfer Phenomena in Darcy Porous Media with Couple-Stress Magnetic Fluid under Maxwell-Cattaneo Model

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Abstract

This study employs classical stability analysis to investigate the combined influence of couple stress and second sound on the onset of ferroconvection within a densely packed porous medium. A generalized Darcy model, incorporating couple stress effects, is integrated into the momentum equation. Simultaneously, the Cattaneo heat flux model governs solid-phase heat transfer, while fluid-phase heat transfer adheres to Fourier's law under the assumption of local thermal equilibrium. Through normal mode analysis, subject to appropriate boundary conditions, critical values for both stationary and oscillatory instabilities are determined. The Cattaneo effect is shown to promote oscillatory convection as the dominant instability mode. Our findings indicate that magnetic forces, magnetization nonlinearity, the Vadasz number, and the inclusion of second sound all accelerate the onset of oscillatory ferroconvection. Conversely, couple stress exhibits a delaying effect on this onset. Furthermore, the analysis extends to examining the impact of various parameters on the resulting convection cell size and oscillation frequency.

Major Findings: *The study reveals that magnetic forces, magnetization nonlinearity, Vadasz number, and second sound accelerate the onset of oscillatory ferroconvection, while couple stress delays it. The analysis also examines the impact of parameters on convection cell size and oscillation frequency.*

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

1.0 Introduction

Ferrohydrodynamics (FHD) provides a theoretical framework for analyzing fluid motion under the influence of strong magnetic polarization forces. Unlike magnetohydrodynamics, which focuses on electrically conductive fluids, FHD investigates the behavior of non-conducting liquids possessing inherent magnetic properties. These liquids, commonly known as magnetic fluids or ferrofluids, are colloidal suspensions of minute ferromagnetic particles dispersed within a non-conducting carrier fluid such as water, kerosene, or hydrocarbons. Their unique characteristics have resulted in widespread applications across diverse fields, including loudspeaker technology, biomedical devices, lubrication systems, vacuum technology, and acoustic engineering[1,2].

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Early research into the thermomechanical interactions within ferrofluids includes Finlayson's seminal work on convective instability in a heated ferrofluid layer[3]. Subsequent investigations by Zebib further explored thermal convection in these fluids[5], while Lalas and Carmi focused on thermoconvective stability in the absence of buoyancy effects[4]. The significant influence of magnetic forces on critical parameters has fueled considerable research interest in ferroconvective instability phenomena, highlighting the complex interplay between magnetic fields and fluid dynamics in these materials[6-10]. This ongoing research continues to reveal the potential for further advancements and applications leveraging the distinctive properties of ferrofluids.

The classical parabolic energy equation, while useful in many contexts, presents the unrealistic implication of infinite heat propagation speed in solids. To address this limitation, Cattaneo introduced a hyperbolic energy equation incorporating a relaxation parameter, thereby enabling the modeling of finite heat propagation speeds[11]. This hyperbolic heat flow model finds relevance in various applications, including nanofluid heat transfer, electronic cooling systems, and biomedical technologies[12]. Straughan demonstrated that the Cattaneo heat flux can induce oscillatory convection in porous media under specific conditions[13]. Further research by Mathew and Maruthamanikandan explored Maxwell-Cattaneo ferroconvection in porous media[14], while Soya Mathew *et al*., investigated gravitational instability in ferromagnetic fluids with non-classical heat conduction[15]. Recent studies, such as that by Balaji *et al*. on ferroconvection under sinusoidal magnetic fields[16] and Vidyashree *et al*. on the effects of magnetohydrodynamic viscosity on ferroconvection in porous media with varying gravity, continue to expand our understanding[17]. Naseer and Maruthamanikandan employed linear stability analysis to investigate oscillatory Maxwell-Cattaneo ferroconvection in a densely packed, rotating porous material saturated with a viscoelastic magnetic fluid[18].

The introduction of additives or suspensions into oils or other liquids often encounters resistance from the base fluid. This resistance generates a couple force, leading to the presence of couple stresses within the liquid. The microrotation of colloidal particles induces distortions and the formation of a spin field within the liquid. This spin field, in turn, creates an antisymmetric tension known as couple stress, classifying such liquids as couple-stress fluids. These fluids find utility in various industrial processes, including crystalline solidification, polymer extrusion, specialized lubrication applications, metallic plate freezing, and microscopic solutions. The non-Newtonian nature of couple-stress fluids necessitates a departure from conventional continuum hypotheses. The micro-continuum hypothesis proposed by Stokes accounts for body couplings, couple stresses, and non-symmetric tensors, providing a more accurate framework for their description[19,20]. Extensive research has explored convective instabilities in couple-stress liquids under the influence of 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[27-47].

Applications such as improving heat transmission, dampening mechanical systems, and creating cutting-edge technical solutions for control mechanisms all depend on an understanding of convection in ferrofluids. The goal of ongoing research in this area is to understand the physics at play, improve material qualities, and investigate possible applications in sectors like as robotics, electronics, and biomedicine. In real-world situations, altering significant elements can postpone or accelerate the beginning of convection. Although couple stress and second sound have been extensively studied, there is a notable lack of research on the relationship between ferrofluids, couple stress, and non-classical heat conduction. Therefore, this study aims to investigate the effect of non-classical heat conduction on ferroconvective oscillatory instability in Maxwell-Cattaneo ferrofluids housed in porous media.

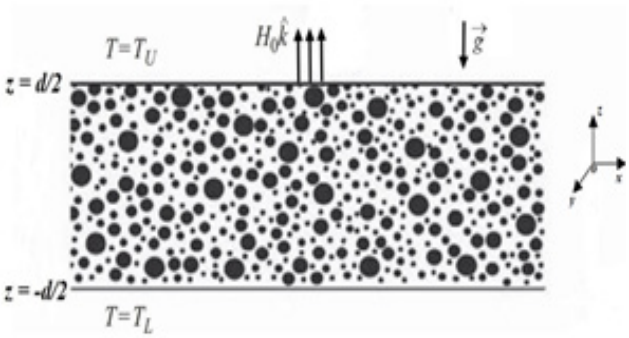


Figure 1. Physical configuration.

2.0 Mathematical Formulation

Let us consider an incompressible Cattaneo couple-stress ferromagnetic fluid saturated in a porous medium housed between the two horizontal surfaces of infinite length with a finite thickness d. The lower surface at $z=-\frac{d}{2}$ and upper surface at $z=\frac{d}{2}$ are maintained at temperatures T_L and T_U respectively where $T_L > T_U$ with $\Delta T = T_L - T_U$ (see figure 1). It is assumed that the temperature varies linearly across the depth at the quiescent state. When the magnitude of ΔT become larger than the critical one, thermal convection will set in due to the buoyancy force. The fluid layer is exposed to a magnetic field $\vec{H}_0$ acting parallel to the vertical z-axis and the gravity force acting vertically downwards. The governing equations with the Boussinesq approximation are

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

$$\frac{\rho_0}{\varepsilon}\frac{\partial \vec{q}}{\partial t} + \frac{\rho_0}{\varepsilon^2}\left(\vec{q}\cdot\nabla\right)\vec{q} = -\nabla p + \rho\vec{g} + \nabla\cdot\left(\vec{H}\vec{B}\right) - \frac{1}{k}\left(\mu_f - \mu_c\nabla^2\right)\vec{q} \tag{2.2}$$

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

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

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

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

Maxwell's equations for a non-conducting fluid with no displacement currents, become

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

3.0 Stability Analysis

Following the stability analysis of small perturbations encompassing normal modes (Finlayson)[3], one obtains the following dimensionless equations

$$\left(1+\frac{\sigma}{Va}\right)\left(D^2 - a^2\right)W + \left(1+M_1\right)R_D a^2\,\Theta - R_D M_1 a^2\, D\Phi = C\left(D^2 - a^2\right)^2 W \tag{3.1}$$

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

$$\left(D^2 - M_3 a^2\right)\Phi - D\Theta = 0 \tag{3.3}$$

The appropriate boundary conditions are $W = D^2W = \Theta = D\Phi = 0$ at $z = \pm 1/2$

3.1 Stationary Instability

In stationary mode equations from (3.1) - (3.3) turn out to be the following

$$\left(D^2 - a^2\right)W + \left(1+M_1\right)R_D a^2\Theta - R_D M_1 a^2 D\Phi - C\left(D^2 - a^2\right)^2 W = 0 \tag{3.4}$$

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

$$\left(D^2 - M_3 a^2\right)\Phi - D\Theta = 0 \tag{3.6}$$

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

The straightforward solution $W = A_1\cos(\pi z)$, $\Theta = A_2\cos(\pi z)$, $\Phi = \frac{A_3}{\pi}\sin(\pi z)$, with A_1, A_2 and A_3 being constants, is taken into consideration. On applying the solvability condition, we obtain the expression for the stationary Darcy-Rayleigh number R_D^{st}.

3.2 Oscillatory Instability

Introducing the frequency of oscillation ω through $\sigma = i\omega$ and since the Darcy-Rayleigh number R_D cannot be imaginary; we obtain R_D in the form $R_D = R_1 + iR_2$ with both R_1 and R_2 are computed by *Mathematica software*. The expression for the oscillatory Darcy-Rayleigh number R_D^{osc} is arrived at upon substituting the expression for ω^2 in R_1.

4.0 Results and Discussion

Using linear stability theory and the normal mode approach, we address the challenge of determining the conditions for both stationary and oscillatory convection in a densely packed porous material saturating a couple-stress magnetic field with second sound. To examine the stability of the system, the Darcy-Rayleigh number is calculated as a function of many factors. The eigenvalue formulation and related critical number was obtained using Mathematica software. The Darcy-Rayleigh number

Table 1. Critical values of the Darcy Rayleigh number and wave number with $C=0.3$, $G=0.01$, $Va=2$ and $M_3=3$.

M_1	Stationary Case		Oscillatory Case	
	$R_{D_c}^{st}$	α_c^{st}	$R_{D_c}^{osc}$	α_c^{osc}
0	14.573	6.207	7.236	6.120
10	1.488	9.784	0.789	9.260
20	0.781	10.044	0.414	9.475
30	0.529	10.139	0.281	9.554
40	0.400	10.189	0.186	9.579
50	0.322	10.219	0.171	9.619

is determined in relation to the couple-stress parameter, Vadasz number, Cattaneo number, non-buoyancy magnetization parameter, and magnetic number in order to address oscillatory instability.

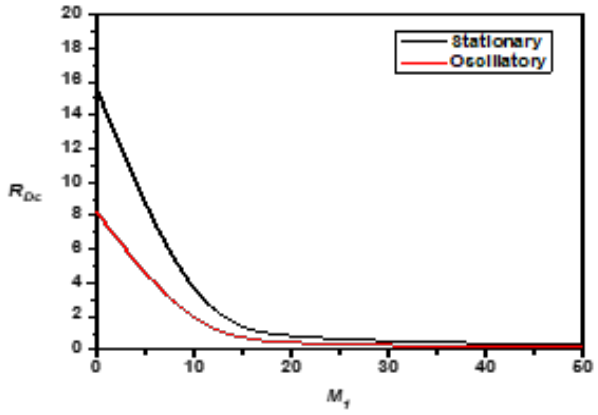


Figure 2. Plot of R_{DC} as a function of M_1.

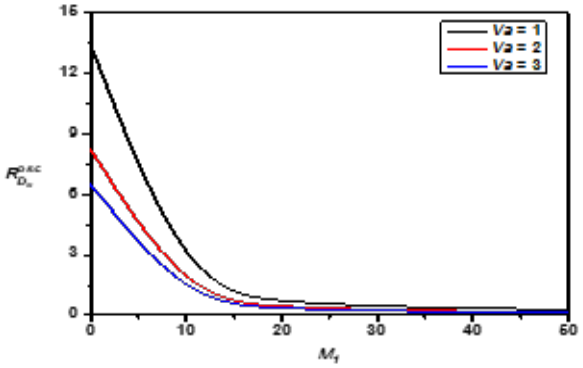


Figure 4. Plot of $R_{D_c}^{osc}$ as a function of M_1 with different values of *Va*.

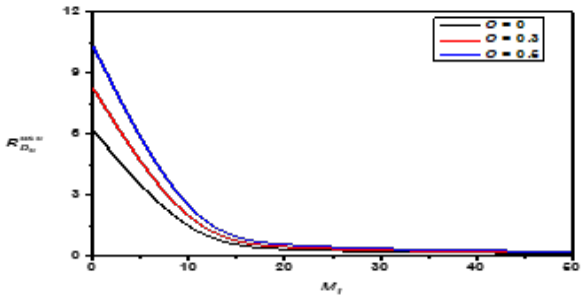


Figure 3. Plot of $R_{D_c}^{osc}$ as a function of M_1 with different values of *C*.

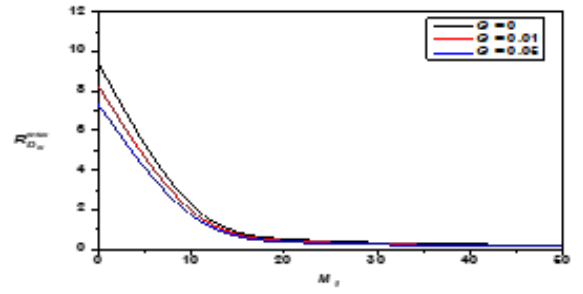


Figure 5. Plot of $R_{D_c}^{osc}$ as a function of M_1 with different values of *G*.

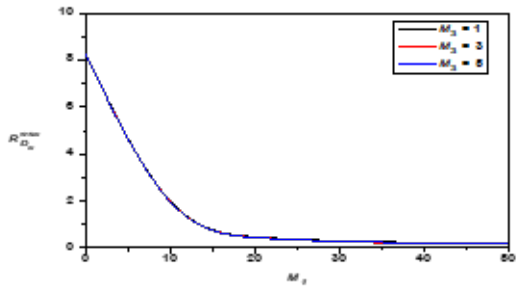


Figure 6. Plot of $R_{D_c}^{osc}$ as a function of M_1 with different values of M_3.

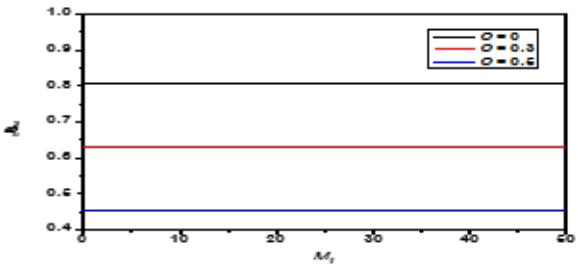


Figure 7. Plot of ω_c^2 as a function of M_1 with different values of C.

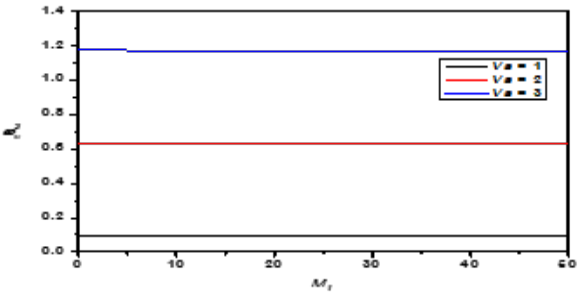


Figure 8. Plot of ω_c^2 as a function of M_1 with different values of Va.

Critical Darcy-Rayleigh numberis expressed as a function of Magnetic number M_1 by keeping all other parameters as constant. The fixed values of the parameters of the problem are taken to be C=0.3, $V_{a=}2$, G=0.01, M_3=3 Which is shown in Table 1. As can be seen in Figure 2, as M_1 increases R_{DC} decreases and hence the system gets destabilized by the effect. We observe that oscillatory convection is preferred to stationary convection as D-R Numberis less than $R_{D_c}^{st}$ and hence the principle of

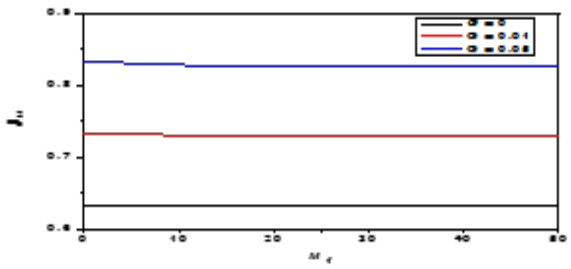


Figure 9. Plot of ω_c^2 as a function of M_1 with different values of G.

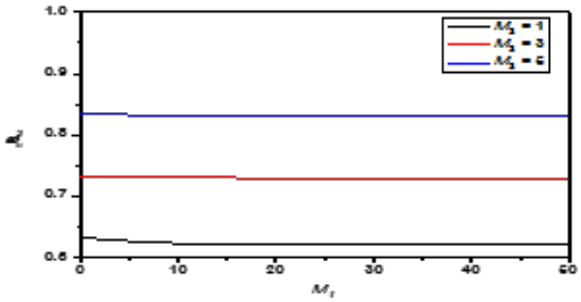


Figure 10. Plot of ω_c^2 as a function of M_1 with different values of M_3

exchange of stabilities is invalid for the problem under consideration.

Oscillatory critical Darcy-Rayleigh number is expressed as a function of M_1 by varying C in Figure 3. Clearly D-R Number increase with an increase in C, which indicates that the couple-stress mechanism postpones oscillatory ferroconvection and hence the system gets stabilized. Oscillatory critical Darcy-Rayleigh number is expressed as a function of M_1 by varying V_a in Figure 4. Evidently decreases with an increase in V_a, which indicates that the Vadasz number accelerates oscillatory ferroconvection leading up to the stabilization of the system.

Oscillatory critical Darcy-Rayleigh number $R_{D_c}^{osc}$ is expressed as a function of M_1 by varying G in Figure 5. It is evident that critical Darcy-Rayleigh number decreases with an increase in G, which indicates that the second sound mechanism expedites oscillatory ferroconvection. Oscillatory critical Darcy-Rayleigh number is expressed as a function of M_1 by varying M_3 in Figure 6. We see that number decreases with an increase in M_3, which means

the magnetic nonlinearity effect accelerates oscillatory ferroconvection. Furthermore, from Figures 7 through 10, one can observe that, the frequency of oscillations ω_c is sensitive to all the parameters of the study without any exception. Computations also reveal that ferroconvection cell size is also affected by all the parameters of the system.

5.0 Conclusions

The study examines the impact of couple stress and second sound on ferroconvection in a porous medium. It uses classical stability analysis, Darcy model, Cattaneo heat flux, and Fourier law. Oscillatory convection becomes the dominant instability mode due to the Cattaneo effect. Factors like magnetic forces, nonlinearity, Vadasz number, and second sound influence it. The assertions that conclude are constructed in the following manner.

- Because of the magnetic forces created by the ferrofluid's magnetization, the system is significantly destabilized.
- It is demonstrated that nonlinearity in the magnetization, Vadasz number, and Catenneo number destabilizes the system.
- The system is stabilized by a pair-stress mechanism.
- As long as the magnetization is strong enough, the impact of different factors on the systems stability will eventually vanish.
- The frequency of oscillatory movements and the critical wave number are computed and found to be sensitive to every issue parameter.

5.1 Applications of the Present Study

- This field of study delves into the dynamics of non-conducting liquids possessing inherent magnetic properties. These liquids, commonly referred to as magnetic fluids or ferrofluids, are colloidal suspensions comprising minute ferromagnetic particles dispersed within a non-conducting carrier fluid - examples include water, kerosene, or various hydrocarbons.
- The exceptional properties exhibited by ferrofluids have engendered a wide array of applications across diverse technological sectors.
- Notable examples include their utilization in advanced loudspeaker technology, sophisticated medical devices, high-performance lubrication systems, cutting-edge vacuum technologies, and precision acoustic engineering applications.
- The unique interplay between magnetic fields and fluid mechanics within ferrofluids continues to drive innovation and expansion of their practical applications.

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