Journal of Chemistry and Technologies, 2024, *32*(3), 826-836

Journal of Chemistry and Technologies

pISSN 2663-2934 (Print), ISSN 2663-2942 (Online).

journal homepage: http://chemistry.dnu.dp.ua
editorial e-mail: chem.dnu@gmail.com

UDC 621.9

CONVECTIVE INSTABILITY IN POROUS MEDIA: IMPACT OF CHEMICAL REACTION ON MAXWELL-CATTANEO COUPLE-STRESS FERROMAGNETIC FLUIDS

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Received 23 July 2024; accepted 2 September 2024; available online 20 October 2024

Abstract

The current study analyzes the initiation of convection in a Maxwell-Cattaneo couple-stress ferrofluid within a porous layer, considering the effects of a chemical reaction. Small perturbations are applied to the fluid under the assumption of a zero-order energy release chemical reaction. The system is cooled from the upper layer while maintaining a steady temperature at the lower boundary. We employed linear stability analysis and determined Rayleigh number using the Galerkin Method (GM). This study emphasizes the influence of magnetic, chemical, Maxwell-Cattaneo, and couple-stress parameters on the initiation of ferro-convection. The findings indicate that both magnetic and chemical reaction parameters hasten the initiation of ferro-convection, while the porous medium and couple-stress parameters have a stabilizing effect. Notably, it is demonstrated that the destabilizing effects of chemical reactions and magnetic stresses can be effectively regulated in the presence of couple-stresses. The solutions provide insights into the potential application of ferromagnetic fluids for controlling efficient heat transfer mechanisms.

Keywords: Ferro convection; Maxwell-Cattaneo law; Couple stress; Chemical reaction; Porous Medium.

КОНВЕКТИВНА НЕСТІЙКІСТЬ У ПОРИСТИХ СЕРЕДОВИЩАХ: ВПЛИВ ХІМІЧНОЇ РЕАКЦІЇ НА НАПРУЖЕННЯ ПАР МАКСВЕЛЛА-КАТТАНЕО В ФЕРОМАГНІТНИХ РІДИНАХ

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Анотація

У цьому дослідженні проаналізовано ініціювання конвекції у ферорідині з парними напруженнями Максвелла-Каттанео в пористому шарі з урахуванням впливу хімічної реакції. До рідини прикладаються малі збурення, припускаючи, що хімічна реакція відбувається з виділенням енергії нульового порядку. Система охолоджується з верхнього шару, підтримуючи сталу температуру на нижній межі. Ми застосували лінійний аналіз стійкості та визначили число Релея за допомогою методу Ґалеркіна. У цьому дослідженні підкреслено вплив магнітних, хімічних параметрів, параметрів Максвелла-Каттанео та параметрів парного напруження на ініціювання фероконвекції. Результати показують, що як магнітні, так і хімічні параметри реакції прискорюють ініціювання фероконвекції, в той час як пористе середовище і параметри парних напружень мають стабілізуючий вплив. Зокрема показано, що дестабілізуючий вплив хімічних реакцій і магнітних напружень можна ефективно регулювати в присутності парних напружень. Розв'язки дають уявлення про потенційне застосування феромагнітних рідин для керування ефективними механізмами теплопередачі.

Ключові слова: фероконвекція; закон Максвелла-Каттанео; парні напруження; хімічна реакція; пористе середовище.

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doi: 10.15421/jchemtech.v32i3.308945

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Introduction

The problem of thermodynamic stability arises from differentiating between stable and unstable flow patterns. Recently, interest in convective flows of fluids subjected to magnetic fields has expanded this class of stability problems. This paper focuses on the thermal convection of Maxwell-Cattaneo couple-stress ferrofluids subjected to chemical reaction and a porous medium.

Lord Rayleigh [1] was the first to propose the convective stability hypothesis for parallel fluid layers. The critical Rayleigh number, examined through traditional stability theory, demarcates a zone of stability from a fluctuating state. Chandrasekar [2] offered a more comprehensive explanation of thermal instability in fluid layers under various conditions, using the Boussinesq approximation. Finlayson [3] pioneered a new approach to ferroconvection by incorporating all assumptions of Rayleigh-Bénard Convection (RBC). Rosensweig [4] conducted a thorough and systematic investigation into the field of ferrofluids. The initial study of ferrofluids was conducted by S.S. Papell [5]. Ferrofluids are artificially created substances that do not naturally exist in a free state. Over the past three decades, significant effort has been devoted to studying ferroconvection, resulting in a wide range of applications for magnetic fluids in dynamic sealing, heat dissipation, damping, and doping of technical materials, among others. The stability of ferrofluids, affected bya vertical magnetic field, is crucial for their application in material science, the medical field, and various technical scenarios. Recently, Vidya Shree et al. [6] investigated the impact of magnetic field-dependent viscosity on ferromagnetic fluids subjected to variable gravity. In a horizontal Darcy-Brinkman porous medium, Soya et al. [7] investigated the impact of ferroconvection with radiative transmission. Sudhir Kumar Pundir [8] examined the effect of thermal convection in Maxwell ferromagnetic fluid through a porous medium.

In fluid theory, the polar impact of pair stress fluids is more significant. Stokes [9] developed the fundamental equations for couple-stress fluids, which are the simplest for microfluids. Thakur et. al [10] inspected the effect of couple stress forces on the convective stability of magnetized ferrofluids saturating a porous medium with various combinations of bounding surfaces. Sirwah and Assaf [11] investigated the stability of a thin couple-stress liquid layer on an inclined plane, revealing that increased couple-stress coefficient and surface tension enhanced stability, while nonlinear analysis provided more accurate stability insights for practical applications in inertial confinement fusion and supernova modeling. In their study, Ishaq et al. [12] investigated the creeping flow of a non-Newtonian couple-stress fluid through a slit with linearly porous walls in a Darcy porous medium, highlighting how physical parameters influence flow behavior and providing insights into kidney disease management and biomedical engineering.

Convective diffusion is commonly studied with chemical processes, as reactions can drive convection. Free convection can occur during an isothermal reaction if the density of the product differs from that of the reactant. Heat effects from the reaction can also induce convection by acting as a distributed heat source or sink. Zero-order reactions, where the reaction rate is independent of reactant concentration, can further enhance this effect. In exothermic reactions within a fluid-saturated porous medium, the generated heat alters fluid density, leading to free convection. In a horizontal porous layer, Nisha and Maruthamanikandan [13] looked into the stability of chemically reactive ferrofluids. It is seen that the magnetic and chemical effects encourage the initiation of magnetic convection when zero-order energy released by CR is taken into account. The impact of porous medium convection in a ferrofluid that is undergoing chemical reaction (CR) with a lower boundary due to steady heat flux was confirmed by Nisha and Maruthamanikandan [14]. Mahesh et al. [15] explored the flow of couple stress nanofluid under an inclined magnetic field, analyzing the effects of parameters such as Schmidt number, Prandtl number, Stefan-Boltzmann constant, and magnetic field on velocity, temperature, and concentration profiles, with exact solutions provided in terms of confluent hypergeometric functions. Suman and Nisha [16] investigated the impact of couple stress on convection initiation in a horizontally oriented porous layer with a chemically reactive ferromagnetic fluid and bottom heating, revealing that magnetic forces and chemical reactions accelerate ferroconvection, while couple stress stabilizes the system.

In conventional thermal instability analysis, the energy equation is parabolic, which implies an infinite speed of heat transport. To address the time lag in response or wave-like behavior, the classical Fourier heat law is replaced by the Maxwell-Cattaneo law. This transition introduces new theoretical developments in heat transfer, where heat transport exhibits wave-like behavior, resulting in a hyperbolic equation that allows for finite propagation speed, known as second sound. The proposed theory is based on the Cattaneo law for heat flux. Soya and Maruthamanikandan [17] in their study usedsmall perturbation scheme to analyze buoyancy-driven Darcy-Brinkman ferroconvection with Maxwell-Cattaneo law, revealing that magnetic and second sound stresses amplify convection thresholds, while porous medium effects counteract this, with high Cattaneo and Prandtl numbers favoring oscillatory instability over stationary modes. Naseer and Maruthamanikandan [18] examined the combined effects of second sound and viscoelasticity on rotating porous medium ferroconvection, finding that oscillatory instability is favored over stationary instability, with various parameters influencing the onset and frequency of convection, and highlighting potential technological applications involving viscoelastic magnetic fluids.The works mentioned in the literature [20–46] had a significant impact on understanding the essence of the reported work.

For a wide range of magnetic fluid technologies, controlling convection is vital, intriguing, and conceptually challenging. The literature review confirms that no research has yet analyzed the effect of second sound on Brinkman ferroconvective instability induced by the interplay of magnetic and couple stresses, combined with a non-autocatalytic exothermic reaction. This study uses the Darcy-Brinkman model with the Maxwell-Cattaneo law to describe flow through porous media, implementing the Maxwell-Cattaneo law in the energy equation. By applying stability analysis with infinitesimally small disturbances using normal modes and the higher-order Galerkin method, derives the media Rayleigh number as a function of both magnetic and non-magnetic parameters. This study aims to address how chemical reactions, second sound, and couple stresses affect the condition for the onset of ferroconvection. The findings could be beneficial for magnetic fluid technologies, such as magnetic field sensors, modulators, ferromagnetic resonators, and optical switches.

Mathematical Articulation

The current problem involves a chemically reactive Maxwell-Cattaneo couple-stress magnetic fluid within a sparsely distributed porous layer, confined between two parallel plates of infinite horizontal length and finite thickness d. The upper plate of the porous medium is maintained at a temperature T_c. Across the entire domain, a zero-order reaction can be triggered by slight temperature fluctuations fromT_c. The lower surface is maintained at a temperature T_h, where$T_h$is greater thanT_c. Gravity acts vertically downwards in this setup (see Figure 1).

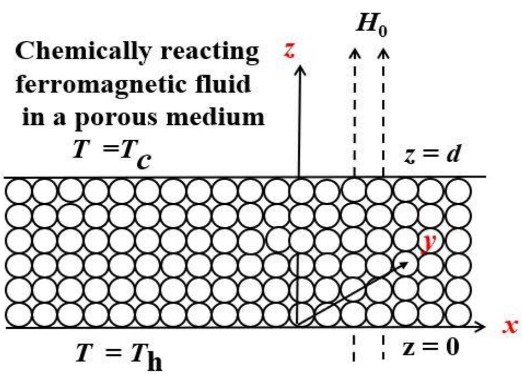

Fig. 1. Physical Outline

Based on Boussinesq approximations, zero-order energy released chemical reaction and the small disturbances experienced by the Maxwell-Cattaneo couple-stress fluid in the porous medium exhibit convective instability describesthe following set of equations

$$\nabla \cdot \vec{q} = 0 \tag{1}$$

$$\rho_0 \left[\frac{1}{\varepsilon} \frac{\partial \vec{q}}{\partial t} + \frac{1}{\varepsilon^2} (\vec{q} \cdot \nabla) \vec{q} \right] = -\nabla p + \rho \vec{g} + \nabla \cdot \left(\vec{H} \vec{B} \right) + \mu \nabla^2 \vec{q} - \frac{\mu'}{k} \vec{q} - \mu_c \nabla^4 \vec{q} \tag{2}$$

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$$\varepsilon C_f\left[\frac{\partial T}{\partial t}+(\vec{q}\cdot\nabla)T\right]+(1-\varepsilon)(\rho_0 C)_s\frac{\partial T}{\partial t}$$
$$+\mu_0 T\left(\frac{\partial \vec{M}}{\partial T}\right)_{V,H}\cdot\left[\frac{\partial \vec{H}}{\partial t}+(\vec{q}\cdot\nabla)\vec{H}\right]=-\nabla\cdot\vec{Q}+Qe^{\left(\frac{-E}{RT}\right)} \quad (3)$$

$$\tau\left[\frac{\partial \vec{Q}}{\partial t}+(\vec{q}\cdot\nabla)\vec{Q}+\vec{\omega}\times\vec{Q}\right]=-\vec{Q}+K_1\nabla T \quad (4)$$

$$\rho=\rho_0\left[1-\beta(T-T_c)\right] \quad (5)$$

$$\vec{M}=\frac{\vec{H}}{H}M(H,T) \quad (6)$$

$$M=M_0+\chi(H-H_0)-K_m(T-T_c) \quad (7)$$

where $\vec{q}$ the fluid velocity, ρ the fluid density, p the reduced pressure, $\vec{g}$ the gravitational acceleration, μ and μ' effective and dynamic viscosity, μ_c the couple-stress viscosity, ε the porosity of the porous medium and k the permeability of the porous medium. $\vec{H}$, $\vec{B}$ and $\vec{M}$ are vectors of magnetic field intensity, magnetic induction and magnetization respectively and μ_0 is the magnetic permeability. The chemical reaction effect is introduced by the term $Qe^{\left(\frac{-E}{RT}\right)}$ where the result of the reactant concentration, a pre-exponential factor and heat of reaction, denoted as Q; the activation energy, represented by E and the universal gas constant, denoted as R. Further, τ is the constant relaxation times, $\vec{Q}$ the heat flux vector, T the temperature, K the effective thermal diffusivity, β the thermal expansion coefficient, χ the magnetic susceptibility, K_m the pyromagnetic coefficient and $C_{V,H}$ is the specific heat at constant magnetic field and volume.

Maxwell's equations are given by

$$\nabla\cdot\vec{B}=0,\ \nabla\times\vec{H}=\vec{0} \quad (8)$$

$$\vec{B}=\mu_0\left(\vec{M}+\vec{H}\right) \quad (9)$$

The temperature is made dimensionless by setting $\theta=\frac{T-T_c}{T_r}$, where $T_r=\frac{RT_c^{\,2}}{E}$ with $\frac{RT_c}{E}<<1$ and the dimensionless temperature boundary conditions aligned with the objective include

$$\theta=0 \text{ at } z=1 \text{ and } \theta=\theta_h \text{ at } z=0. \quad (10)$$

The fluid is quiescent in the initial state and is provided by $\vec{q}=\vec{q}_b(z)=0$, $\rho=\rho_b(z)$, $p=p_b(z)$, $\theta=\theta_b(z)$, $\vec{H}=\vec{H}_b(z)$, $\vec{M}=\vec{M}_b(z)$, $\vec{B}=\vec{B}_b(z)$.

The solution for the steady state from equations (1) to (9) is provided by

$$\frac{dp_b}{dz}=-\rho_b g+B_b\frac{dH_b}{dz} \quad (11)$$

$$K\frac{d^2\theta_b}{dz^2}+\frac{Qe^{\left(\frac{-E}{RT_c}\right)}}{T_r}C_f e^{\theta_b}=0 \quad (12)$$

$$\rho_b=\rho_0\left[1-\beta T_r\theta_b\right] \quad (13)$$

$$\frac{d}{dz}\left(M_b+H_b\right)=0 \quad (14)$$

$$M_b(z)=M_0+\chi\left(H_b-H_0\right)-K_m T_r\theta_b \quad (15)$$

$$H_b(z)=H_0+\frac{K_m T_r\theta_b}{1+\chi} \quad (16)$$

$$M_b(z)=M_0-\frac{K_m T_r\theta_b}{1+\chi} \quad (17)$$

$$B_b(z)=\mu_0\left(M_0+H_0\right) \quad (18)$$

Adopting the methodology of Malashetty et al. [19], the solution of eqn. (11) reads

$$\theta_b=\ln\left(\frac{l_1}{2F}\right)+\ln\left[1-\left(\frac{1-l_2\exp\left(-\sqrt{l_1}\,z\right)}{1+l_2\exp\left(-\sqrt{l_1}\,z\right)}\right)^2\right], \quad (19)$$

where the constants l_1 and l_2 in eqn. (19) are implicitly calculated using

$$\exp\left(\sqrt{l_1}\right)\left[\frac{1-\sqrt{1-\dfrac{2F}{l_1}}}{1+\sqrt{1-\dfrac{2F}{l_1}}}\right]=\left[\frac{1-\sqrt{1-\dfrac{2F\exp(\theta_h)}{l_1}}}{1+\sqrt{1-\dfrac{2F\exp(\theta_h)}{l_1}}}\right] \quad (20)$$

$$l_2=\exp\left(\sqrt{l_1}\right)\left[\frac{1-\sqrt{1-\dfrac{2F}{l_1}}}{1+\sqrt{1-\dfrac{2F}{l_1}}}\right] \quad (21)$$

where $F=\dfrac{Cd^2}{\kappa}$ is the Frank-Kamenetskii number, $C=\dfrac{Qe^{\left(\frac{-E}{RT_c}\right)}}{T_r}$ and $\kappa=\dfrac{K}{\varepsilon C_f}$

Linear Stability Analysis

Employing normal modes in the conventional stability analysis [2], [13], [19], the resulting non-dimensional equations are:

$$\frac{\sigma}{P_r}\left(D^2-a'^2\right)W+R_a a'^2\theta+D_a^2\left(D^2-a'^2\right)W-\Lambda\left(D^2-a'^2\right)^2W$$
$$+\Gamma\left(D^2-a'^2\right)^3W+Na'^2\left(\frac{d\theta_b}{dz}\right)D\Phi-Na'^2\left(\frac{d\theta_b}{dz}\right)\theta=0 \quad (22)$$

$$(1+2G\sigma)\left[\lambda\sigma\theta+\left(\frac{d\theta_b}{dz}\right)W-Fe^{\theta_b}\theta\right]-\left(D^2-a'^2\right)\theta-G\left(\frac{d\theta_b}{dz}\right)+\left(\frac{d\theta_b}{dz}\right)\left(D^2-a'^2\right)W$$
$$-2GFe^{\theta_b}\left(\frac{d\theta_b}{dz}\right)W=0$$

$$D^2\Phi-M_3a'^2\Phi-D\theta=0 \quad (23)$$

where σ the rate of growth, Φ the magnetic scalar potential, $P_r=\dfrac{\mu_f}{\rho_0\kappa}$ the Prandtl number, $\Lambda=\dfrac{\mu}{\mu_f}$ the Brinkman number, $D_a=\dfrac{d}{\sqrt{k}}$ the Darcy number, $R_a=\dfrac{\beta\rho_0 g d^3 R T_c^2}{\mu_f\kappa}$ the media Rayleigh number, $\Gamma=\dfrac{\mu_c}{\mu_f d^2}$ the couple stress parameter, $M_3=\dfrac{1+\frac{M_0}{H_0}}{1+\chi}$ the non-buoyancy magnetization parameter, $N=\dfrac{\mu_0 K_m^2 T_r^2 d^2}{\mu_f\kappa(1+\chi)}$ the media magnetic number, $G=\dfrac{\tau\xi}{2d^2}$ Cattaneo Number.

Stationary Instability

The simultaneous equations with respect to the stationary instability (σ =0) are given since the principle of exchange of stability (PES) is applicable to the RBC problem of ferrofluids where the chemical reaction is occurring (Finlayson [3]).

$$R_a a'^2\theta+D_a^2\left(D^2-a'^2\right)W-\Lambda\left(D^2-a'^2\right)^2W$$
$$+\Gamma\left(D^2-a'^2\right)^3W+Na'^2\left(\frac{d\theta_b}{dz}\right)D\Phi-Na'^2\left(\frac{d\theta_b}{dz}\right)\theta=0 \quad (25)$$

$$\left(D^2-a'^2\right)\theta-\left(\frac{d\theta_b}{dz}\right)W+Fe^{\theta_b}\theta+G\left(\frac{d\theta_b}{dz}\right)\left(D^2-a'^2\right)W$$

$$+2GFe^{\theta_b}\left(\frac{d\theta_b}{dz}\right)W=0 \tag{26}$$

$$D^2\Phi-M_3a'^2\Phi-D\theta=0 \tag{27}$$

The applicable boundary conditions are

$$W=D^2W=D^4W=0 \quad at \quad z=0 \text{ and } at\ z=1$$

$$\theta=D\Phi=0 \quad at \quad z=0 \text{ and } at\ z=1 \tag{28}$$

The suitable trial functions which satisfy the boundary conditions are given by

W_i =sin $i\pi z$ θ_i =sin $i\pi z$ $\phi_i=\cos i\pi z$ (29)

Method of Solution

By using GM, it is possible to find the solution to the system of equations (25) through (27) with homogeneous boundary conditions (28) that produces an eigen value problem with $R_a$as an eigenvalue (Finlayson, [3]). Let's hire the GM.

W=$\Sigma A_iW_i\theta=\Sigma B_i\theta_i\phi=\Sigma C_i\phi_i$ (30)

where A_i,B_i,C_i are constants and W_i,θ_i,ϕ_i are the trial functions.

Results and Discussions

The current study focuses the thermal instability of a chemically reactive couple-stress Maxwell-Cattaneo ferrofluid which is sparsely distributed in a porous medium. A slight perturbation is placed on the fundamental state, which is made to appear to be static. To find the eigenvalue, the GM is used. The fundamental temperature profile for various values of F is shown in Fig. 2. As F values rise, it is shown that the fundamental temperature profile changes noticeably from being almost linear for lower values of F to becoming significantly less linear. Asymmetry in curves is also demonstrated by the rise in F values. The growing heat energy produced by chemical reaction is the cause of this nonlinearity's character.

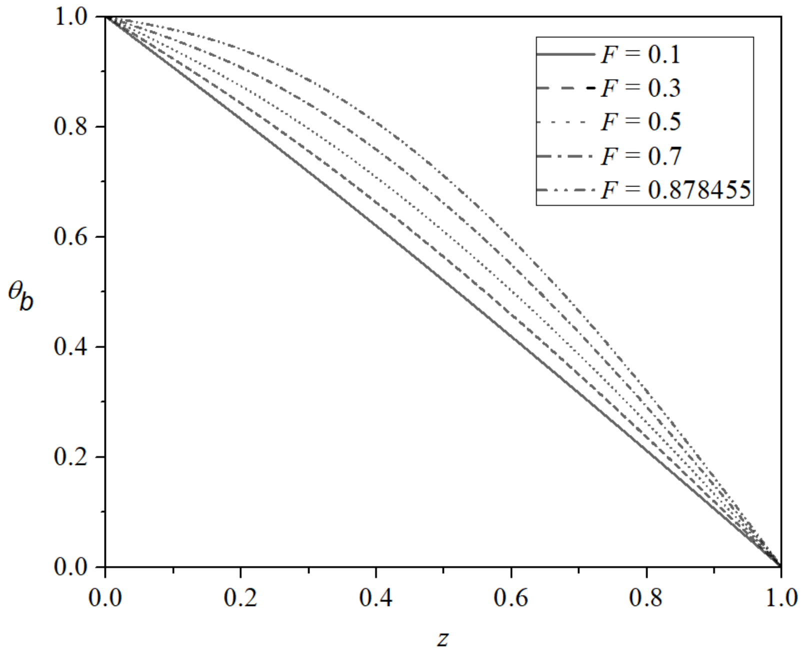

Fig. 2. Basic Temperature profile for various values of F

Fig. 3 shows the fluctuation of the Critical Magnetic Rayleigh Number, CMRN (R_{ac}), as a mapping of D_a for various values of *F*. The value of CMRN (R_{ac}) accelerates along with the Darcy number D_a. As a result, the system becomes stable due to the presence of the porous layer.

Fig. 4 shows the fluctuation of R_{ac} with respect to the pair stress parameter (Γ) for various values of *F*. An increase in the couple stress parameter (Γ) stabilizes the system, which results in a higher value of CMRN (R_{ac}).

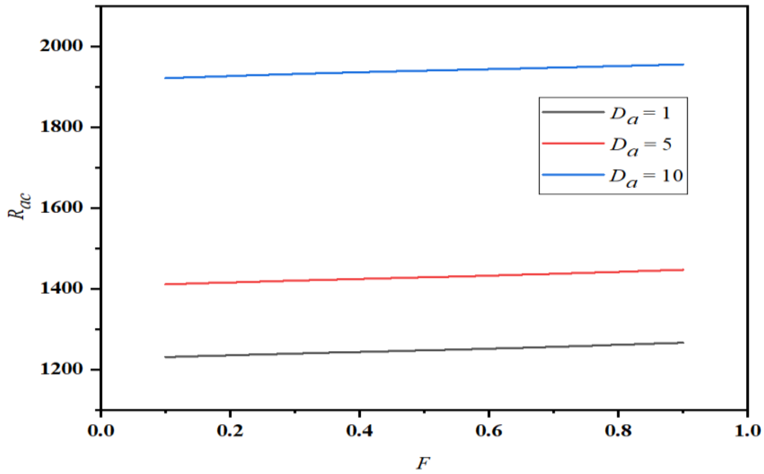

Fig. 3. Graph of R_{ac}versus F with different values in D_a

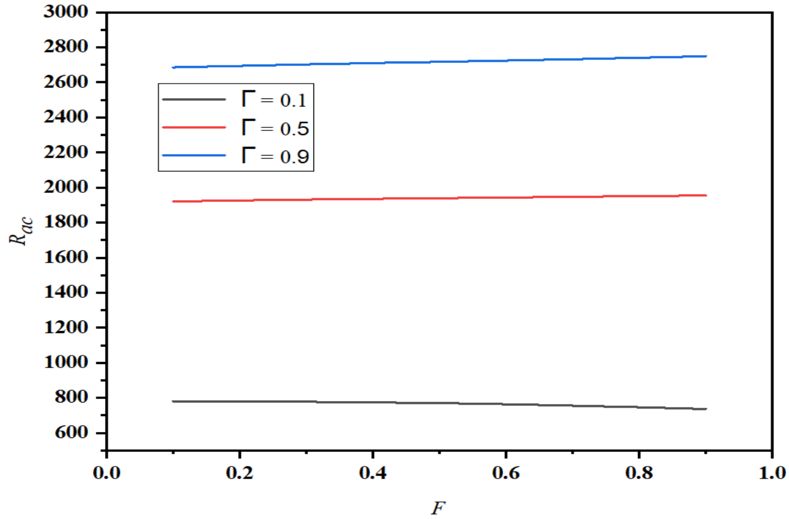

Fig. 4. Graph of R_{ac}versus F with different values in Γ

As a mapping of the non-buoyancy magnetization parameter (M_3), Fig. 5 shows the fluctuation of R_{ac} for various values of F. The system becomes less stable as the non-buoyancy magnetization parameter (M_3) value increases and the CMRN (R_{ac}) value lowers.

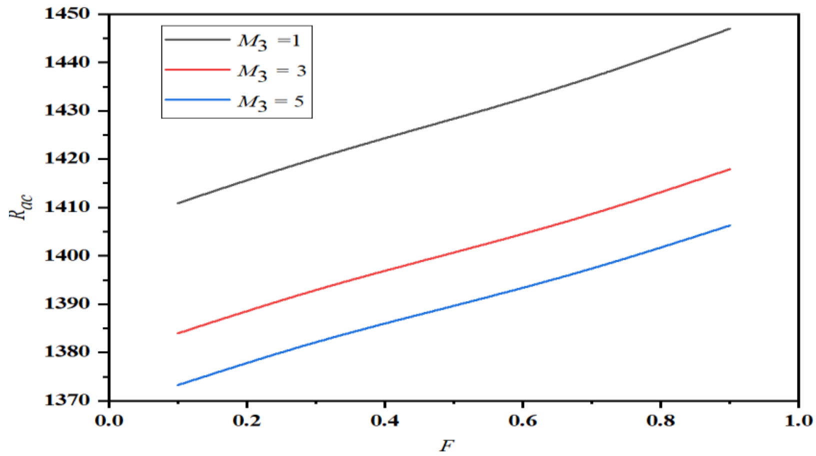

Fig. 5. Graph of R_{ac}versus F with different values in M_3

The variation of R_{ac} is shown in Fig. 6 illustrating its dependence on the Brinkman number (Λ) across various values of *F*. An increase in the Brinkman number leads to a rise in the critical Rayleigh number, thereby stabilizing the system.

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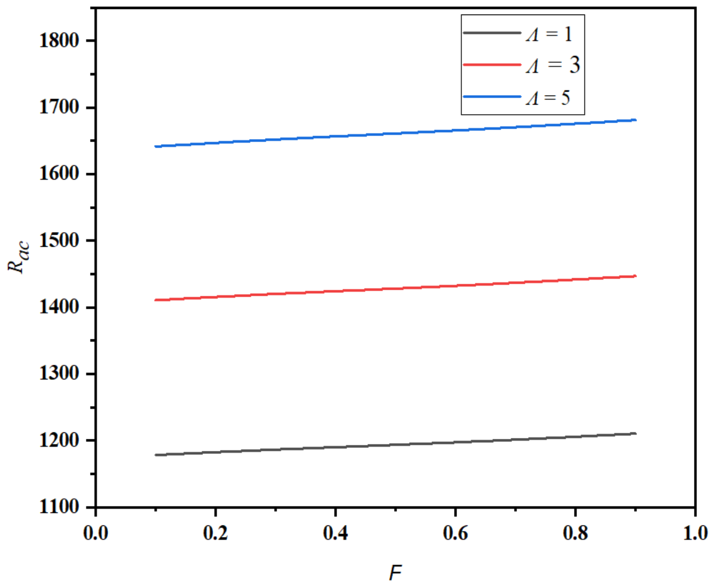

Fig. 6. Graph of R_{ac} versus *F* with different values in *Λ*

The dependency of R_{ac} with the Media Magnetic Number(N) across various values of *F* is shown in Fig. 7. The value of the CMRN (R_{ac}) drops as the medium Rayleigh number (N) rises, leading to a destabilising influence on the system.

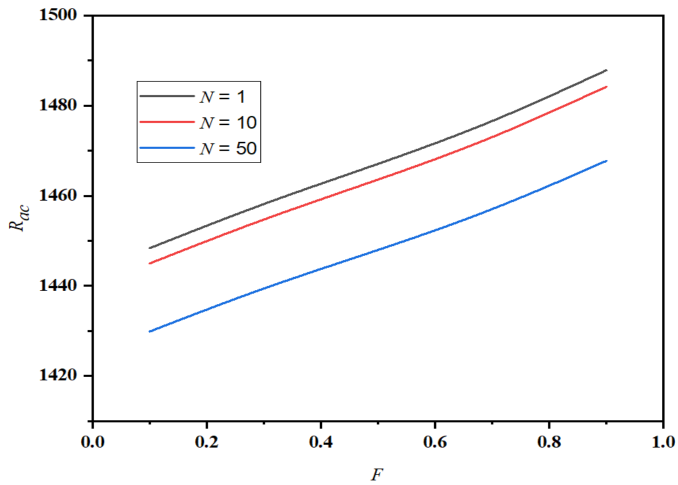

Fig. 7. Graph of R_{ac} versus *F* with different values in *N*

The dependency of R_{dc} with the Cattaneo Number(G) across various values of *F* is shown in Fig. 8. The value of the CMRN (R_{dc}) drops as the Cattaneo Number(G) rises, leading to a destabilising influence on the system.

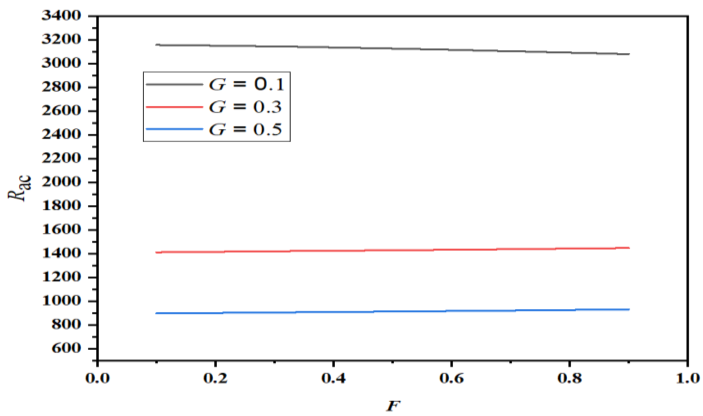

Fig. 8. Graph of R_{ac} versus *F* with different values in *G*

Conclusions

In a horizontal porous medium, the thermal stability of a chemically reactive Maxwell-Cattaneo CSMF is investigated. The thermo-mechanical interaction for a ferrofluid in Brinkman model with chemical reaction and couplestress was examined in the current work. The primary findings of the current investigation are

- Nonlinearity and asymmetries in the fundamental temperature profile are caused by chemical reaction. This asymmetry causes chemical reactions to become unstable.
- The oscillatory methods are ignored and the PES are well-founded.
- The system's stability is disputed by chemical reactions and magnetism, which compete with one another to open the door to instability.
- The system has a destabilizing effect as Cattaneo effect increases.
- The stability of the system is enhanced by the interaction of stress and porous characteristics.
- The setup is made more unstable by the non-buoyancy magnetization setting.

The outcomes from this study are consistent with those from Nisha Mary Thomas and S. Maruthamanikandan [13; 14], Soya Mathew and S. Maruthumanikandan [17] and M.S. Malashetty [19] as well as other studies.

Acknowledgements

The authors express their gratitude to the Department of Mathematics at CHRIST University, Bangalore, for their unwavering support in accomplishing this goal. The writers are grateful for the most insightful feedback provided by the referees.

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