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Linear stability analysis of electroconvection in a polarized dielectric porous layer with couple stresses under a sinusoidally time-varying electric potential

C. Rudresha [1] ✉, C. Balaji [2], V. Vidya Shree [3], S. Maruthamanikandan [4]

[1] Sir M Visvesvaraya Institute of Technology, Bangalore, Karnataka, India

[2] CMR Institute of Technology, Bangalore, Karnataka, India

[3] SJB Institute of Technology, Bangalore, Karnataka, India

[4] Sreenidhi University, Hyderabad, Telangana, India

✉ rudresha_maths@sirmvit.edu

ABSTRACT

The linear stability of electroconvection in a horizontally oriented, thermally unstable dielectric fluid layer saturated with a Darcy porous medium and influenced by couple-stress effects are investigated. The system is subjected to a sinusoidally time-varying electric potential applied at the boundaries. The novelty of this work lies in the combined effects of couple stresses, electric field modulation, and Darcy-porous medium, an area not extensively explored in the existing literature. Using the Boussinesq approximation and a regular perturbation technique, we deal with the governing eigenvalue problem and analyze the critical conditions for the onset of convection. The analysis reveals that electric field modulation can exert either a stabilizing or destabilizing influence depending on the modulation frequency and material parameters. At low frequencies, the destabilizing role of the electric Rayleigh number becomes more pronounced, while couple stress effects contribute to system's stabilization. Additionally, the Vadasz number significantly modifies the stability behavior, enhancing the effects of modulation at high frequencies. Our findings highlight the potential of electric field modulation as a viable mechanism for controlling therma l instability in particle-laden dielectric fluids confined within porous structures. The results provide new insights into electrohydrodynamic flow control in engineering systems involving smart fluids and porous media.

KEYWORDS

couple stresses • dielectric fluid • electric field modulation • porous media • linear stability • electroconvection

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Introduction

The theory of couple-stress fluids was first introduced by Stokes [1], who generalized Newtonian fluid mechanics to account for microstructural effects such as body couples and particle rotations. These formulations are particularly useful for describing the behavior of complex fluids such as polymers, colloids, and biological suspensions. The study of convection in porous media has received sustained attention due to its broad engineering and geophysical applications, including geothermal energy, filtration, insulation, and chemical processes. Foundational contributions by Ingham and Pop [2], Vafai [3,4], and Nield and Bejan [5] established the theoretical framework for convection in porous layers mainly focusing on Newtonian fluids.

Extensions to non-Newtonian and microstructured fluids have been widely explored. Sharma and collaborators studied couple-stress fluids under magnetic fields and rotation highlighting his stabilizing tendencies in porous layers [6–15]. Maruthamanikandan [16] analyzed instabilities in dielectric and ferrofluids, while Rudraiah et al. [17] investigated electrohydrodynamic (EHD) stability in couple-stress fluid flow through porous channels. These studies demonstrated how porous resistance and microstructural effects alter the onset of convection compared to classical Rayleigh–Bénard systems. Further contributions considered hyperbolic heat transfer [18] and radiative effects in dielectric convection [19] showing how non-Fourier and radiative mechanisms can delay or promote instabilities.

Parametric forcing has also been a subject of interest. Semenov [20] examined instability in liquid dielectrics under variable electric fields, while Smorodin, Velarde, and others [21,22] demonstrated the role of alternating and modulated electric fields in exciting or suppressing instabilities in conducting and dielectric layers. More recent work by Rudresha and his collaborators have systematically studied electroconvection in porous media under electric field modulation considering compact packing and couple-stress effects [23–26]. These studies revealed that porous permeability, modulation frequency, and fluid microstructure strongly affect critical Rayleigh number thresholds.

In parallel, significant progress has been made in porous media convection. Liu et al. [27] and Zhong et al. [28] examined the role of porosity in Rayleigh–Bénard convection demonstrating its influence on flow structure and heat transfer. Other studies focused on instability mechanisms in thermomechanical systems, including thermoacoustic engines [29], swirling vapor flows [30], and nonlinear averaging methods for dynamical systems [31–36]. At the same time, Rudresha et al. [37,38] investigated convection in viscoelastic dielectric fluids under sinusoidal electric fields, while Balaji et al. [39] considered Darcy–Brinkman models under time-dependent magnetic fields, further enriching the theory of EHD and magnetoconvection.

The role of material properties has also been emphasized. Ivukin et al. [40] explored heat transfer optimization in LED (light emitting diode) lamp heat sinks, while Pozdnyakov and Sedakova [41] analyzed wear mechanisms in polymer friction pairs under vacuum and atmospheric conditions. Gupta et al. [42] studied hydromagnetic stability in nanofluid layers with Hall currents showing that nanoscale physics introduces new stabilization pathways.

Although these studies have significantly advanced the understanding of convection in porous and dielectric systems, several limitations still remain. Most analyses focus either on Newtonian fluids or steady external forcing, with limited attention given to couple-stress fluids in porous layers under sinusoidally varying electric fields. In particular, the combined influence of porous resistance, microstructural stresses, and temperature-dependent dielectric permittivity has not been analytically addressed. The present work fills this gap by performing a stability analysis of a dielectric couple-stress fluid in a Darcy porous medium subject to sinusoidal electric field modulation. By employing a regular perturbation approach, corrections to the critical Rayleigh number are obtained, and the influence of parameters such as the electric number, Vadasz number, modulation frequency, porosity, and viscosity ratio are systematically studied. The results provide new insights into electroconvection control and have implications for applications in geothermal systems, MEMS (microelectromechanical systems), electrothermal cooling, and advanced porous heat exchangers.

Mathematical formulation

To investigate the onset of electroconvection under realistic and technologically relevant conditions, we consider a horizontal porous fluid layer of finite thickness d filled with an incompressible, thermally expanding couple-stress fluid. This layer, influenced by gravity, is heated from below and subjected to a time-periodic electric potential across its boundaries. The combined impact of porous resistance, couple-stress viscosity, and sinusoidal electric modulation on the stability of the base state is systematically studied. Unlike classical Rayleigh-Bénard problems, this formulation accounts for a time-dependent electric field, where the modulation acts as a control parameter. It also incorporates non-Newtonian couple-stress effects, which are essential in fluids with microstructure (e.g., suspensions, polymeric fluids), and porous media through a Darcy model. These additions provide a significant departure from the standard formulations.

We establish a Cartesian coordinate system (x, y, z), with the z-axis directed vertically upwards and the origin located at the lower boundary of the porous layer. A temperature difference ΔT is applied across the layer to introduce thermal stratification. The electric potential on the boundaries is sinusoidally modulated in time: $\phi = \pm U(\eta_1 + \eta_2 cos\omega t)$, where U is the potential amplitude, ω is the modulation frequency, and η_1 and η_2 characterize the steady and oscillating components of the imposed electric field. The porous matrix is assumed homogeneous with constant permeability K and porosity δ. The present analysis is based on the following assumptions:

1. Darcy porous medium: the fluid motion obeys Darcy's law with permeability K and porosity δ.
2. Boussinesq approximation: density variations are considered only in the buoyancy term.
3. Incompressible couple-stress fluid: microstructural stresses are included through couple-stress viscosity.
4. Small modulation amplitude: the electric potential modulation parameters η_1 and η_2 satisfy $| \eta_i | \ll 1$.
5. Temperature-dependent permittivity: the dielectric permittivity varies linearly with temperature.
6. Electrostatic approximation: magnetic effects and displacement currents are neglected.
7. Mechanically free and electrically conducting boundaries: stress-free mechanical conditions with prescribed electric potential.
8. Neglect of porous-matrix deformation: the porous skeleton is rigid and stationary.
9. Neglect of Brinkman term: flow resistance follows the Darcy model without viscous shear corrections.

Under these assumptions, the governing equations include:

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

$$\rho = \rho_0[1 - \alpha(T - T_0)], \tag{2}$$

where $\vec{q} = (u, v, w)$ is the Darcy-Brinkman velocity, T is the temperature, α is the thermal expansion coefficient, and ρ_0 is the density at reference temperature T_0.

Accounting for fluid microstructure and electric field influence, the linearized momentum equation (couple-stress fluid in porous medium) becomes:

$$\frac{1}{\delta}\frac{\partial \vec{q}}{\partial t} = -\frac{1}{\rho_0}\nabla p + \frac{\rho}{\rho_0}\vec{g} - \frac{1}{\rho_0 K}[\mu - \mu_c \nabla^2]\vec{q} - \frac{1}{2\rho_0}(\vec{E}\cdot\vec{E})\nabla\varepsilon, \tag{3}$$

where μ is the dynamic viscosity, $\mu_c$is the couple-stress viscosity, $\vec{E} = -\nabla\phi$ is the electric field, $\varepsilon$is the temperature-dependent dielectric permittivity, ω denotes the modulation frequency of the applied electric field, and K is the intrinsic permeability of the porous medium. This formulation extends classical Darcy flow by incorporating micro-rotational effects and dielectrophoretic forces, critical for systems with non-uniform electric properties.

Heat transport equation is:

$$A\frac{\partial T}{\partial t} + (\vec{q}\cdot\nabla)T = \kappa\nabla^2 T, \tag{4}$$

where: A is the effective heat capacity ratio of the porous medium and κ is the thermal diffusivity.

Maxwell's electrostatic equations are:

$$\nabla \times \vec{E} = 0 \text{ or } \vec{E} = -\nabla\phi, \tag{5}$$

$$\nabla\cdot[\varepsilon\vec{E}] = 0. \tag{6}$$

The permittivity ε is assumed to vary linearly with temperature:

$$\varepsilon = \varepsilon_0[1 - e(T - T_0)], \tag{7}$$

with e (> 0)representing the thermal sensitivity of permittivity, a key source of electric buoyancy.

Basic state

In the basic quiescent state, we have $\vec{q}_b = 0$, $T_b = T_0 - \beta z$, $\vec{E}_b = -\nabla\phi_b$ and the background electric potential is:

$$\phi_b = \frac{-2U(\eta_1 + \eta_2 \cos\omega t)}{\log(1 + e\beta d)}\log(1 + e\beta z) + U(\eta_1 + \eta_2\cos\omega t). \tag{8}$$

With the expression for the electric field:

$$E_b = \frac{2U(\eta_1 + \eta_2\cos\omega t)}{d}(1 - e\beta z). \tag{9}$$

Perturbation and linearization

We introduce small perturbations: $\vec{q} = \vec{q}'$, $p = p_b + p'$, $T = T_b + T'$, $\varepsilon = \varepsilon_b + \varepsilon'$, $\phi = \phi_b + \phi'$, $\rho = \rho_b + \rho'$, $\vec{E} = \vec{E}_b + \vec{E}'$.

Non-dimensionalization (dropping *) is carried out using: $(x, y, z) = (dx^*, dy^*, dz^*)$, $T' = \Delta T T^*$, $t = \frac{Ad^2}{\kappa}t^*$, $\vec{q}' = \frac{\kappa}{d}\vec{q}^*\phi = 2U(\eta_1 + \eta_2\cos\omega t)e\Delta T\phi^*$.

The resulting dimensionless linearized equations are:

1. Vertical momentum equation is:

$$\frac{1}{Va}\frac{\partial}{\partial t}(\nabla^2 w) = R\nabla_1^2 T - \nabla^2 w + C\nabla^4 w + R_e(1 + \eta_3\cos\omega t)^2\frac{\partial}{\partial z}(\nabla_1^2\phi) + {} + R_e(1 + \eta_3\cos\omega t)^2\nabla_1^2 T. \tag{10}$$

2. Poisson equation for potential is:

$$\nabla^2\phi = -\frac{\partial T}{\partial z}. \tag{11}$$

3. Heat equation is:

$$\frac{\partial T}{\partial t} - w = \nabla^2 T, \tag{12}$$

where $R = \frac{\alpha \rho_0 g \Delta T K d}{\mu \kappa}$ is the Darcy Rayleigh number, $R_e = \frac{4U^2 e^2 \varepsilon_0 \beta^2 \Delta T K \eta_1^2}{\mu \kappa}$ is the electric Darcy Rayleigh number, $Va = \frac{\delta \nu d^2}{K \kappa}$ is the Vadasz number, $C = \frac{\mu_c}{\mu d^2}$ is the couple stress parameter and $\eta_3 = \frac{\eta_2}{\eta_1}$ is modulation amplitude ratio.

4. Boundary conditions are:

$$w = D^2 w = T = \phi = 0 \text{ at } z = 0,1. \tag{13}$$

Eliminating T and ϕ from Eqs. (10)–(12), we obtain the governing equation for w:

$$\left(\frac{1}{Va}\frac{\partial}{\partial t} + 1 - C\nabla^2\right)\left(\frac{\partial}{\partial t} - \nabla^2\right)\nabla^4 w = R\nabla^2\nabla_1^2 w + R_e(1 + \eta_3 \cos \omega t)^2 \nabla_1^2 w. \tag{14}$$

Along with the boundary conditions:

$$w = \frac{\partial^2 w}{\partial z^2} = \frac{\partial^4 w}{\partial z^4} = 0 \text{ at } z = 0,1. \tag{15}$$

Method of solution

To investigate the linear stability of the basic state under the influence of a time-dependent sinusoidal electric field, we seek solutions to the governing Eq. (14) using a regular perturbation technique. Our objective is to determine the eigenfunction w and corresponding critical Rayleigh number R that characterize the onset of convection.

We expand the dependent variables in powers of a small perturbation parameter ε, assuming the solution is close to the threshold of instability:

$$\left.\begin{array}{l} w = w_0 + \varepsilon w_1 + \varepsilon^2 w_2 + \ldots\ldots \\ R = R_0 + \varepsilon R_1 + \varepsilon^2 R_2 + \ldots\ldots \end{array}\right\}. \tag{16}$$

Substituting Eq. (16) into the governing Eq. (14) and collecting terms of like powers of ε, we obtain the following hierarchy of linear equations:

Zeroth-order equation: $Lw_0 = 0.$ (17)

First-order equation: $Lw_1 = R_1 \nabla_1^2 \nabla^2 w_0 + 2R_e f \nabla_1^4 w_0.$ (18)

Second-order equation: $Lw_2 = R_1 \nabla_1^2 \nabla^2 w_1 + 2R_e f \nabla_1^4 w_1 + R_2 \nabla^2 \nabla_1^2 w_0.$ (19)

The linear operator L is defined as:

$$L = \left(\frac{1}{Va}\frac{\partial}{\partial t} + 1 - C\nabla^2\right)\left(\frac{\partial}{\partial t} - \nabla^2\right)\nabla^4 - R_0 \nabla_1^2 \nabla^2 - R_e \nabla_1^4. \tag{20}$$

The function $f = \cos \omega t = R_{eal}\{e^{-i\omega t}\}$ arises from the sinusoidal modulation of the electric field, and all perturbation functions w_n are subject to the homogeneous boundary conditions (15). This formulation retains the time-dependent nature of the forcing, which introduces parametric resonance effects into the eigenvalue structure, a key feature of the present analysis.

Solution of the zeroth-order system

The marginally stable mode, corresponding to the onset of convection, is obtained from the general solution of Eq. (17). Considering the most unstable mode (lowest harmonic), we choose the trial solution as:

$$w_0 = \sin \pi z e^{i(lx+my)}, \tag{21}$$

which satisfies the boundary conditions exactly. Here, $a^2 = l^2 + m^2$denotes the square of the horizontal wave number. Substituting Eq. (21) into Eq. (17), the corresponding critical Rayleigh number at zeroth order is obtained as:

$$R_0 = \frac{\left(\pi^2+a^2\right)^2+C\left(\pi^2+a^2\right)^3}{a^2} - \frac{R_e a^2}{\pi^2+a^2}. \tag{22}$$

The first term represents the classical contribution from buoyancy and couple stress, while the second term arises due to the electric field-induced dielectrophoretic destabilization.

In Fig. 1, the thermal Rayleigh number R_0 is plotted against the wave number α for different values of the electric Rayleigh number R_e. Figure 1 clearly shows the destabilizing influence of the dielectrophoretic force, as increasing R_e shifts the marginal stability curve downward, thereby reducing the critical Rayleigh number.

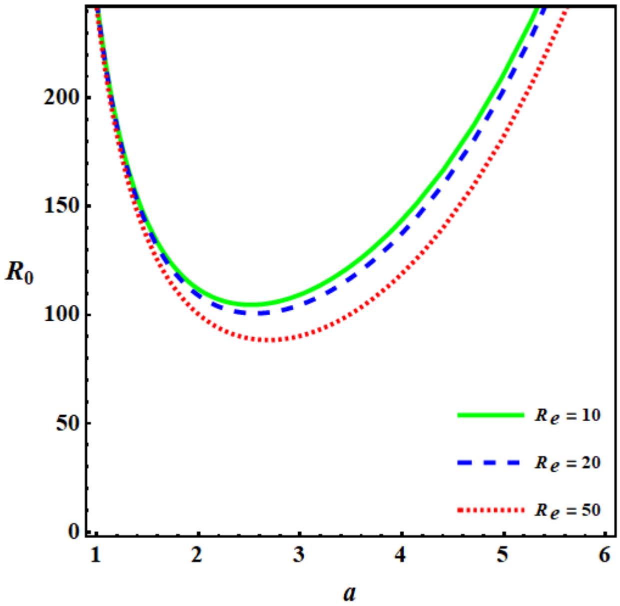

Fig. 1. Darcy Rayleigh number R_0 plotted against the wavenumber a for various electric Darcy Rayleigh numbers number R_e at $C = 0.1$

Solvability condition for second-order correction

To extract R_{2c}, we apply a Fredholm-type solvability condition to Eq. (19), requiring the orthogonality of its right-hand side to the null space of the adjoint operator (i.e., the base mode$\sin \pi z$). After taking a time average over one oscillation period of the imposed electric field, we obtain:

$$R_{2c} = \frac{R_e^2 a^6}{\pi^2+a^2}\left[\sum_{n=1}^{\infty} \frac{A_n}{A_n^2+B_n^2}\right] - \frac{R_e a^2}{\pi^2+a^2}, \tag{23}$$

where the time-periodic modulation introduces a frequency-dependent stabilizing or destabilizing correction to the Rayleigh number. The quantities A_n and B_n encode the temporal interaction between the electric field and fluid inertia and are given by:

$$A_n = -2\left[\frac{\omega^2}{Va}(n^2\pi^2 + a^2)^2 - (n^2\pi^2 + a^2)^3 - C(n^2\pi^2 + a^2)^4 + R_0 a^2(n^2\pi^2 + a^2) + R_e a^4\right],$$

$$B_n = \omega\left\{(n^2\pi^2 + a^2)^3\left[C + \frac{1}{Va}\right] + (n^2\pi^2 + a^2)^2\right\}.$$

This analytical structure demonstrates the nonlinear coupling between modulation frequency ω , couple stress effects, and electrical Darcy Rayleigh forcing, which is central to the novelty of this work.

Results and Discussion

This work presents an analytical investigation into the influence of a sinusoidally time-varying electric field on the onset of thermal convection in a couple-stress fluid contained within a thermally unstable Darcy porous layer. The primary focus is to understand and control the onset of convection by incorporating two key physical mechanisms absent in the classical Rayleigh-Bénard configuration:

1. Suppression of convection due to suspended microstructure, captured by the couple stress parameter C.
2. Time-periodic modulation of the electric field, acting at the boundaries, described by the electric field $\vec{E}(t)$.

A critical observation is that oscillatory convection does not arise in couple-stress fluids under the present configuration, and the electric field modulation is limited to the horizontal boundaries. The analysis assumes a small amplitude of electric field modulation. The results depend sensitively on the modulation frequency ω. At low frequencies ($\omega < 1$), the slow modulation significantly perturbs the system, amplifying disturbances and promoting instability. At high frequencies, the electric forcing tends to average out over time, and the system mimics the unmodulated configuration, thereby restoring stability. Hence, a moderate value of ω is chosen to reveal the competing effects of destabilization and stabilization. Moreover, due to the presence of suspended particles and the consequent enhancement in viscosity (as per Einstein's relation), a higher Vadasz number Va is considered relative to a clean fluid.

To assess the physical relevance of the results, dimensional estimates were obtained using typical dielectric fluid properties. The modulation frequencies required for instability are in the range of 10–100 rad/s. The corresponding temperature differences for onset are approximately 8–20 °C. The electric potential differences required lie in the range of 200–600 V. Representative fluid properties used in the estimates include density ρ = 950 kg m^{-3}, kinematic viscosity ν = 10^{-5}–10^{-4} m^2 s^{-1}, and dielectric permittivity ε = (2–5)·10^{-11} F m^{-1}. These values are consistent with common dielectric liquids and validate the physical feasibility of the predicted instability thresholds.

Influence of the electric Rayleigh number R_e

Figure 2 shows the variation of the second-order correction to the Rayleigh number, R_{2c}, with modulation frequency ω, for different values of the electric Darcy Rayleigh number R_e, while keeping the couple stress parameter C and Vadasz number Va fixed. At low frequencies, increasing R_e leads to more negative values of R_{2c}, indicating destabilization due to enhanced electric forcing at the boundaries. As the modulation frequency increases, R_{2c} approaches zero, reflecting reduced influence of the time-varying field. Thus, at lower ω, electric field modulation can effectively trigger instability, whereas at higher ω, it fails to disturb the system significantly, yielding a quasi-steady regime.

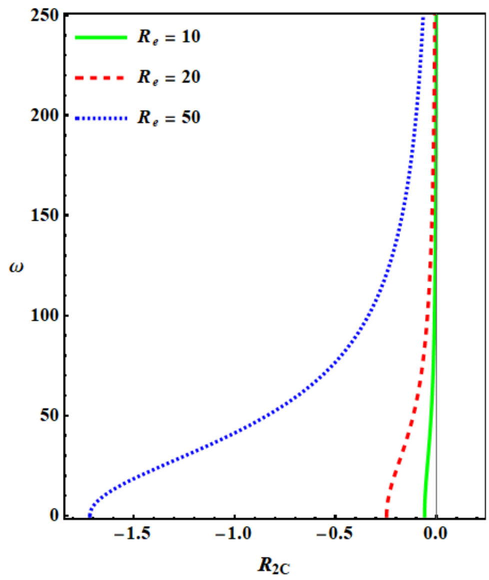

Fig. 2. Variation of correction Rayleigh number R_{2c} with modulation frequency ω for different values of electric Darcy Rayleigh number R_e at $C = 0.1$ and $Va = 10$

Role of couple stress parameter C

Figure 3 displays how R_{2c} varies with ω for different values of the couple stress parameter C. As C increases, R_{2c} increases for all frequencies, implying a stabilizing effect due to the microstructural resistance offered by suspended particles. This behavior is supported by Einstein's viscosity law $\mu_e = \mu_0(1 + 2.5\lambda\varphi)$, where μ_e and μ_0 are the effective and clean fluid viscosities, λ is the shape factor (≥ 1), and φ is the volume fraction of particles. Increased viscosity leads to higher energy dissipation, thereby impeding convective motion. While the Einstein relation is linear and valid for dilute suspensions, for higher concentrations a nonlinear correction is required, which may further enhance this stabilization.

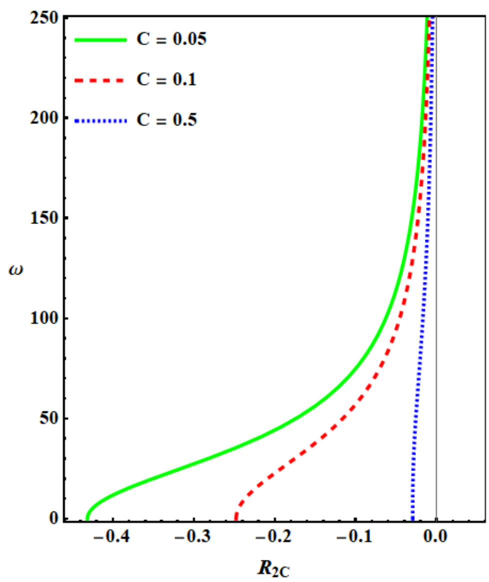

Fig. 3. Variation of R_{2c} with ω for different values of couple stress parameter C at $Va = 10$ and $R_e = 20$

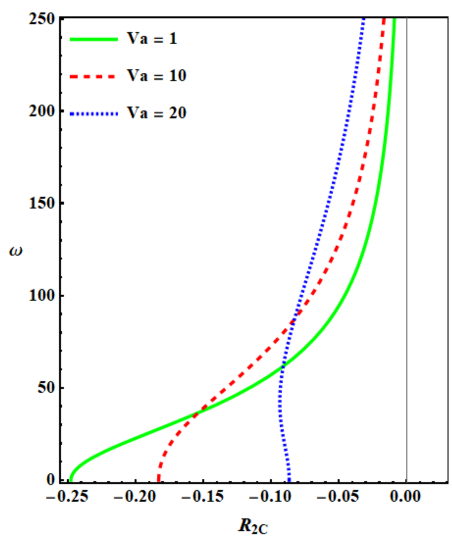

Fig. 4. Variation of R_{2c} with ω for different Vadasz numbers Va at $C = 0.1$ and $R_e = 20$

Impact of the Vadasz number Va

Figure 4 illustrates the impact of the Vadasz number Va on R_{2c} for various modulation frequencies. A larger Va corresponds to an increase in R_{2c}, suggesting delayed convection onset due to stronger momentum diffusion relative to thermal diffusion. This result is particularly important in couple-stress fluids where the microstructure significantly influences viscosity. The combined effect of high C and Va creates a dissipative environment that resists perturbations. Additionally, strong electric fields distort field lines, and such distortions interact with the fluid's microstructure to suppress convective growth.

Electric modulation destabilizes the system at low frequencies but becomes ineffective at high frequencies. Couple stress effects increase the critical threshold, reinforcing system stability. Thermal diffusion (high Va) complements the couple stress damping, especially in particle-laden fluids. These findings highlight that the interplay between electric field forcing, microstructural effects, and porous media transport mechanisms enables fine-tuned control of convective instability. This study therefore offers a framework for designing electrically controlled thermal systems in porous or micro-structured environments, with potential applications in filtration, microfluidics, and enhanced heat transfer technologies.

To validate the present analytical formulation, we compare the results obtained from the model with several known limiting cases that correspond to existing studies:

1. Unmodulated electric field ($\eta_3 = 0$): In this limit, the modulation term disappears and the critical Darcy–Rayleigh number reduces to the steady electric field case. The resulting trend agrees with the unmodulated electroconvection analyses of Smorodin et al. [21] and Rudresha et al. [23–25].
2. Absence of couple-stress effects ($C = 0$): Eliminating microstructural stresses reduces the model to Newtonian dielectric convection in a Darcy porous medium. The behaviour of the critical threshold matches the results reported by Velarde and Smorodin [22] and Rudraiah et al. [17].
3. Large permeability (high Darcy number): when the porous resistance becomes negligible, the system smoothly approaches the classical Rayleigh-Bénard convection limit for dielectric fluids. This limiting behaviour is consistent with standard results in literature. These comparisons confirm that the present model correctly recovers earlier established results in the absence of electric modulation, couple stresses, or porous resistance, thereby validating the analytical solution method used in this work.

Conclusion

This study investigates the onset of electroconvection in a horizontal dielectric fluid layer embedded in a Darcy porous medium, incorporating couple-stress effects under the influence of a time-periodic electric field. A linear stability analysis was employed to explore how electric field modulation, couple stresses, and porous media parameters interact to affect convective behavior. The key conclusions are summarized below:

1. Low-frequency electric field modulation exhibits minimal influence on system stability. However, at moderate and high frequencies, the modulation can significantly alter the stability threshold.

2. Increasing the couple stress parameter enhances system stability. For fluids with suspended particles, this parameter plays a dominant role in suppressing the onset of convection, especially at lower modulation frequencies.
3. While electric field modulation can stabilize the flow, a high electric Rayleigh number counteracts this effect by promoting convection, particularly at intermediate modulation frequencies.
4. The Vadasz number modulates the thermal response due to fluid inertia in porous media. It amplifies the destabilizing effect of modulation at higher frequencies but contributes to stabilization at lower frequencies.

In summary, the results demonstrate that electric field modulation, when combined with Darcy resistance and couple-stress effects, provides a tunable mechanism to delay or promote the onset of electroconvection. These findings have potential applications in engineering systems where convective control in porous or particle-laden fluids is critical, such as electrohydrodynamic cooling, geophysical flows, and materials processing.

CRediT authorship contribution statement

Rudresha Chandrappa conceptualized the problem and supervised the study. **Sokalingam Maruthamanikandan** performed the mathematical analysis and derivations. **Chandrashekar Balaji** and **Venkatesh Vidya Shree** contributed to the interpretation of results and manuscript organization. All authors reviewed and approved the final manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

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