RUDRESHA C
BALAJI C
VIDYA SHREE V
and
S. MARUTHAMANIKANDAN

Effect of electric field modulation on electro-convection in a dielectric fluid-saturated porous medium

The stability of a horizontal sparsely packed porous layer of a dielectric fluid heated from below is examined when the fluid layer is subjected to time-dependent electric field modulation. The dielectric constant is assumed to be a linear function of temperature. The regular perturbation method is used to find the critical Rayleigh number and the corresponding wavenumber for small amplitude electric field modulation. The stability of the system characterized by a correction Rayleigh number is computed as a function of thermal, electric, and porous parameters, and the frequency of electric field modulation. It is found that the onset of electro-convection can be delayed or advanced by the presence of these parameters. The effect of various parameters is found to be significant for moderate values of the frequency of electric field modulation. Some of the known results are recovered as special cases of the present study. The findings of the present study have possible implications in the control of electro-convection with a time-varying electric field.

Keywords: Convection, Darcy-Brinkman model, dielectric fluid, electric field, modulation.

1.0 Introduction

Time-dependent forces acting on a fluid can have a significant impact on instability thresholds and provide an effective method of controlling convection in a wide range of engineering applications. Periodic forcing on liquids can take the form of vibrations, modulations of heat transfer or surface heat flux, or alternating electric field.

Dielectrophoretic forces influence the critical temperature gradient. Dielectrophoretic forces are caused by an electric field and a dielectric constant gradient. For a certain set of boundary conditions explored by Turnbull, (1969), the principle of exchange of stabilities is shown to be valid. M. Takashima, (1976) investigates the effect of rotation on the beginning of convective instability in a dielectric fluid confined between two horizontal planes under the operation of a vertical AC electric field and a vertical temperature gradient. Castellanos et al., (1984) look at how temperature affects the dielectric constant and ionic mobility of a horizontal dielectric liquid layer subjected to an electric field and heating from below. To define regions of steady and oscillatory convective instability, the Galerkin approach is applied. Maekawa et al., (1992) theoretically explored the onset of electric convection and buoyancy convection in AC and DC electric fields, as well as the effect of the electric field on the critical AC and DC electric Rayleigh numbers, the critical Rayleigh number. A DC electric field and uniform internal heat generation were used to explore the impact of a DC electric field and uniform internal heat generation on the onset of convection in a poorly conducting dielectric fluid layer heated from below. As a result, as Shivakumara et al., (2007) has demonstrated, an increase in the value of the electric Rayleigh number can have both destabilising and stabilising effects. Siddheshwar et al., (2019) investigated the impact of changing viscosity and temperature on the start of electro-convection in a Newtonian dielectric liquid, and this study focussed on external control of convection in dielectric liquids. According to Siddheshwar et al., (2020), the chain creation of suspended particles generated by polarisation in an electric field contributes to the electric field dependency of viscosity. They argue that viscosity's field dependencies indicate that the property must drop in value as temperature rises and increase as electric field strength rises.

Lapwood, (1948) addressed the instability of a fluid layer in a porous medium subjected to a vertical temperature gradient, as well as the possibility of convective flow. Wooding, (1960) investigated the thermal boundary layer of the exponential form that exists in a porous material. If the system's Rayleigh number does not exceed a critical positive value and the wave-number of the critical neutral disturbance is finite, the layer is stable. Malashetty et al., (2010) researched convection in a sparsely packed porous material with a nonuniform temperature gradient that is a function of both position and time. They noticed a mismatch between the

Messrs. Rudresha C, Balaji C, Vidya Shree V and S. Maruthamanikandan, Department of Mathematics, School of Engineering, Presidency University, Bengaluru 560064, India. E-mail: rudresha.c@presidencyuniversity.in

results for a Darcy porous medium (low permeability) and conventional viscous fluid. Jianlin Guo and P. N. Kaloni, (1995) examined into the nonlinear stability of a double diffusive porous layer and discovered that the Rayleigh number's critical value is highly influenced by the other nondimensional numbers. Shivakumara et al., (2011) addressed the theoretical linear stability of a viscoelastic fluid saturated horizontal porous layer whose walls are subjected to time-periodic temperature modulation. They looked at three different forms of temperature modulations near the boundary. The lower wall temperature is modulated while the upper wall temperature remains constant in symmetric, asymmetric, and only the lower wall temperature is modulated. The effect of all three types of modulations is found to be destabilising when compared to the unmodulated system. Shivakumara et al., (2011) analysed electrothermo-convection in a rotating horizontal layer of Brinkman porous material for various types of velocity boundary conditions. Gaikwad and Begum, (2012) studied the combined effect of small amplitude gravity modulation and rotation on the onset of convection in a viscoelastic horizontal fluid layer and in a fluid saturated porous layer for a wide range of modulation, Deborah number, Prandtl number, Taylor number, Darcy number, and normalised porosity values.

Gravity modulation generates ferroconvective instability in the Darcy-Brinkman model ferrofluid-filled porous layer, and the effects of magnetic force, porous medium, and gravity modulation diminish when the frequency of the time periodic body force is significantly large, as Thomas and Maruthamanikandan, (2018) investigated. Semenov, (1994) investigated the parametric instability of a nonuniformly heated horizontal surface of liquid dielectric with free isothermal boundaries in a transverse electric field, finding instability at some points. The critical electric field strength changes with frequency and is several times bigger than the critical strength of a continuous electric field. Smorodin et al., (1999) investigated the influence of a varied periodic heat flow on the top open unreformable surface of a layer of liquid semiconductor or ionic melt on the instability of the initial liquid quasiequilibrium. The resonance between the applied heat wave and spontaneous disturbances inside the liquid defined parametric excitation domains. Velarde and Smorodin, (2000) investigated the initiation of motion in a horizontal layer of weakly conducting fluid in the presence of a transverse temperature differential and a vertically changing electric field. When a liquid dielectric layer with rigid, high electroconductive borders is subjected to a transverse temperature gradient and an alternating electric field with harmonic modulation, the convective instability of the layer is explored L. Smorodin and G. Velarde, (2001). The onset of flow motion of an initially motionless dielectric liquid horizontal layer subjected to a transverse temperature gradient and a time varying electric field is investigated in two cases: (i) the onset of flow motion of an initially motionless dielectric liquid horizontal layer subjected to a transverse temperature gradient and a time varying electric field, and (ii) the onset of flow motion of an initially motionless dielectric liquid horizontal layer subjected to a transverse temperature gradient and a time.

The electro-hydrodynamic of a saturated porous material were investigated by Del Río and Whitaker, (2001). They proved that the concept of local electrical equilibrium is specified, and that if this condition is met, a one equation model for linked momentum and electric charge transfer is also valid. Different formulations of Maxwell's equations for the fluid and solid phases must be employed when local electrical equilibrium is not valid. Rudraiah and Gayathri, (2009) investigated electro-convection in a horizontal dielectric fluid saturated with a densely packed porous layer under the simultaneous action of a vertical electric field and a vertical temperature gradient when the walls of the layer are subjected to time periodic temperature modulation. Shivakumara, Rudraiah, et al., (2011) investigated the combined impact of a vertical AC electric field and the boundaries on the formation of Darcy–Brinkman convection in a dielectric fluid saturated porous layer heated from below or above. Gayathri et al., (2015) studied the initiation of electro-convection in a horizontal dielectric fluid saturated with a densely packed porous layer and exposed to a uniform temperature gradient and an alternating electric field. To represent flow in a porous material, they employed a modified Darcy equation, and to solve the related eigenvalue problem, they used a regular perturbation approach with small amplitude approximation.

The present study focusses on the effect of electric modulation in a dielectric fluid saturating porous media using perturbation approach. The stability of the system characterized by a correction Rayleigh number is computed as a function of thermal, electric, and porous parameters, and the frequency of electric field modulation. It is found that the onset of electro-convection can be delayed or advanced by the presence of these parameters. The effect of various parameters is found to be significant for moderate values of the frequency of electric field modulation. Some of the known results are recovered as special cases of the present study.

2.0 Mathematical formulation

The flow pattern considered a dielectric fluid saturated porous layer that maintains the boundary between infinite horizontal surface z = 0 and z = d under the effect of a vertically acting uniform electric field and modulated electric potential varies with time t. Constant different temperature T=T_0 and T=T_1 is maintained on these boundaries (Fig.1). U is the amplitude of the potential difference and ω is the modulation frequency. To keep things simple, we will look at the free-free isothermal boundary conditions at the walls. To put it another way, the fluid is constrained by a stress-free

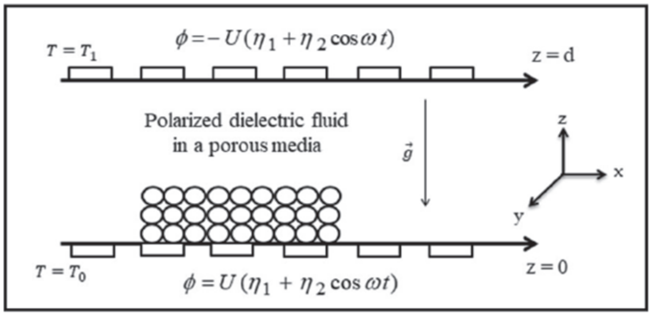

Fig.1: Physical configuration

non-deformable surface with a temperature set at the borders. Brinkman's equation is a popular variant to Darcy's equation. In the absence of inertial terms, this takes the form now there are two viscous terms.

The first is the standard Darcy term, while the second is comparable to the Laplacian component in the Navier-Stokes equation. Also, if the effective Brinkman viscosity is equal to the fluid viscosity, the continuity of normal stress reduces to the continuity of pressure for an incompressible fluid. The fluid is an incompressible and porous medium with a linear temperature function, according to the problem's governing equations Shivakumara, Rudraiah, et al., (2011), Masaki Takashima and Ghosh, (1979) and the Boussinesq approximation.

$$\nabla \cdot \vec{q} = 0 \quad \text{... (1)}$$

$$\rho_0 \frac{1}{\delta}\left[\frac{\partial \vec{q}}{\partial t} + \frac{1}{\delta}(\vec{q}\cdot\nabla)\vec{q}\right] = -\nabla p + \rho\vec{g} - \left(\frac{\mu}{K} - \mu_m \nabla^2\right)\vec{q} - \frac{1}{2}\left(\vec{E}\cdot\vec{E}\right)\nabla\varepsilon \quad \text{... (2)}$$

$$A\frac{\partial T}{\partial t} + (\vec{q}\cdot\nabla)T = \kappa\nabla^2 T \quad \text{... (3)}$$

As a result M. Takashima, (1976), because the fluid is dielectric, we presume there are no free charges. There are also no induced or applied magnetic fields. The applicable Maxwell equations are listed below.

$$\nabla \cdot \left[\varepsilon \vec{E}\right] = 0 \quad \text{... (4)}$$

$$\nabla \times \vec{E} = 0 \Rightarrow \vec{E} = -\nabla\phi \quad \text{... (5)}$$

$$\rho = \rho_0\left[1 - \alpha(T - T_0)\right] \quad \text{... (6)}$$

$$\varepsilon = \varepsilon_0\left[1 - e(T - T_0)\right] \quad \text{... (7)}$$

where, $\vec{E}$ is electric field, ω is density of the fluid, ε is assumed to be dielectric constant, K is the permeability, δ is porosity, μ is the dynamic viscosity, μ_m is the effective viscosity, $\vec{q}$ is the velocity of the fluid. since the fluid is dielectric assume that ρ_e is free charge density assumed to be zero, A is the specific heat ratio. The above equations admit an equilibrium, which is the basic solution in which $\vec{q} = \vec{q}_b(z) = 0$; $\varepsilon = \varepsilon_b(z)$; $\vec{E} = \vec{E}_b = \left[0, 0, E_b(z)\right]$; $T = T_b(z)$; $\phi = \phi_b(z)$; $p = pb(z)$ and $\rho = \rho b(z)$; where the quantities with suffix b represent the basic state and they satisfy the equations

$$\phi_b = \frac{-2UL_1}{\log(1 + e\beta d)}\log(1 + e\beta z) + UL_1 \quad \text{... (8)}$$

and

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

where, $E_0 = \dfrac{2U\left(\eta_1 + \eta_2\cos\omega t\right)e\beta}{\log(1 + e\beta d)}$

3. Linear stability analysis

We now superimpose the infinitesimal perturbations on the basic state of the form $\vec{q} = \vec{q}\,' = (u', v', w')$; $T = T_b + T'$; $\vec{E} = \vec{E}_b + \vec{E}'$; $\varepsilon = \varepsilon_b + \varepsilon'$; $\phi = \phi_b + \phi'$; $p = p_b + p'$; Using these prime quantities into (1) - (7) and eliminate the pressure term to the following partial differential equations using transformation

$$\nabla \cdot \vec{q}\,' = 0 \quad \text{... (10)}$$

$$\vec{E}\,' = -\nabla\phi' \quad \text{... (11)}$$

$$\rho' = -\alpha\rho_0 T' \quad \text{... (12)}$$

$$\varepsilon' = -e\varepsilon_0 T' \quad \text{... (13)}$$

Following Rudraiah and Gayathri, (2009), we assume $e\beta \ll 1$. Accordingly, we discard any term involving $e\beta$ compared to similar terms in the absence of that factor, eqn. (2) and (3) written as

$$\frac{\rho_0}{\delta}\frac{\partial}{\partial t}\left(\nabla^2 w'\right) = \alpha\rho_0 g\nabla_1^2 T' - \frac{\mu}{K}\nabla^2 w' + \mu_m\nabla^4 w' + e^2\beta\varepsilon_0\frac{4L_1U^2}{d^2}\nabla_1^2 T' + \frac{2L_1U}{d}e\beta\varepsilon_0\frac{\partial}{\partial z}\left(\nabla^2\phi'\right) \quad \text{... (14)}$$

$$\left(\nabla_1^2 + \frac{\partial^2}{\partial z^2}\right)\phi' = \frac{-2UL_1 e}{d}\frac{\partial T'}{\partial z} \quad \text{... (15)}$$

$$A\frac{\partial T'}{\partial t} - \beta w' = \kappa\nabla^2 T' \quad \text{... (16)}$$

where, $L_1 = \left(\eta_1 + \eta_2\cos\omega t\right)$, Eqn. (14) to (16) dimensionless through the following transformations $(x, y, z) = \left(dx^*, dy^*, dz^*\right)$; $\phi = 2U\left(\eta_1 + \eta_2\cos\omega t\right)e\Delta T\,\phi^*$; $T = \Delta T\,T^*$; $t = \dfrac{Ad^2}{\kappa t}$; $w = \dfrac{\kappa}{d}w^*$; to obtain after dropping the asterisks for simplify and combining nondimensionalized equation,

$$L_2L_3\nabla^4 w = \left(R\nabla^2 + R_eL_4\nabla_1^2\right)\nabla_1^2 w \quad \text{... (17)}$$

where, $L_2 = \left(\dfrac{1}{P}\dfrac{\partial}{\partial t} + (Da)^2 - \Lambda\nabla^2\right)$, $P = \dfrac{\delta\gamma}{A\kappa}$ is the Prandtl number, $R = \dfrac{\alpha\rho_0 g d^3\Delta T}{\mu\kappa}$ is the Darcy-Rayleigh number,

$D = \frac{d}{\sqrt{k}}$ is the Darcy number, $\eta_3 = \frac{\eta_2}{\eta_1}$ is the ratio of the amplitude, $R_e = \frac{4e^2U^2\beta\varepsilon_0 \Delta T d \eta_1^2}{\mu\kappa}$ is the electrical Rayleigh number, $\Lambda = \frac{\mu_m}{\mu}$ is the Brinkman number, $L_3 = \left(\frac{\partial}{\partial t} - \nabla^2\right)$, $L_4 = (1+\eta_3 f)^2$, Thus equation (17) must be solved subject to the dimensionless homogeneous boundary conditions

$$w = \frac{\partial^2 w}{\partial z^2} = \frac{\partial^4 w}{\partial z^4} = 0 \text{ at } z = 0, 1 \quad \text{... (18)}$$

4.0 Perturbation procedure

$$\left.\begin{aligned} w &= w_0 + \eta_3 w_1 + \eta_3^2 w_2 + ... \\ R &= R_0 + \eta_3 R_1 + \eta_3^2 R_2 + ... \end{aligned}\right\} \quad \text{... (19)}$$

Substituting (19) into (17) and equating the coefficients of like powers of η_3, we obtain the following system of equations up to $O\left(\eta_3^2\right)$

$$L w_0 = 0 \quad \text{... (20)}$$

$$L w_1 = R_1 \nabla^2 \nabla_1^2 w_0 + 2 R_e f \nabla_1^2 w_0 \quad \text{... (21)}$$

$$L w_2 = R_1 \nabla^2 \nabla_1^2 w_1 + R_2 \nabla^2 \nabla_1^2 w_0 + 2 R_e f \nabla_1^4 w_1 \quad \text{... (22)}$$

where,

$$L = L_2 L_3 \nabla^4 - R_0 \nabla_1^2 \nabla^2 - R_e \nabla_1^4 \quad \text{... (23)}$$

Eqn. (19) is the one used in the study of convection in a horizontal dielectric fluid saturated porous layer subjected to a uniform electric field and should be marginally stable.

$$w_0 = \sin \pi z \quad \text{... (24)}$$

The corresponding stationary Rayleigh number,

$$R_0 = \frac{(Da)^2\left(\alpha^2+\pi^2\right)^2}{\alpha^2} + \frac{\Lambda\left(\alpha^2+\pi^2\right)^3}{\alpha^2} - \frac{R_e \alpha^2}{\left(\alpha^2+\pi^2\right)} \quad \text{... (25)}$$

We are looking for the solution of w in the form $w(x, y, z, t) = w(z,t) e^{i(\alpha_x x + \alpha_y y)}$ and hence obtain, $\nabla_1^2 w = -\alpha^2 w$ then equation (23) becomes

$$L e^{-i\omega t} \sin n\pi z = L(\omega, n) e^{-i\omega t} \sin n\pi z \quad \text{... (26)}$$

where,

$$\begin{aligned} L(\omega, n) = &-\omega^2 A_n\left(n^2\pi^2+\alpha^2\right) - R_e \alpha^4 \\ &+ C_n\left(n^2\pi^2+\alpha^2\right) - R_0 \alpha^2\left(n^2\pi^2+\alpha^2\right) \\ &- i\omega\left\{B_n\left(n^2\pi^2+\alpha^2\right)+C_n\right\} \end{aligned} \quad \text{... (27)}$$

Since we are interested in determining the valve of R_{2c}, the non-zero correction to R, there is no need to solve for w_0.

The solubility condition for equation (22) requires that steady of the right-hand side should be orthogonal to sinπ z

$$R_{2c} = \frac{2R_e^2 \alpha^6}{\left(\alpha^2+\pi^2\right)}\left[\sum_{n=1}^{\infty} \frac{X_n}{Y_n}\right] \quad \text{... (28)}$$

where,

$$\begin{aligned} X_n = &-\omega^2 A_n\left(n^2\pi^2+\alpha^2\right) - R_e \alpha^4 \\ &+ C_n\left(n^2\pi^2+\alpha^2\right) - R_0 \alpha^2\left(n^2\pi^2+\alpha^2\right) \end{aligned}$$

$$Y_n = B_n\left(n^2\pi^2+\alpha^2\right) + C_n$$

$$A_n = \frac{1}{P}\left(n^2\pi^2+\alpha^2\right) - (Da)^2\left(n^2\pi^2+\alpha^2\right)^2$$

$$\mathrm{B}_n = \frac{1}{P}\left(n^2\pi^2+\alpha^2\right)^2 + (Da)^2\left(n^2\pi^2+\alpha^2\right)$$

$$C_n = \Lambda\left(n^2\pi^2+\alpha^2\right)^3$$

5.0 Results and discussion

In a saturated porous medium, the influence of modulation on the onset of convection is examined. To find the critical thermal Rayleigh number as a function of modulation frequency, Brinkman number Λ, Darcy parameter Da, electrical Rayleigh number R_e, and Prandtl number P, a perturbation technique with the amplitude of the modulating electric field as a perturbation parameter is used and we consider the following results of Thomas and Maruthamanikandan, (2018). The sign of the correction critical Rayleigh number R_{2c} determines the system's stability. In comparison with an unmodulated system, the positive and negative represent the stabilising and destabilising effects of the electric field modulation on the system.

Figs. 2 to 5 represent the fluctuation with modulation frequency ω. When ω is small enough R_{2c}, becomes negative, meaning that a modulated electric field has a destabilising impact. When ω is modest and large enough, however, the opposite effect occurs, and is positive. As a result, subcritical instability is feasible if ω is small enough, but supercritical instability is present otherwise.

Fig.2 shows the correction Rayleigh number R_{2c} vs ω for various values of the electric Rayleigh number R_e with P=5, Da=20 and Λ=0.5. R_{2c} is negative for a short range of frequencies in this diagram, showing that electric field modulation has a destabilizing effect on the system if ω is small. However, when ω is modest and large, R_{2c} increases, showing that the electric field modulation has a stabilizing impact on the system. Furthermore, the size of the corrective Rayleigh number R_{2c} grows as the electrical Rayleigh number R_e increases, showing that Rayleigh number has the impact of delaying the commencement of convection. Moreover, the curves for various R_e values are all very close to zero. As a result, when ω approaches zero, the modulation has little effect on the stability system.

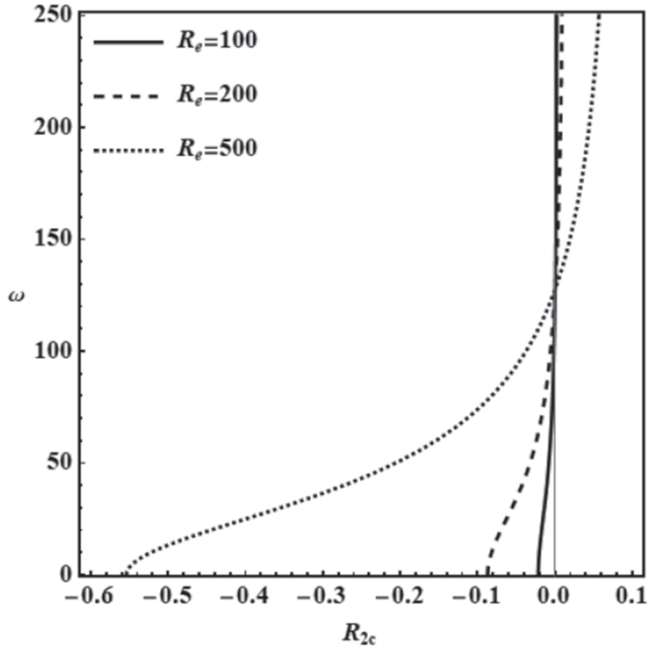

Fig.2: R_{2c} vs ω for different values of R_e when Da=20, Λ=5.0 and P=5

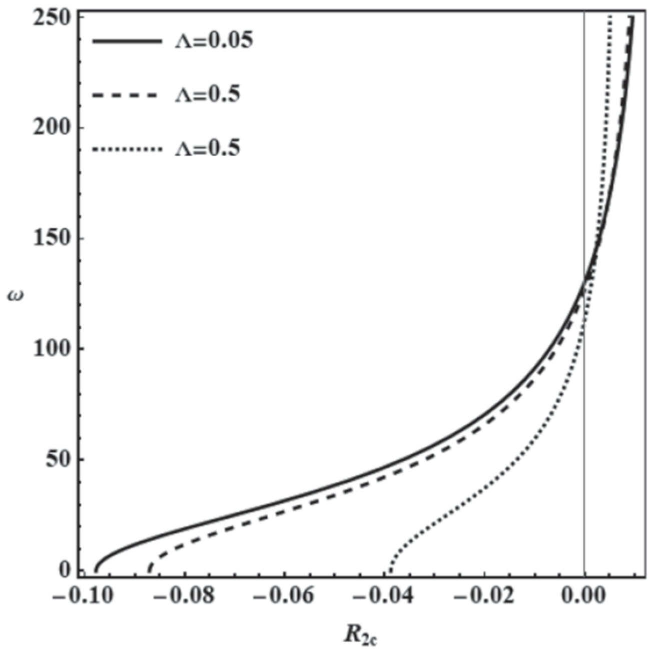

Fig.4: R_{2c} vs ω for different values of Λ when R_e=200, Λ=5.0 and P=5

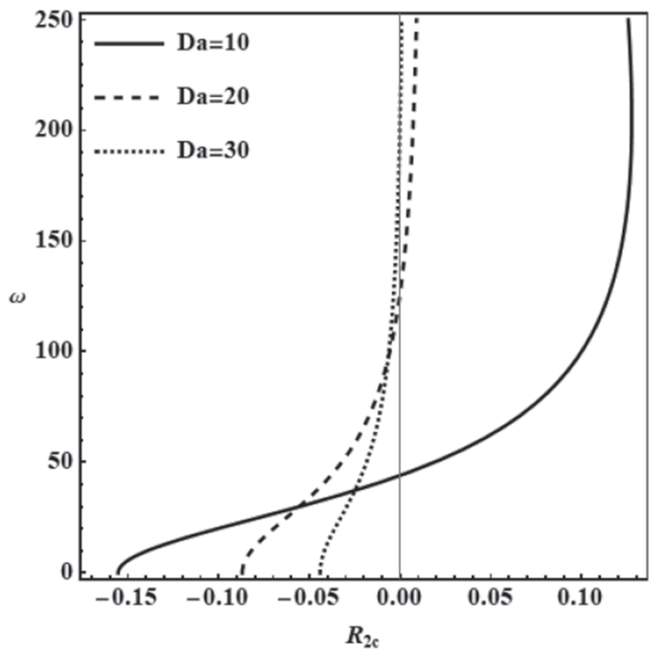

Fig.3: R_{2c} vs ω for different values of Da when R_e=200, Da=5.0 and P=5

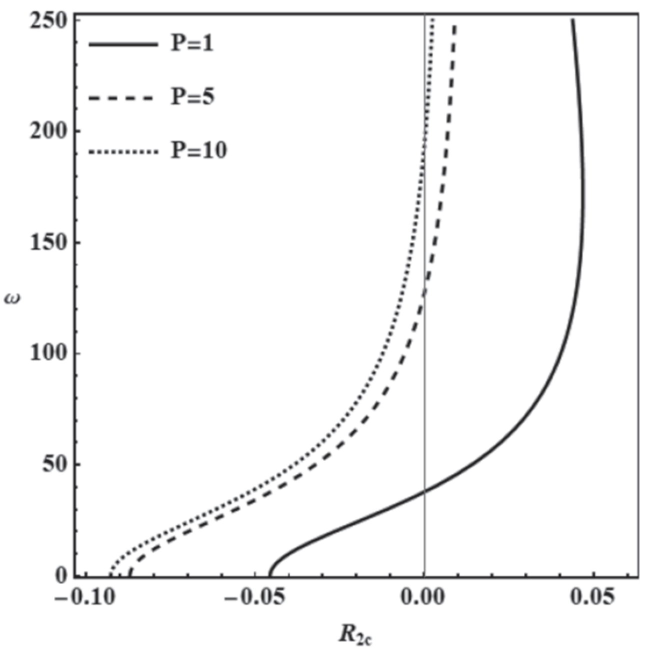

Fig.5: R_{2c} vs ω for different values of P when Λ=5.0, Da=20 and P=5

When R_e=200, Λ=0.5 and P=5, Fig.3 displays the departure of Da from R_{2c}. Correction Rayleigh number R_{2c} clearly grows as Da increases, assuming that ω is modest. If ω is moderate or large, however, the pattern is reversed.

As a result, when R_{2c} is negative for small ω, it indicates that the Darcy parameter has a destabilizing effect on the electric field modulation dielectric fluid layer in a saturated porous medium, whereas when R_{2c} is positive decreasing for moderate and large ω, it indicates that modulation has a destabilizing effect on the stability system.

In the case of electric field modulation in a porous layer, the variation of R_{2c} with frequency for different values of the Brinkman number Λ is illustrated in Fig.4. for small values of the Brinkman number Λ, R_{2c} becomes negative provided that ù is small, showing that the electric field modulation reduces the beginning of convection relative to the unmodulated condition. The modulation has reduced the stabilizing influence on the stability system for moderate and high values of ω. In a saturated porous media with a variable electric field, the effect of the Brinkman number Λ is clearly to advance the onset of convection.

For varying values of the Prandtl number P, Fig.5 shows the R_{2c} versus ω. In this diagram, we can see that R_{2c} lowers as P increases, demonstrating that P has an augmenting convective impact in electro-convection. The effect of large values of ω, on the other hand, indicates that P reduces the stabilising influence on the stability system.

6.0 Conclusions

Using the regular perturbation approach, the effect of electric field modulation on electro-convection in a porous media is investigated. The following conclusions have been reached because of the research.

- At low frequencies, the effect of electric field modulation is found to be destabilising.
- On the system given, electric field modulation has a mutually hostile effect. The frequency of electric field modulation is both low and moderate.
- The Prandtl number enhances the amplifying effect of the electric field modulation frequency, which is both low and moderate.
- When the frequency of the time periodic body force is sufficiently high, the effect of electric force, porous medium, and electric field modulation disappears.

7.0 References

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