Research Article

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Electrohydrodynamic Instability of a Rotating Walters' (model B') Fluid in a Porous Medium: Brinkman model

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Abstract: In this study, the instability of Walters' (model B') viscoelastic fluid in a Darcy-Brinkman-Boussinesq system heated from below saturating a porous medium in electrohydrodynamics is considered. By applying the linear stability analysis and normal modes, the dispersion relation accounting for the effect of Prandtl number, electric Rayleigh number, Darcy number, Brinkman-Darcy number, Taylor number and kinematic viscoelasticity parameter is derived. The effects of electric Rayleigh number, Darcy number, Brinkman-Darcy number and Taylor number on the onset of stationary convection have been investigated both analytically and graphically.

Keywords: Walter' (model B') fluid, rotation, AC electric field, viscosity, viscoelasticity, Brinkman model, porous medium

1 Introduction

In the classical Darcy equation, the Laplacian (viscous) term (Brinkman term) is added in the governing equation for flow through a porous medium, known as Darcy-Brinkman equation. The equation has been widely used to examine the high-porosity porous media. In recent years, the Darcy-Brinkman equation has been employed in biomedical hydrodynamic studies and in the modelling of thin fibrous surface layer coating blood vessels (Khaled and Vafai [1]). Rana and Jamwal[2] studied the effect of rotation on the onset of compressible viscoelastic fluid saturating a Darcy-Brinkman porous medium, while Rana *et al.* [3] studied the effect of rotation on the onset of convection in the Walters' (model B') viscoelastic fluid heated from below in a Brinkman porous medium.

A detailed account of thermal instability of Newtonian fluid under the various assumptions of hydrodynamics, hydromagnetics and electrohydrodynamics has been given by Chandrasekhar [4], Landau [5], Robert [6], Castellanos [7], Melcher *et al.* [8] and Jones [9]. For the last few decades, various researchers studied the electrohydrodynamic instability by taking different types of fluids because it has various applications in EHD enhanced thermal transfer, EHD pumps, EHD in microgravity, micromechanical systems, drug delivery, micro-cooling system, nanotechnology and so on. A great advantage of the EHD pumps is that there is no need for a moving component such as pistons. Also, it is fabricated and assembled. Such type of pumps are widely used in micromechanical systems, drug delivery and micro-cooling system (Gross and Porter [10], Turnbull [11], Maekawa *et al.* [12], Smorodin [13], Galal [14] and Chang *et al.* [15]). The problems of thermal instability in a fluid under the action of AC electric field has been studied by Takashima [16], Takashima and Ghosh [17], Takashima and Hamabata [18], Othman [19], Shivakumara *et al.* [20–22] and Rana *et al.* [23].

Recently, Rana *et al.* [24] studied the electrohydrodynamic instability of an elastico-viscous Walters' (model B') dielectric fluid layer. In the present paper, the study is extended to Brinkman model and the effect of rotation is also investigated. This necessitates two additional parameters, namely Brinkman-Darcy number $\tilde{D}a$, and Taylor number Ta. To the best of my knowledge, this problem has not been studied as yet.

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2 Mathematical model of the problem and governing equations

Here, we consider an infinite horizontal layer of an incompressible Walters' (model B') viscoelastic fluid in a Darcy-Brinkman-Boussinesq system of thickness d, confined by the planes $z = 0$ and $z = d$ as shown in Figure 1. The layer is rotating about the z-axis with constant angular velocity $\Omega = (0, 0, \Omega)$ and uniform vertical AC electric field applied across the layer, which is acted upon by a gravity force g = (0, 0, −g) aligned in the z-direction. The temperatures at the lower and upper boundaries are taken to be T_0 and T_1 ($T_0 > T_1$).

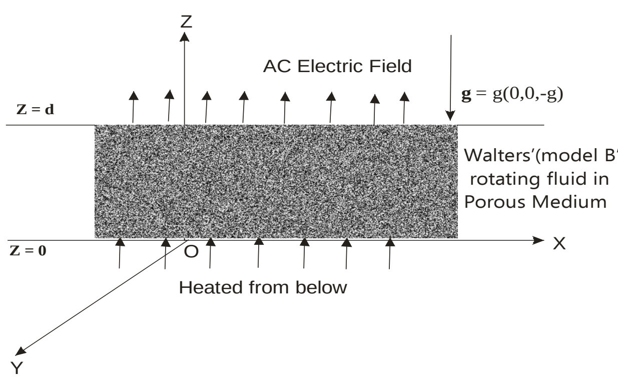

Figure 1: Physical configuration

Let ρ, μ, μ′, K, k_1 $\mathbf{q}$(u, v, w), $\mathbf{g}$, $\mathbf{\Omega}$, T, κ, A and $\boldsymbol{E}$ denote respectively, the density, viscosity, viscoelasticity, dielectric constant, medium permeability, Darcy velocity vector, acceleration due to gravity, angular velocity, temperature, thermal diffusivity, ratio of heat capacity and the root-mean-square value of electric field. Then, the equations of conservation of mass, momentum and thermal energy for Walters' (model B') viscoelastic fluid in a Darcy-Brinkman-Boussinesq (Chandrasekhar [4], Takashima [16], Shivakumara [22], and Rana *et al.* [23, 24]) system are:

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

$$\frac{\rho}{\varphi}\left[\frac{\partial \mathbf{q}}{\partial t} + \frac{1}{\varepsilon}(\mathbf{q}\cdot\nabla)\,\mathbf{q}\right] = -\nabla P + \rho\mathbf{g} + \tilde{\mu}\nabla^2\mathbf{q} - \frac{1}{k_1}\left(\mu - \mu'\frac{\partial}{\partial t}\right)\mathbf{q} + 2\rho\,(\mathbf{q}\times\mathbf{\Omega}) - \frac{1}{2}(\mathbf{E}\cdot\mathbf{E})\,\nabla K, \tag{2}$$

$$A\frac{\partial T}{\partial t} + (\mathbf{q}\cdot\nabla)\,T = \kappa\nabla^2 \mathrm{T}, \tag{3}$$

where

$$\mathrm{P} = p - \frac{\rho}{2}\frac{\partial K}{\partial \rho}(\mathbf{E}\cdot\mathbf{E}) \tag{4}$$

is the modified pressure (Takashima [16]).

The Maxwell equations are:

$$\nabla\times\mathbf{E} = 0 \tag{5}$$

$$\nabla\cdot(K\mathbf{E}) = 0 \tag{6}$$

Let V be the root mean square value of electric potential, the electric potential can be expressed as:

$$\mathbf{E} = -\nabla V \tag{7}$$

The dielectric constant is assumed to be the linear function of temperature and is of the form:

$$K = K_0\left[1 - \gamma\,(T - T_0)\right] \tag{8}$$

where $\gamma > 0$, is the thermal coefficient of expansion of dielectric constant and is assumed to be small.

The equation of state is:

$$\rho = \rho_0\left[1 - \alpha\,(T - T_0)\right], \tag{9}$$

where α is coefficient of thermal expansion and the suffix zero refers to values at the reference level z = 0.

Let $\mathbf{q}'$, T′, $\mathbf{E}'$, ρ', K', P' be the perturbations in $\mathbf{q}$, T, $\mathbf{E}'$, ρ, K', P' respectively.

By applying infinitesimal perturbations on the basic state, we get:

$$\mathbf{q} = \mathbf{q}',\ \ T = T_b + T',\ \ \mathbf{E} = \mathbf{E}_b + \mathbf{E}', \rho = \rho_b + \rho', \quad \mathrm{K} = \mathrm{K_b} + K',\ \ P = P_b + P' \tag{10}$$

Then the linear stability equations in non-dimensional form (after neglecting the primes for simplicity) are:

$$\left[\frac{1}{\mathrm{Pr}}\frac{\partial}{\partial t} + \frac{1}{Da}\left(1 - F\frac{\partial}{\partial t}\right) - \tilde{D}a\nabla^2\right]\nabla^2 w = Ra_t\nabla_h^2 T - \sqrt{Ta}\frac{\partial \xi}{\partial z} + Ra_e\nabla_h^2\left(T - \frac{\partial V}{\partial z}\right), \tag{11}$$

$$\left[\frac{1}{\mathrm{Pr}}\frac{\partial}{\partial t} + \frac{1}{Da}\left(1 - F\frac{\partial}{\partial t}\right) - \tilde{D}a\nabla^2\right]\xi = \sqrt{Ta}\frac{\partial w}{\partial z}, \tag{12}$$

$$\left[A\frac{\partial}{\partial t} - \nabla^2\right]T = w, \tag{13}$$

$$\nabla^2 V = \frac{\partial T}{\partial z}, \tag{14}$$

where, we have used the dimensionless variables

$$(\mathrm{x}', \mathrm{y}', \mathrm{z}',) = \left(\frac{\mathrm{x, y, z}}{\mathrm{d}}\right), \quad \mathbf{q}' = \frac{d}{\kappa}\mathbf{q}, \quad \mathrm{t}' = \frac{\kappa}{\mathrm{d}^2}\mathrm{t},$$

$$\mathrm{T}' = \frac{1}{\Delta T}\mathrm{T}, \quad \xi' = \frac{\mathrm{d}^2}{\kappa}\xi, \quad \mathrm{V}' = \frac{1}{\gamma \mathrm{E}_0 \Delta T d}V$$

and dimensionless parameters as: $\mathrm{Pr} = \frac{\nu\varphi}{\kappa}$; the Prandtl number, $Da = \frac{k_1}{d^2}$; the Darcy number, $\tilde{D}a = \frac{\tilde{\mu}k_1}{\mu d^2}$; the Brinkman-Darcy number, $F = \frac{\mu'}{\mu}$; the viscoelasticity parameter, $Ta = \frac{4\Omega^2 d^4}{\varphi\nu^2}$; the modified Taylor number, $Ra_t = \frac{g\alpha\Delta T d^3}{\nu\kappa}$; the thermal Rayleigh number, $Ra_e = \frac{\gamma^2 K_0 E_0^2 (\Delta T)^2 d^2}{\mu\kappa}$; the AC electric Rayleigh number and $\xi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}$; the z-component of vorticity.

We assume that the temperature at the boundaries is kept fixed, the fluid layer is confined between the two boundaries. The boundary conditions appropriate (Chandrasekhar [4], Takashima [16], Shivakumara *et al.* [22] and Rana *et al.* [23, 24] to the problem are:

$$w = \frac{\partial^2 w}{\partial z^2} = \frac{\partial \xi}{\partial z} = \frac{\partial V}{\partial z} = 0, T = 0 \text{ or } DT = 0. \tag{15}$$

3 Linear stability analysis

We assume that the perturbation quantities have x, y and t dependence of the form

$$[w, \ T, \mathrm{V}, \ \xi] = \left[W(z), \ \Theta(z), \ \Phi(z), Z(z)\right] \exp\left(ilx + imy + \omega \mathbf{t}\right), \tag{16}$$

where *l and m* are the wave numbers in the *x* and *y* direction, respectively, and ω is the complex growth rate of the disturbances.

Using Eq. (16) in Eqs. (11)–(15), we obtain:

$$\left[\frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) - \tilde{D}a\left(D^2 - a^2\right)\right]\left(D^2 - a^2\right)W = -Ra_t a^2 \Theta - \sqrt{Ta}DZ + Ra_e a^2(\Theta - D\Phi), \tag{17}$$

$$\left[\frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) - -\tilde{D}a\left(D^2 - a^2\right)\right]Z = \sqrt{Ta}DW, \tag{18}$$

$$\left[A\omega - \left(D^2 - a^2\right)\right]\Theta = W, \tag{19}$$

$$\left(D^2 - a^2\right)\Phi = D\Theta, \tag{20}$$

$$w = D^2 W = DZ = D\Phi = 0, \Theta = 0 \tag{21}$$

where $a^2 = l^2 + m^2, D = \frac{d}{dz}$.

Eqs. (17)–(20) form a double eigenvalue problem for Ra_t or Ra_e and ω with respect to the boundary conditions (21).

We assume the solution to W, Θ, Φ and Z of the form:

$$W = W_0 \sin \pi z, \quad \Theta = \Theta_0 \sin \pi z \quad \Phi = \Phi_0 \cos \pi z \quad Z = Z_0 \cos \pi z, \tag{22}$$

which satisfy the boundary conditions of Eq. (22).

Substituting Eq. (22) into Eqs. (17)–(20), we obtain the following matrix equation:

$$\begin{bmatrix} \left[\frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) + \tilde{D}aJ^2\right]J^2 & -a^2(Ra_t + Ra_e) & \pi\sqrt{Ta} & -Ra_e a^2 \pi \\ -1 & \omega + J^2 & 0 & 0 \\ -\pi\sqrt{Ta} & 0 & \frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) + \tilde{D}aJ^2 & 0 \\ 0 & \pi & 0 & J^2 \end{bmatrix} \begin{bmatrix} W_0 \\ \Theta_0 \\ Z_0 \\ \Phi_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \tag{23}$$

where $J^2 = \pi^2 + a^2$ is the total wave number.

The linear system (21) has a non-trivial solution if and only if

$$\begin{vmatrix} \left[\frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) + \tilde{D}aJ^2\right]J^2 & -a^2(Ra_t + Ra_e) & \pi\sqrt{Ta} & -Ra_e a^2 \pi \\ -1 & \omega + J^2 & 0 & 0 \\ -\pi\sqrt{Ta} & 0 & \frac{\omega}{\mathrm{Pr}} + \frac{1}{Da}(1 - F\omega) + \tilde{D}aJ^2 & 0 \\ 0 & \pi & 0 & J^2 \end{vmatrix} = 0,$$

which yields

$$Ra_t = \frac{A\omega + J^2}{a^2}\left[\left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)\omega + \frac{1}{Da} + \tilde{D}aJ^2\right] + \frac{\pi^2 Ta}{a^2}\frac{J^2 + A\omega}{\left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)\omega + \frac{1}{Da} + \tilde{D}aJ^2} - \frac{a^2}{J^2}Ra_e. \tag{24}$$

Eq. (22) is the dispersion relation accounting for the effect of Prandtl number, electric Rayleigh number, Darcy number, Brinkman-Darcy number, Taylor number and kinematic viscoelasticity parameter in a layer of Walters' (model B') viscoelastic fluid in a porous medium.

Taking $\omega = i\omega_i$ in Eq. (24), we obtain

$$Ra_t = \Delta_1 + i\omega_i \Delta_2, \tag{25}$$

where

$$\Delta_1 = \frac{J^2}{a^2}\left[\frac{1}{Da} + \tilde{D}aJ^2 - A\left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)\omega_i^2\right] + \frac{\pi^2 Ta}{a^2}\left[\frac{\frac{J^2}{Da} + \tilde{D}aJ^2 + A\left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)\omega_i^2}{\frac{1}{Da^2} - \left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)^2\omega_i^2 + +\tilde{D}a^2 J^4}\right] - \frac{a^2}{J^2}Ra_e \tag{26}$$

and

$$\Delta_2 = \frac{J^2}{a^2}\left[\frac{A}{Da} + A\tilde{D}aJ^2 + \left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)J^2 \right. \quad (27)$$

$$\left. +\pi^2 Ta \frac{\frac{A}{Da} + A\tilde{D}aJ^2 - J^2\left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)}{\frac{1}{Da^2} + \tilde{D}a^2J^4 - \left(\frac{1}{\mathrm{Pr}} - \frac{F}{Da}\right)^2\omega_i^2}\right].$$

Hence, it follows from Eq. (25) that either $\omega_i = 0$ (exchange stability, steady onset) or $\Delta_2 = 0$, $\omega_i \neq 0$ (overstability, oscillatory onset).

4 Stationary convection

For stationary convection, putting $\omega = 0$ in Eq. (24), we obtain

$$(Ra_t)_s = \frac{\left(\pi^2 + a^2\right)^2}{a^2 Da} + \frac{\pi^2\left(\pi^2 + a^2\right)DaTa}{a^2} \quad (28)$$

$$+ \frac{\left(\pi^2 + a^2\right)^3\tilde{D}a}{a^2} - \frac{a^2}{\pi^2 + a^2}Ra_e.$$

Eq. (26) expresses the thermal Rayleigh number as a function of the dimensionless resultant wave number a and the parameters Ta, Da and Ra_e. It is found that the kinematic viscoelasticity parameter F vanishes with ω and the Walters' (model B') viscoelastic dielectric fluid acts like an ordinary Newtonian dielectric fluid. Eq. (26) is identical to that obtained by Shivakumara *et al.* [22] and Rana *et al.* [23, 24].

In the absence of Brinkman model, Eq. (26) reduces to

$$(Ra_t)_s = \frac{\left(\pi^2 + a^2\right)^2}{a^2} + \frac{\pi^2\left(\pi^2 + a^2\right)DaTa}{a^2}. \quad (29)$$

In the absence of AC electric field (*i.e.*, when $Ra_e = 0$), Eq. (28) reduces to

$$(Ra_t)_s = \frac{\left(\pi^2 + a^2\right)^2}{a^2} \quad (30)$$

$$+ \frac{\left(\pi^2 + a^2\right)^3\tilde{D}a}{a^2} + \frac{\pi^2\left(\pi^2 + a^2\right)DaTa}{a^2}.$$

which is in good agreement with the equation derived by Chandrasekhar [4], Shivakumara [21] and Rana *et al.* [23, 24].

In the absence of rotation (*i.e.*, when $Ta = 0$), Eq. (28) reduces to

$$(Ra_t)_s = \frac{\pi^2 + a^2}{a^2 Da} + \frac{\left(\pi^2 + a^2\right)^3\tilde{D}a}{a^2} - \frac{a^2}{\pi^2 + a^2}Ra_e. \quad (31)$$

Eq. (29) is in good agreement with the equation obtained by Robert [6] and Rana *et al.* [23, 24].

To study the effect of rotation and AC electric field on electrohydrodynamic stationary convection, we examine the behavior of $\frac{\partial(Ra_t)_s}{\partial Da}$, $\frac{\partial Ra_t}{\partial \tilde{D}a}$ $\frac{\partial(Ra_t)_s}{\partial Ta}$ and $\frac{\partial(Ra_t)_s}{\partial Ra_e}$ analytically.

From Eq. (26), we obtain

$$\frac{\partial(Ra_t)_s}{\partial Da} = \frac{\pi^2\left(\pi^2 + a^2\right)}{a^2}\left[Ta - \frac{1}{\pi^2 Da^2}\right] \quad (32)$$

which is positive if $Ta > 1/\pi^2 Da^2$. Thus, the Darcy number inhibits the onset of electrohydrodynamic stationary convection implying thereby that the Darcy number has a stabilizing effect on the system, which is in an agreement with the results derived by Takashima [16], Shivakumara [21] and Rana and Jamwal [22]. However, in the absence of rotation, the Darcy number has a destabilizing effect:

$$\frac{\partial(Ra_t)_s}{\partial Da} = \frac{\pi^2\left(\pi^2 + a^2\right)}{a^2}\left[Ta - \frac{1}{\pi^2 Da^2}\right]$$

which is negative if $Ta < 1/\pi^2 Da^2$, that is, rotation is small. Therefore, Darcy number has a destabilizing effect on the system.

It is evident from Eq. (26) that

$$\frac{\partial(Ra_t)_s}{\partial \tilde{D}a} = \frac{\left(\pi^2 + a^2\right)^3}{a^2} \quad (33)$$

which is positive. Thus, the Brinkman-Darcy number inhibits the onset of electrohydrodynamic stationary convection thereby implying that rotation has a stabilizing effect on the system, which is in agreement with the results derived by Rana *et al.* [3].

It is evident from Eq. (26) that

$$\frac{\partial(Ra_t)_s}{\partial Ta} = \frac{\pi^2\left(\pi^2 + a^2\right)Da}{a^2} \quad (34)$$

which is positive. Thus, rotation inhibits the onset of electrohydrodynamic stationary convection thereby implying that rotation has a stabilizing effect on the system, which is an agreement with the results derived by Takashima [16], Rana and Jamwal [2] and Shivakumara [22].

$$\frac{\partial Ra_t}{\partial Ra_e} = -\frac{a^2}{\pi^2 + a^2}, \quad (35)$$

which is negative thereby implying that AC electric field hastens the electroconvection and it has a destabilizing effect on the system, which is in an agreement with the results derived by Takashima [15], Shivakumara [20–22] and Rana *et al.* [23, 24].

We now study the effect of Darcy number, Brinkman-Darcy number, Taylor number and AC electric field numerically by giving some numerical values to the parameters to depict the stability characteristics. The dispersion relation (26) is analyzed numerically. Graphs have been plotted by giving some numerical values to the parameters, to depict the stability characteristics.

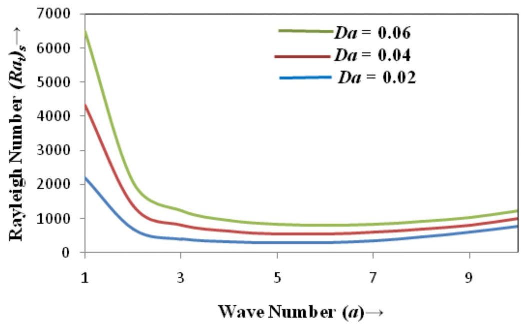

Figure 2: Variation of thermal Rayleigh number $(Ra_t)_s$ with the wave number *a* for different values of the Darcy number *Da*

In Figure 2, the thermal Rayleigh number $(Ra_t)_s$ is plotted against the dimensionless wave number *a* for different values of Darcy number (*Da*), while the values of Brinkman-Darcy number, electric Rayleigh number and Taylor number are kept fixed. This shows that the thermal Rayleigh number $(Ra_t)_s$ increases with an increase in the Darcy number (*Da*). Thus, the Darcy number has a stabilizing effect on stationary convection, which is in agreement with the result obtained analytically from Eq. (30).

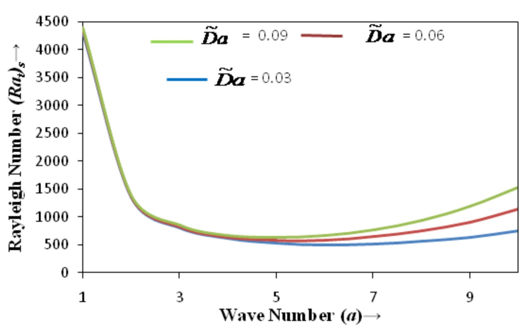

Figure 3: Variation of thermal Rayleigh number $(Ra_t)_s$ with the wave number *a* for different values of the Brinkman-Darcy number $\tilde{D}a$

In Figure 3, the thermal Rayleigh number $(Ra_t)_s$ is plotted against the dimensionless wave number *a* for different values Brinkman-Darcy number ($\tilde{D}a$), while the values of Darcy number electric Rayleigh number and Taylor number are kept fixed. This shows that the thermal Rayleigh number $(Ra_t)_s$ increases with an increase in the Brinkman-Darcy number ($\tilde{D}a$). Thus, the Brinkman-Darcy number has a stabilizing effect on stationary convection, which is in agreement with the result obtained analytically from Eq. (31).

In Figure 4, the thermal Rayleigh number $(Ra_t)_s$ is plotted against the dimensionless wave number *a* for different values of Taylor number (*Ta*), while the values of Brinkman-Darcy number, electric Rayleigh number and Darcy number are kept fixed. This shows that the thermal Rayleigh number $(Ra_t)_s$ increases with an increase in the Taylor number (*Ta*). Thus, rotation has a stabilizing effect on stationary convection, which is in agreement with the result obtained analytically from Eq. (32).

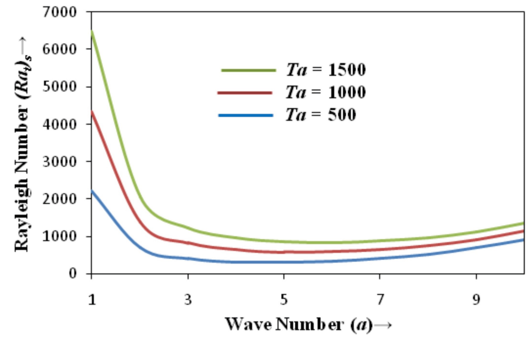

Figure 4: Variation of thermal Rayleigh number $(Ra_t)_s$ with the wave number *a* for different values of the Taylor number *Ta*

In Figure 5, the thermal Rayleigh number $(Ra_t)_s$ is plotted against dimensionless wave number *a* for different values of the electric Rayleigh number (Ra_e), while the values of electric Taylor number (*Ta*) and Darcy number (*Da*) are kept fixed. This shows that as (Ra_e)increases, the thermal Rayleigh number $(Ra_t)_s$ decreases. Hence, AC electric field has a destabilizing effect on the stationary convection, which is in agreement with the result obtained analytically from Eq. (33).

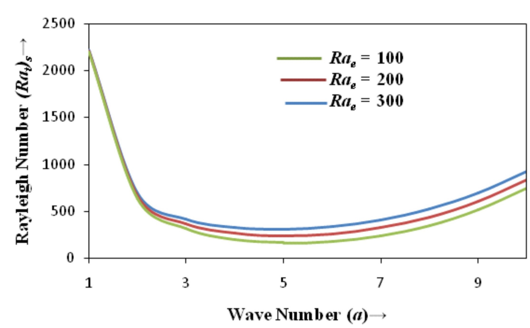

Figure 5: Variation of thermal Rayleigh number $(Ra_t)_s$ with the wave number *a* for different values of AC electric Rayleigh number Ra_e

5 Conclusions

The thermal instability of Walters' (model B') viscoelastic rotating fluid layer in electrohydrodynamics has been investigated for the case of free-free boundaries by using linear stability analysis. For the case of stationary convection, the non-Newtonian electrohydrodynamic Walters' (model B') viscoelastic rotating fluid acts like an ordinary Newtonian rotating fluid. Darcy number, Brinkman-Darcy number and Taylor number, all three inhibit the onset of electrohydrodynamic stationary convection and has stabilizing effects on the stationary convection, while AC electric field hasten the onset of electrohydrodynamic stationary convection and has a destabilizing effect on the stationary convection. Figures 2, 3 and 4 clearly depict the stabilizing effects of Darcy number, Brinkman-Darcy number and Taylor number respectively, while Figure 5 depicts the destabilizing effect of AC electric field.

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