Gian C. Rana

Department of Mathematics
Sidharth Govt. College, Nadaun-177 005
Himachal Pradesh, INDIA
Visiting Faculty
Department of Mathematics
Apex Professional University, Pasighat
Arunachal Pradesh,
INDIA

Ramesh Chand

Department of Mathematics
Government College Nurpur
District Kangra Himachal Pradesh,
INDIA

Dhananjay Yadav

Department of Chemical Engineering
Jeju National University Jeju- 690756
South Korea

The Onset of Electrohydrodynamic Instability of An Elastico-Viscous Walters' (Model B') Dielectric Fluid Layer

In this paper we investigate the effect of AC electric field on the onset of instability of an elastico-viscous Walters' (model B') dielectric fluid layer stimulated by the dielectrophoretic force due to the variation of dielectric constant with temperature. By applying linear stability theory and normal mode analysis method, we derive the dispersion relation describing the influence of viscelasticity and AC electric field. For the case of stationary convection, it is observed that Walters' (model B') fluid behaves like an ordinary Newtonian fluid whereas AC electric field hastens the stationary convection. The present results are in good agreement with the earlier published results.

Keywords: *Walter' (model B') fluid, AC electric field, Electrohydrodynamic, Viscosity, Viscoelasticity.*

1. INTRODUCTION

Electrohydrodynamics can be considered as a branch of fluid mechanics which deals with the effect of electrical forces. It can also be regarded as that part of electrodynamics which is necessitated with the influence of moving media on electric fields. A review of electrodynamically enhanced heat transfer in liquids has been studied by Jones [1] while the most interesting problems in electrohydrodynamics which involve both the effect of fluid in motion and the influence of the field in motion was discussed by Melcher et al. [2]. A detailed account of thermal instability of Newtonian fluid under the various assumptions of hydrodynamics has been discussed by Chandrasekhar [3] while the electrodynamics of continuous media and later electrohydrodynamic convection in fluids was studied by Landau [4], Robert [5] and Castellanos [6]. A short discussion on the applications of electrohydrodynamic (EHD) instability has been given by Lin [7]

The study of electrohydrodynamic instability in dielectric fluid attracts many researchers for the past few decades because it has various applications in EHD enhanced thermal transfer, EHD pumps, EHD in microgravity, micromechanic systems, drug delivery, micro-cooling system, nanotechnology etc. Chen et al. [8] discussed the advances and applications of electrohydrodynamics in brief. They say that EHD heat transfer came out as an alternative method to enhance heat transfer, which is known as electrothermohydrodynamics (ETHD). Many researches have been studied the effect of AC or DC electric field on natural convection in a horizontal dielectric fluid layer by taking different types of fluids. The onset of electrohydodynamic convection in a horizontal layer of dielectric fluid was studied by Gross and Porter [9], Turnbull [10], Maekawa et al. [11], Smorodin and Velarde [12], Galal [13], Rudraiah and Gayathri [14] and Chang et al. [15]. Takashima and Ghosh [16] studied the electrohydrodynamic instability in a viscoelastic liquid layer and found that oscillatory modes of instability exist only when the thickness of the liquid layer is smaller than about 0.5 mm and for such a thin layer the force of electrical origin is much more important than buoyancy force while Takashima and Hamabata [17] studied the stability of natural convection in a vertical layer of dielectric fluid in the presence of a horizontal AC electric field.

The theory of fluids with non-linear constitutive equations so called non-Newtonian fluids started by Reiner [18] for compressible fluids and Walters' [19] for incompressible fluids. With the growing importance of non-Newtonian fluids having applications in geophysical fluid dynamics, chemical technology and petroleum industry attracted widespread interest in the study on non-Newtonian fluids. There are many elastico-viscous fluids that cannot be characterized by Maxwell's constitutive relations or by Oldroyd's constitutive relations. One such type of fluids is Walters' (model B') elastico-viscous fluid having relevance in chemical technology and industry. Walters' [19] reported that the mixture of polymethyl methacrylate and pyridine at 25^0C containing 30.5g of polymer per litre with density 0.98g per litre behaves very nearly as the Walters' (model B') elastico-viscous fluid. Walters' (model B') elastico-viscous fluid form the basis for the manufacture of many important polymers and useful products. In the case of Walters' (model B') fluid, the term $\left[\mu\nabla^2\mathbf{q}\right]$ in the equations of motion is replaced by the term $\left[\left(\mu-\mu'\dfrac{\partial}{\partial t}\right)\nabla^2\mathbf{q}\right]$, where μ and μ' are the viscosity and viscoelasticity of

the incompressible Walters' (model B') fluid, ∇^2 is the Laplacian operator and **q** is the Darcian (filter) velocity of the fluid. This has been widely accepted as simplest nonlinear viscoelastic model that takes account of frame invarince in the nonlinear regime. The model adequately represents highly elastic fluids, for which the viscosity remains sensibly constant over a wide range of shear rates, hence covering a wide range of practical fluids. Also the constitutive equation is one of the simplest viscoelastic laws that accounts for normal stress effects responsible for the periodic phenomena arising in viscoelastic fluids. Because of these reasons, the model has been widely accepted for experimental measurements and flow visualization on the instability of viscoelastic flows. The stability of Walters' (Model B') superposed fluid in porous medium has been studied by Sharma and Rana [20] while the thermal instability of compressible Walters' (model B') fluid in the presence of hall currents and suspended particles has been studied by Gupta and Aggarwal [21].

Keeping in mind the various applications as mentioned above, our main aim in the present paper is to study the effect of uniform AC electric field on the onset of instability of an elastico-viscous Walters' (model B') fluid. To the best of my knowledge, this problem has not been studied as yet.

2. MATHEMATICAL MODEL

Here we consider an infinite horizontal layer of an incompressible Walters' (model B') elastico-viscous fluid of thickness d, bounded by the planes $z = 0$ and $z = d$ as shown in fig. 1. The fluid layer is acted upon by a gravity force $\boldsymbol{g} = (0, 0, -g)$ aligned in the z direction and the uniform vertical AC electric field applied across the layer. The temperature T at the lower and upper boundaries is assumed to take constant values T_0 and T_1 ($< T_0$) respectively.
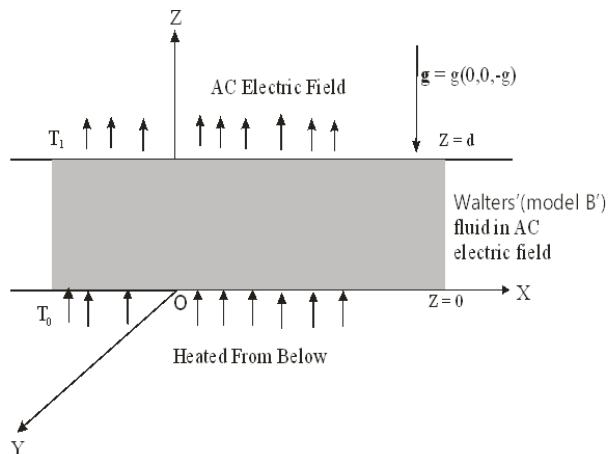

Fig. 1 Physical Situation of the Problem

2.1 Governing Equations

Let $\rho, \mu, \mu^{'}, p, K,$ **q**(u, v, w), **g**, T, κ and $\boldsymbol{E}$ denote respectively, the density, viscosity, viscoelasticity, pressure, dielectric constant, Darcy velocity vector, acceleration due to gravity, temperature, thermal

diffusivity and the root-mean-square value of electric field. Then the equations of conservation of mass, momentum and thermal energy for Walters' (model B') elastico-viscous fluid (Chandrasekhar [3], Walters' [19], Takashima [15], Sharma and Rana [20] and Robert [5]) are

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

$$\rho \frac{d\mathbf{q}}{dt} = -\nabla P + \rho \mathbf{g} + \left(\mu - \mu^{'} \frac{\partial}{\partial t}\right)\nabla^2 \mathbf{q} - \frac{1}{2}(\mathbf{E} \cdot \mathbf{E})\nabla K, \tag{2}$$

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

where $\dfrac{d}{dt} = \dfrac{\partial}{\partial t} + \dfrac{1}{\varepsilon}(\mathbf{q} \cdot \nabla)$ stands for convection derivative and

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

is the modified pressure.

The Coulomb force term $\rho_e \mathbf{E}$, where ρ_e is the free charge density, is of negligible order as compared with the dielectrophoretic force term for most dielectric fluids in a *60Hz* AC electric field. Thus, we retain only the dielectrophoretic term, i. e. last term in equation (2) and neglect the Coulomb force term. Furthermore, the electrical relaxation times of most dielectric liquids appear to be sufficient long to prevent the build up of free charge at standard power line frequencies. At the same time, dielectric loss at these frequencies is very low that it makes no significant contribution to the temperature field. It is also seen that the dielectrophoretic force term depends on $(\mathbf{E} \cdot \mathbf{E})$ rather than **E**. As the variation of **E** is so speedy, the root-mean-square value of **E** is used as effective value in determining the motion of fluids. So we can consider the AC electric field as the Dc electric field whose strength is equal to the root mean square value of the AC electric field.

A charged body in an electric field tends to along the electric field lines and impart momentum to the surrounding fluid. The Maxwell equations are

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

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

Using Eq. (5), the electric potential can be expressed as

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

where V is the root mean square value of electric potential. The dielectric constant is assumed to be 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

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

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

2.2 Basic State

The basic state of the system is taken to be quiescent layer (no settling) and is given by

$$\begin{aligned} \mathbf{q} &= \mathbf{q}_b(z), P = P_b(z), T = T_b(z), \\ \mathbf{E} &= \mathbf{E}_b(z), K = K_b(z), \rho = \rho_b(z) \end{aligned}, \qquad (10)$$

where the subscript b denotes the basic state.

Substituting equations given in (10) in Eqs. (1) – (9), we obtain

$$0 = -\nabla \frac{P_b(z)}{\rho_0} + \frac{\rho_b(z)}{\rho_0} \mathbf{g} - \frac{1}{2\rho_0} \left(\mathbf{E}^2 \right) \nabla K, \quad (11)$$

$$\frac{d^2 T_b(z)}{dz^2} = 0, \qquad (12)$$

$$K_b(z) = K_0 \left[1 - \gamma (T_b - T_0) \right] \qquad (13)$$

$$\rho_b(z) = \rho_0 \left[1 - \alpha (T_b - T_0) \right], \qquad (14)$$

$$\nabla \cdot \left(K_b E_b \right) = 0. \qquad (15)$$

Solving Eq. (12) by using the following boundary conditions

$$T_b(z) = T_0 \text{ at } z = 0 \text{ and } T_b(z) = T_1 \text{ at } z = d, (16)$$

we obtain

$$T_b = T_0 - \Delta T z / d. \qquad (17)$$

In view of Eq. (15) and noting that $E_{bx} = E_{by} = 0$. It follows that

$$K_b E_{bz} = K_0 E_0 = \text{constant (say)}. \qquad (18)$$

Then

$$\mathbf{E} = \mathbf{E}_b(z) = \frac{E_0}{1 + \gamma \Delta T z / d}. \qquad (19)$$

Hence

$$V_b(z) = -\frac{E_0 d}{\gamma \Delta T} \log \left(1 + \gamma \Delta T z / d \right), \qquad (20)$$

where

$$E_0 = -\frac{V_1 \gamma \Delta T / d}{\log \left(1 + \gamma \Delta T \right)} \qquad (21)$$

is the root-mean-square value of the electric field at z = 0.

2.2 Perturbation Solutions

To study the stability of the system, we superimposed infinitesimal perturbations on the basic state, so that

$$\begin{aligned} \mathbf{q} &= \mathbf{q}', T = T_b + \mathrm{T}', \ \mathbf{E} = \mathbf{E}_b + \mathbf{E}', \\ \rho &= \rho_b + \rho', \mathrm{K} = \mathrm{K}_b + K', P = P_b + P' \end{aligned} \qquad (22)$$

where $\mathbf{q}', \mathrm{T}', \mathbf{E}', \rho', K', P'$ be the perturbations in $\mathbf{q}, T, \mathbf{E}, \rho, K, P$ respectively. Substituting Eq. (10) in Eqs. (1) – (9), linearizing the equations by neglecting the product of primed quantities, eliminating the pressure from the momentum Eq. (2) by operating curl twice and retaining the vertical component and non-dimensionalizing the resulting equations by introducing the dimensionless variables as follows:

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

$$\mathrm{T}' = \frac{1}{\Delta T} \mathrm{T}, \ \mathrm{V}' = \frac{1}{\gamma \mathrm{E}_0 \Delta T d} V$$

Neglecting the primes for simplicity, we obtain the linear stability equations as

$$\left[\frac{1}{\mathrm{Pr}} \frac{\partial}{\partial t} - \left(1 - F \frac{\partial}{\partial t} \right) \nabla^2 \right] \nabla^2 w$$

$$= Ra_t \nabla_h^2 T + Ra_e \nabla_h^2 \left(T - \frac{\partial V}{\partial z} \right), \qquad (23)$$

$$\left[\frac{\partial}{\partial t} - \nabla^2 \right] T = w, \qquad (24)$$

$$\nabla^2 V = \frac{\partial T}{\partial z}, \qquad (25)$$

where we have dimensionless parameters as:

$$\mathrm{Pr} = \frac{\nu}{\kappa}, \ F = \frac{\mu'}{\mu}, \qquad (26\mathrm{a,b})$$

$$Ra_t = \frac{g \alpha \Delta T d^3}{\nu \kappa}, \qquad (27)$$

$$Ra_e = \frac{\gamma^2 K_0 E_0^2 (\Delta T)^2 d^2}{\mu \kappa}, \qquad (28)$$

The parameter *Pr* is The Prandtl number and *F* is the viscoelasticity parameter while Ra_t is the familiar thermal Rayleigh number and Ra_e is the AC electric Rayleigh number.

Here we assume that the temperature at the boundaries is kept fixed, the fluid layer is confined between two boundaries. The boundary conditions appropriate (Chandrasekhar [1], Takashima [15], Rana

and Jamwal [23] and Shivakumara et al. [27]) to the problem are

$$w = \frac{\partial^2 w}{\partial z^2} = \frac{\partial V}{\partial z} = 0, T = 0 \text{ or } DT = 0. \quad (29)$$

3. LINEAR STABILITY ANALYSIS

Following the normal mode analyses, we assume that the perturbation quantities have x, y and t dependence of the form:

$$[w, T, V] = [W(z), \Theta(z), \Phi(z)] \times$$
$$\exp(ilx + imy + \omega t), \quad (30)$$

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.

Substituting Eq. (30) in Eqs. (23) – (25) and (29), we get:

$$\left[\frac{\omega}{\text{Pr}} - (1 - F\omega)(D^2 - a^2)\right](D^2 - a^2)W$$
$$= -Ra_t a^2 \Theta + Ra_e a^2(\Theta - D\Phi), \quad (31)$$

$$[\omega - (D^2 - a^2)]\Theta = W, \quad (32)$$

$$(D^2 - a^2)\Phi = D\Theta, \quad (33)$$

$$W = D^2 W = D\Phi = 0, \Theta = 0 \text{ or } D\Theta = 0, (34)$$

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

Eqs. (31) – (33) form an eigenvalue problem for Ra_t or Ra_e and ω with respect to the boundary conditions (34).We assume the solution to W, Θ, Φ and Z of the form

$$W = W_0 \sin \pi z , \quad \Theta = \Theta_0 \sin \pi z ,$$

$$\Phi = \Phi_0 \cos \pi z , \quad (35)$$

which satisfy the boundary conditions of Eq. (34). Substituting Eq. (35) into Eqs. (31) – (33), we obtain the following matrix equation

$$\begin{bmatrix} \left(\frac{1}{\text{Pr}} - FJ^2\right)J^2\omega + J^4 & -a^2(Ra_t + Ra_e) & -Ra_e a^2 \pi \\ -1 & \omega + J^2 & 0 \\ 0 & \pi & J^2 \end{bmatrix} \times$$
$$(36)$$

$$\begin{bmatrix} W_0 \\ \Theta_0 \\ \Phi_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix},$$

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

The linear system (36) has a non-trivial solution if and only if

$$\begin{vmatrix} \left(\frac{1}{\text{Pr}} - FJ^2\right)J^2\omega + J^4 & -a^2(Ra_t + Ra_e) & -Ra_e a^2 \pi \\ -1 & \omega + J^2 & 0 \\ 0 & \pi & J^2 \end{vmatrix} = 0,$$

which yields

$$Ra_t = \frac{J^2(J^2 + \omega)}{a^2}\left[\left(\frac{1}{\text{Pr}} - FJ^2\right)\omega + J^2\right]$$
$$- \frac{a^2}{J^2} Ra_e. \quad (37)$$

Eq. (37) is the dispersion relation accounting for the effect of Prandtl number, electric Rayleigh number, Taylor number and kinematic visco-elasticity parameter in a layer of Walters' (model B') elastico-viscous dielectric fluid.

Setting $\omega = i\omega_i$ in equation (37) and clearing the complex quantities from the denominator, we obtain

$$Ra_t = \Delta_1 + i\omega_i \Delta_2, \quad (38)$$

where

$$\Delta_1 = \frac{J^2}{a^2}\left[J^4 - \left(\frac{1}{\text{Pr}} - FJ^2\right)\omega_i^2\right] - \frac{a^2}{J^2} Ra_e, \quad (39)$$

and

$$\Delta_2 = \frac{J^2}{a^2}\left[J^4 + \left(\frac{1}{\text{Pr}} - FJ^2\right)J^2\right]. \quad (40)$$

Since Ra_t is a physical quantity, it must be a real value. Hence, it follows from Eq. (43) that either $\omega_i = 0$ (exchange stability, steady onset) or $\Delta_2 = 0$, $\omega_i \neq 0$ (overstability, oscillatory onset).

4. THE STATIONARY CONVECTION

For stationary convection, putting ω = 0 in equation (37) reduces it to

$$Ra_t = \frac{(\pi^2 + a^2)^3}{a^2} - \frac{a^2}{\pi^2 + a^2} Ra_e. \quad (41)$$

Eq. (41) expresses the thermal Rayleigh number as a function of the dimensionless resultant wave number a and the parameters Ra_e. It is found that the kinematic viscoelasticity parameter F vanishes with ω and the Walters' (model B') elastico-viscous dielectric fluid behaves like an ordinary Newtonian dielectric fluid. Eq. (41) is in good agreement with the equation obtained by Roberts [3].

In the absence of AC electric field (i. e., when $Ra_e = 0$), Eq. (41) reduces to

$$Ra_t = \frac{\left(\pi^2 + a^2\right)^3}{a^2}. \qquad (42)$$

which is exactly the same equation as derived by Chandrasekhar [1].

To find the critical value of Ra_t, we differentiate Eq. (44) with respect a^2 and equate to zero to obtain a polynomial in a_c^2 in the form

$$2\left(a_c^2\right)^5 + 5\pi^2\left(a_c^2\right)^4 + 5\pi^4\left(a_c^2\right)^3 + \\ \pi^2\left(2\pi^4 - Ra_e\right)\left(a_c^2\right)^2 + 5\pi^8\left(a_c^2\right) - \pi^{10} = 0. \qquad (43)$$

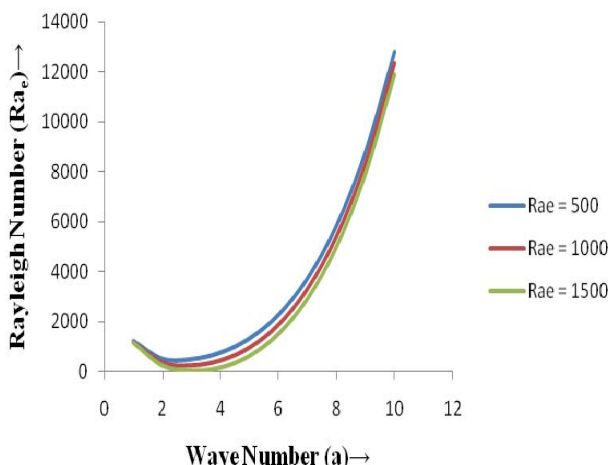From Eq. (43), it is observed that the critical wave number varies with Ra_e.

To study the effect of AC electric field on electrohydrodynamic stationary convection , we examine the behaviour of $\dfrac{\partial Ra_t}{\partial Ra_e}$ analytically.

From Eq. (41), we obtain

$$\frac{\partial Ra_t}{\partial Ra_e} = -\frac{a^2}{\pi^2 + a^2}, \qquad (44)$$

which is negative implying thereby AC electric field hastens the electroconvection implying thereby AC electric field has destabilizing effect on the system which is in an agreement with the results derived by Takashima and Ghosh [16].

The dispersion relation (44) is analyzed numerically. Graphs have been plotted by giving some numerical values to the parameters, to depict the stability characteristics.

Fig 2. Variation of thermal Rayleigh number Ra_t with the wave number *a* for different values of AC electric Rayleigh number Ra_e.

In fig. 2, the thermal Rayleigh number Ra_t is plotted against dimensionless wave number *a* for different values of electric Rayleigh number $\left(Ra_e\right)$ as shown. This shows that as $\left(Ra_e\right)$ increases the thermal Rayleigh number Ra_t decreases. Thus AC electric field has destabilizing effect on stationary convection which is in good agreement with the result obtained analytically from Eq. (44).

5. CONCLUSIONS

The effect of AC electric field on the onset of instability of Walters' (model B') elastico-viscous dielectric fluid layer heated from below has been investigated for the case of free-free boundaries by using perturbation theory and linear stability analysis based on normal modes. For the case of stationary convection, the non-Newtonian electrohydrodynamic Walters' (model B') elastico-viscous dielectric fluid behaves like an ordinary Newtonian fluid. AC electric field hasten the onset of electrohydrodynamic stationary convection as $\partial Ra_t/\partial Ra_e < 0$ indicating that the thermal Rayleigh number Ra_t is an decreasing function of electric Rayleigh number Ra_e. Thus AC electric field has destabilizing effect on the stationary convection.

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NOMENCLATURE

Q	Velocity vector
a	Wave number
d	Thickness of the horizontal layer
E	Root-mean-square value of the electric field
$\mathbf{E}_0$	Root-mean-square value of the electric field at $z = 0$
g	Acceleration due to gravity
K	Dielectric constant
K_0	Reference dielectric constant at T_0
l, m	Wave numbers in x and y directions
P	Modified pressure, defined by Eq. 4
Pr	Prandtl number, defined by Eq. 26a
F	Viscoelasticity parameter, defined by Eq. 26b
Ra_t	Thermal Rayleigh number, defined by Eq. 27
Ra_e	AC electric Rayleigh number, defined by Eq. 28
t	Time
T	Temperature
T_0	Temperature at the lower boundary
T_1	Temperature at the upper boundary
V	Root-mean-square value of the electric potential
W	Amplitude of vertical component of perturbed velocity
k	Thermal conductivity
(x,y,z)	space co-ordinates

Greek symbols

μ	Viscosity of fluid
μ'	Viscoelastisity of fluid
α	Coefficient of thermal expansion
γ	Coefficient of thermal expansion of dielectric constant
κ	Thermal diffusivity of the fluid
ρ	Density of fluid
ρ_e	Free charge density
σ	Electrical conductivity of fluid
ω	Growth rate of disturbances
∇_h^2	Horizontal Laplacian operator
∇	Laplacian operator
Φ	Amplitude of perturbed dielectric potential V
Θ	Amplitude of perturbed temperature T

НАСТАНАК ЕЛЕКТРО И ХИДРОДИНАМИЧКЕ НЕСТАБИЛНОСТИ КОД ЕЛАСТИЧНО-ВИСКОЗНОГ ВОЛТЕРСОВОГ (МОДЕЛ Б') СЛОЈА ДИЕЛЕКТРИЧНОГ ФЛУИДА

Gian C. Rana, Ramesh Chand i Dhananjay Yadav

У овом раду се истражује утицај електричног поља наизменичне струје на настанак нестабилности еластично-вискозног Волтерсовог (модел Б') слоја

диелектричног флуида под утицајем диелектрофоретске силе настале варирањем диелектричне константе са температуром. Применом теорије линеарне стабилности и методе анализе нормалног мода извели смо релацију дисперзије која описује утицај вискоеластичности и електричног поља наизменичне струје. У случају стационарне конвекције је утврђено да се Волтерсов (модел Б') флуид понаша као обичан њутновски флуид, док електрично поље наизменичне струје убрзава стационарну конвекцију. Добијени резултати су у складу са раније објављеним резултатима.