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Effects of laser radiation, transverse electric field and roughness of the boundary on Rayleigh-Taylor instability in a thin poorly conducting viscous fluid

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ABSTRACT

This paper deals with the Rayleigh-Taylor Instability (RTI) at the interface between heavy poorly conducting fluid supported by a lighter poorly conducting fluid in the presence of transverse electric field, thermal radiation and roughness with slip boundary condition at bottom rough wall and no-shear condition at the top interface. Analytical solutions are obtained for modified Navier-Stokes and energy equations in the presence of applied electric field and laser radiation. These solutions are computed for different values of electric number, Bond number, roughness parameter and laser frequency parameter and found that roughness of the wall and electric field reduce the growth rate of RTI considerably.

Key words: Electrohydrodynamic RTI, Surface Roughness, Electric Field, Laser Intensity

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INTRODUCTION

The interfacial science continues to be the frontier area of research in view of its importance for the understanding, control, and exploitation of the many physical, chemical and biological processes, such as, Inertial Fusion Energy (IFE), heat transfer across barriers, friction between surfaces and its mitigation, catalysis, adhesion, failure of polymers, biomechanical and bio medical engineering. Of the three types of surface instabilities, namely Rayleigh-Taylor Instability (RTI), Kelvin-Helmholtz Instability (KHI) and Richtmyer-Meshkov Instability (RMI), the RTI, that is instability of heavy fluid layer supported by a lighter fluid, has attracted considerable attention because of its wide variety of applications in engineering, physical and biological sciences. RTI can occur under gravity and equally under an acceleration of a lighter fluid in the direction towards denser fluid. The RTI in the case of gravitational field in hydrodynamics and magnetohydrodynamics(MHD) has been investigated extensively (see[1]) in the literature but much attention has not been given to its study in electrohydrodynamics (EHD) caused by acceleration of the lighter poorly conducting fluid arising in solidification of alloys in material science processing. For example, in the area of failure of metallic glasses, grain boundary layer in metals and crazing in amorphous non-cross link polymers (see [7] and [10]). These polymer failures have been known to occur normally by the formation and growth of planar defects. These defects look like cracks but, in fact, are load bearings. Both craze slip advance and widening are thought to occur due to RT instability process. In such situations it is important and desirable to suppress the growth rate of RTI because of its importance in biomedical engineering and in IFE.

In bio-medical engineering alloys like Nickel-Titanium and Titanium based alloys are of interest due to their high level of bio compatibility and bio integration with human body. These alloys are poorly electrically conducting where the electrical conductivity is a strong function of temperature. The variation of conductivity with the temperature arising in the solidification of these alloys releases charges which in turn generates an electric field known as thermally induced electric field. In addition there may be an applied electric field due to embedded electrodes at the boundaries. The total electric field (that is sum of induced and applied electric field) together with density of charge distribution give rise to electric force. This in turn produces surface instability of Rayleigh-Taylor type, which may cause the side effects like haemolysis (see [1]) and also erode the endothelium, the walls of the arteries in coronary artery diseases (CAS), due to laser surgery used to dissolve plaques formed on the endothelium. These side effects have to be controlled for efficient functioning of implanted artificial organs in the body. Such replacements with built in mechanisms to control surface instabilities are shown to be superior to metal organs made up of Steel or Cobalt–Chromium-Molybdenum implants (see [15] and [16]). For success of bio-integration with surrounding host tissues involving fixed charge density (FCD) implant surface must be stabilized using surface roughness and naturally available electric field in the body. In addition, this mechanism is also desirable to promote the growth of the bone tissue around the implant.

Apart from this biomedical engineering application, the control that is reduction of growth rate, of RTI is also of importance for efficient extraction of Inertial Fusion Energy (IFE). In IFE, it is known (see [3]) that the accelerating frame moving with the ablative front, there is a dense fluid adjacent to a lighter fluid with the effective inwardly directed gravitational force leading to instability known as Rayleigh-Taylor Instability (RTI). The main challenge in IFE is to control the RTI growth rate to achieve high gain in the IFE target.

In the present paper we propose to overcome this difficulty by making use of Navier-slip due to rough surface of the IFE target wall assuming Deuterium and Tritium (DT), the two Hydrogen isotopes, are poorly conducting incompressible alloys and symmetrically irradiated by high power laser beams of intensity of order of 2 x 10^{14} W/cm^2. The assumption of incompressibility assumed in this paper are adequate because the perturbation considered here are not bounded by gravitational scale heights (see [8]) but depends on the surface tension scale of the system. Therefore, the primary objective of this paper is to show that the Navier-slip produced by the roughness at the ablative surface of IFE target and the combined induced and applied electric field suppress the growth rate of Electrohydrodynamic Rayleigh-Taylor Instability (ERTI) in the presence of laser radiation.

To achieve this objective, this paper is planned as follows. The required basic equations along with electrohydrodynamic (EHD) approximations and the relevant boundary conditions are given in section 2. In section 3 we obtain the solution of the problem as well as the dispersion relation incorporating the effect of laser radiation. Some limiting cases and important conclusions are drawn in the final section 4.

2. Mathematical Formulation

We consider a thin film, denoted as Region 1 (see fig. 1) of unperturbed thickness *h* filled with an incompressible, viscous, poorly electrically conducting light fluid of constant density ρ_1 bounded below by a rough rigid surface which is at a constant temperature T_0 at $y = 0$ and above by a dense incompressible, viscous, poorly conducting liquid of density ρ_2 denoted as region 2 as shown in figure 1.

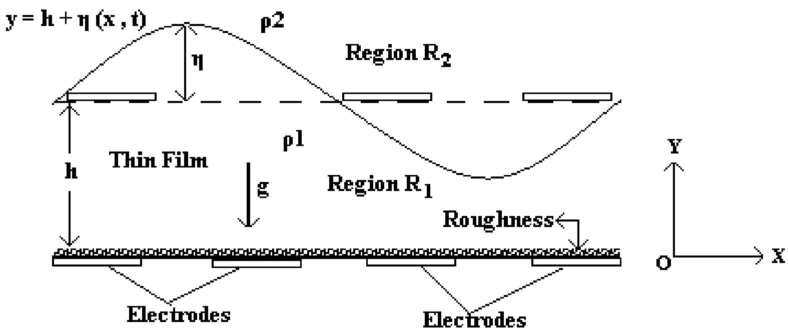

Fig 1: Physical configuration

Laser radiation is used to overcome the repulsive force between DT and to fuse them. The fluid in the thin film is then set in motion by acceleration normal to the interface and small perturbations are amplified when acceleration is directed from light poorly conducting liquid in the film towards heavy poorly conducting liquid above the interface. This instability at the interface, by definition, is RTI. We consider a rectangular coordinate system (*x*, *y*) as shown in figure 1 with x-axis parallel to the film and y-axis normal to the film with $\eta(x,t)$ as the perturbed interface between two fluids in regions R_1 and R_2, where R_2 is a region of dense liquid and R_1 is a region of light liquid. For this configuration the required basic equations following [11] are:

The conservation of momentum:

$$\rho\left(\frac{\partial \vec{q}}{\partial t} + (\vec{q}\cdot\nabla)\vec{q}\right) = -\nabla p + \mu\nabla^2\vec{q} + \rho_e\vec{E}\ . \tag{2.1}$$

The conservation of mass for incompressible fluid:

$$\nabla\cdot\vec{q} = 0\,. \tag{2.2}$$

The conservation of energy including the effect of laser radiation:

$$\rho c_p\left[\frac{\partial T}{\partial t} + (\vec{q}.\nabla)T\right] = k\nabla^2 T + \Omega I e^{-\Omega y}\,. \tag{2.3}$$

To obtain relevant Maxwell's equations we use the following EHD approximations:

(i) $\sigma << 1$, that is the electrical conductivity of the liquid, is negligibly small because we are considering poorly conducting liquid. This approximation implies that the induced magnetic field is negligible and there is no applied magnetic field, hence the electric field is conservative so that

$$\vec{E} = -\nabla\phi \tag{2.4}$$

where ϕ is the electric potential.

(ii) The assumption (i) given above limits the modulation frequency and electrical conductivity of the liquid. That is $\frac{\omega}{2\pi} << \frac{c}{h}$, $\sigma << \frac{1}{h}\left(\frac{\varepsilon_e}{\mu_h}\right)^{\frac{1}{2}}$ where *c* is the phase velocity of the electromagnetic wave in the liquid. These show that we can easily neglect the induced magnetic field.

(iii) Non-uniform polarization and electric charge injection are negligible, so that convection current $\rho_e\vec{q}$ is negligible.

(iv) The film thickness *h* is much smaller than the thickness *H* of the dense fluid above the film. That is $h << H$.

(v) The surface elevation η is assumed to be small compared to film thickness *h*. That is $\eta << h$.

(vi) The Strouhal number ε, which is a measure of the local acceleration to inertial acceleration in equation (2.1) is negligibly small. That is

$$\varepsilon = \frac{L}{t_o U} << 1$$

where $L = \sqrt{\frac{\gamma}{\delta}}$, $t_o = \frac{\mu\gamma}{h^3\delta^2}$ and *U* are respectively the characteristic length, time and velocity, γ is the surface tension and $\delta = g\,(\rho_2 - \rho_1)$.

(vii) We consider high viscous fluid so that inertial acceleration term in equation (2.1) can be neglected in comparison with viscous term.

The Maxwell equations needed, after using the above EHD approximations, are

The Gauss Law:

$$\nabla\cdot\vec{E} = \frac{\rho_e}{\varepsilon_e}\,. \tag{2.5}$$

The Faraday's law:

$$\nabla\times\vec{E} = 0\,. \tag{2.6}$$

The conservation of electric charges:

$$\frac{\partial\rho_e}{\partial t} + \nabla\cdot\vec{J} = 0\,, \tag{2.7}$$

where $\vec{J}$ is the sum of the conduction current $\sigma\vec{E}$ and convection current $\rho_e\vec{q}$ due to the fluid motion. That is

$$\vec{J} = \sigma\vec{E} + \rho_e\vec{q} \tag{2.8}$$

where $\sigma = \sigma_o\,[1 + \alpha_h(T - T_0)]$. Since $\sigma << 1$, it depends on the conduction temperature $T - T_0 = \beta y$. Then σ takes the form

$$\sigma = \sigma_o\,[1 + \alpha_h\,\beta\,y] \tag{2.9}$$

Here $\vec{q} = (u, \mathrm{v})$ the velocity, ρ the density of the fluid, ρ_e the density of electric charges, p the pressure, $\vec{E}$ the electric field, μ the viscosity of fluid, T is the temperature, k is the thermal conductivity, C_p is the specific heat at constant pressure, I is the intensity of laser radiation, Ω is the absorption coefficient, $\vec{J}$ is the current density, ε_e is the dielectric constant of free space, σ is the electrical conductivity of the fluid, $\beta = \frac{\Delta T}{h}$ and ΔT is the difference in temperature.

The EHD assumptions discussed in section 2 also enabled us to use the creeping flow approximations, which allow us to neglect certain terms in the perturbation equations in order to arrive at closed form asymptotic solution for the interface evolution. Under these approximations the basic equations (2.1) to (2.3) reduce to:

For region 1:

$$0 = -\frac{\partial p}{\partial x} + \mu \frac{d^2 u}{dy^2} + \rho_e E_x \tag{2.10}$$

$$0 = -\frac{\partial p}{\partial y} + \rho_e E_y \tag{2.11}$$

$$v_a \frac{\partial T_f}{\partial y} = \kappa_f \frac{\partial^2 T_f}{\partial y^2} + I_0 \Omega e^{-\Omega y} \tag{2.12}$$

$$\frac{\partial u}{\partial x} + \frac{\partial \mathrm{v}}{\partial y} = 0 \tag{2.13}$$

For region 2:

$$0 = \kappa_l \frac{\partial^2 T_l}{\partial y^2} \pm I_0 \Omega e^{-\Omega y} \tag{2.14}$$

where v_a is the velocity of the ablative surface, ± depends on whether I_0 is in the direction or opposing gravity.

From eqn.(2.5), using eqns.(2.4), (2.8), (2.9) and the approximations discussed above, we get

$$\rho_e = \varepsilon_e \gamma_1 \frac{\partial \phi}{\partial y}, \tag{2.15}$$

where $\gamma_1 = \alpha_h \beta$.

From the continuity of charges given by eqn.(2.7), for steady charge density distribution, using eqns. (2.8) and (2.9), we get

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \gamma_1 \frac{\partial \phi}{\partial y} = 0\,. \tag{2.16}$$

Equation (2.16) has to be solved using the boundary conditions

$$\left.\begin{aligned} \phi &= \frac{V}{h} x && \text{at} \quad y = 0 \\ \varphi &= \frac{V}{h}(x - x_o) && \text{at} \quad y = h \end{aligned}\right\} \tag{2.17}$$

We have to find the solution of eqn.(2.10) using the boundary conditions

$$\left.\begin{aligned} \frac{\partial u}{\partial y} &= 0 && \text{at} \quad y = h \\ -\beta_1 \frac{\partial u}{\partial y} &= u && \text{at} \quad y = 0 \end{aligned}\right\} \tag{2.18}$$

the second condition in eqn. (2.18) is the Navier-slip condition (see [9]) valid for rough surface at y = 0 where β_1 is the slip coefficient.

Also eqns.(2.12) and (2.14) are solved using the boundary conditions

$$\left.\begin{array}{ll} T_f = T_0 \quad \text{at} \quad y = 0, & \dfrac{\partial T_l}{\partial y} = 0 \quad \text{as} \quad y \to \infty, \\ \kappa_f \dfrac{\partial T_f}{\partial y} = -\lambda (T_f - T_0) \quad \text{at} \quad y = h, & \kappa_l \dfrac{\partial T_l}{\partial y} = -\lambda (T_l - T_0) \quad \text{at} \quad y = h \end{array}\right\} \tag{2.19}$$

where λ is the heat transfer coefficient, suffices *f* and *l* denote film in region 1 and liquid in region 2 respectively and T_0 is the temperature of rigid boundary.

3. Method of solution

Eqns. (2.10) to (2.19) are made dimensionless, using

$$u^* = \frac{u}{\delta_0 h^2/\mu},\ p^* = \frac{p}{\delta_0 h},\ \theta = \frac{T}{T_0},\ \rho_e^* = \frac{\rho_e}{\varepsilon_0 V/h^2},\ E^* = \frac{E}{V/h},\ x^* = \frac{x}{h},\ y^* = \frac{y}{h},\ \delta_0 = g\rho_1\alpha_T T_0$$

Where the asterisks (*) denote the dimensionless quantities and neglecting *s, we get

$$0 = -\frac{\partial p}{\partial x} + \frac{d^2 u}{dy^2} + 2\Delta \rho_e E_x \tag{3.1}$$

$$0 = -\frac{\partial p}{\partial y} + 2\Delta \rho_e E_y \tag{3.2}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{3.3}$$

$$v_a \frac{\partial \theta_f}{\partial y} = \frac{1}{R_a}\frac{\partial^2 \theta_f}{\partial y^2} + N_f e^{-\Omega_0 y} \tag{3.4}$$

$$0 = \frac{\partial^2 \theta_l}{\partial y^2} \pm N_l e^{-\Omega_0 y} \tag{3.5}$$

$$\rho_e = \gamma_1 \frac{\partial \phi}{\partial y} \tag{3.6}$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \gamma_1 \frac{\partial \phi}{\partial y} = 0 \tag{3.7}$$

$$\left.\begin{array}{l} \phi = x \quad \text{at} \quad y = 0 \\ \varphi = x - x_o \quad \text{at} \quad y = 1 \end{array}\right\} \tag{3.8}$$

$$\left.\begin{array}{l} \dfrac{\partial u}{\partial y} = 0 \quad \text{at} \quad y = 1 \\ -\beta_1 \dfrac{\partial u}{\partial y} = u \quad \text{at} \quad y = 0 \end{array}\right\} \tag{3.9}$$

$$\left.\begin{array}{l} \theta_f = 1 \quad \text{at} \quad y = 0 \\ \dfrac{\partial \theta_f}{\partial y} = -B_i(\theta_f - 1) \quad \text{at} \quad y = 1 \end{array}\right\} \tag{3.10}$$

$$\left.\begin{array}{l} \dfrac{\partial \theta_l}{\partial y} = -B_i(\theta_l - 1) \quad \text{at} \quad y = 1 \\ \dfrac{\partial \theta_l}{\partial y} = 0 \quad \text{as} \quad y \to \infty \end{array}\right\} \tag{3.11}$$

where $\Delta = \dfrac{\varepsilon_e V^2}{\delta_0 h^3}$ electric number, $R_a = \dfrac{\delta_0 h^3}{\kappa \mu_f}$ Rayleigh number, $N_f = \dfrac{I_0 \Omega_0 \mu_f}{\delta_0 h^2 T_0}$ and $N_\ell = \dfrac{I_0 \Omega_0 h}{\kappa T_0} = N_f R_a$ dimensionless laser intensity in regions 1 and 2 respectively, $\Omega_0 = \Omega h$ absorption coefficient, $\beta_1 = \beta_1 / h$ Roughness parameter, B_i = $B_i = \lambda h / \kappa$ Biot number.

Solving eqn.(3.7) using eqn. (3.8), we get

$$\varphi = x - \frac{x_0 \left(1 - e^{-\gamma_1 y}\right)}{1 - e^{-\gamma_1}} \tag{3.12}$$

Solving eqns.(3.1) to (3.3) by assuming $\dfrac{\partial p}{\partial x}$ = constant (i.e., independent of y but function of x) using eqns.(3.9) and (3.12), we get

$$v(1) = \frac{\partial^2 p}{\partial x^2}\left(\frac{1}{3} - \beta_1\right). \tag{3.13}$$

Solutions of eqns.(3.4) and (3.5), using eqns.(3.10) and (3.11), are

$$\theta_f = 1 - a_1\left[e^{-\Omega_0 y} - 1 + a_2\left(1 - e^{cy}\right)\right] \tag{3.14}$$

and

$$\theta_l = 1 + \frac{N_l e^{-\Omega_0 y}}{\Omega_0{}^2} + \frac{N_l e^{-\Omega_0}}{\Omega_0{}^2 B_i}\left(\Omega_0 - B_i\right) \tag{3.15}$$

where $a_1 = \dfrac{N_f R_a}{\Omega_0(\Omega_0 + c)}$, $a_2 = \dfrac{\left(B_i - B_i e^{-\Omega_0} - \Omega_0 e^{-\Omega_0}\right)}{\left(ce^c - \left(1 - e^c\right)B_i\right)}$ $and\ c = v_a R_a$

3.1 Dispersion relation

In this section we obtain the dispersion relation by incorporating the effect of laser radiation to study the stability of the system. The interface conditions are

the kinematic condition $\dfrac{\partial \eta}{\partial t} + u\dfrac{\partial \eta}{\partial x} = \text{v}$ at $y = h$

and for linear theory this takes the form

$$\text{v} = \frac{\partial \eta}{\partial t} \quad \text{at} \quad y = h. \tag{3.16}$$

The dynamic condition is

$$p = -\delta\eta - \gamma\frac{\partial^2 \eta}{\partial x^2} \pm \frac{\varepsilon_e E_x^2}{2}\frac{\eta}{h} \quad \text{at} \quad y = h. \tag{3.17}$$

Eqns.(3.16) and (3.17) are made dimensionless using dimensionless quantities defined earlier and obtain

$$\text{v} = \frac{\partial \eta}{\partial t} \quad \text{at} \quad y = 1 \tag{3.18}$$

$$p = -\left(\theta_{l_1} - \theta_{f_1}\right)\eta - \frac{1}{B}\frac{\partial^2 \eta}{\partial x^2} \pm \Delta\,\eta \qquad \text{at } y = 1 \tag{3.19}$$

where ± on right hand side of eqn. (3.19) will depend on whether the applied voltage is in the direction or opposing the direction of gravity, B = $\dfrac{\delta_0 h^2}{\gamma}$ the Bond number which measures the relative importance of gravitational effect to surface tension γ, $\theta_{f_1} = \theta_f(1)$ and $\theta_{l_1} = \theta_l(1)$. Then eqn. (3.18), using eqns. (3.13) and (3.19), becomes

$$\frac{\partial \eta}{\partial t} = \left[-\left(\theta_{l_1} - \theta_{f_1} \pm \Delta\right) \frac{\partial^2 \eta}{\partial x^2} - \frac{1}{B} \frac{\partial^4 \eta}{\partial x^4} \right] \left(\frac{1}{3} - \beta_1 \right). \tag{3.20}$$

we look for the solution of eqn. (3.20) in the form

$$\eta = \eta_o \, exp \left\{ i \, \ell \, x + nt \right\}. \tag{3.21}$$

From eqn.(3.20), using eqn.(3.21), we get the required dispersion relation

$$n = \ell^2 \left(\theta_{l_1} - \theta_{f_1} - \frac{\ell^2}{B} \pm \Delta \right) \left(\frac{1}{3} - \beta_1 \right). \tag{3.22}$$

RESULTS AND DISCUSSION

Our aim in this paper is to predict the effects of Navier – slip due to rough surface of the boundary, surface tension at the interface, the applied transverse non-uniform electric field and laser radiation on the growth rate n of the RTI. The growth rate n given by eqn. (3.22) can be written as

$$n = n_b - \ell \, \beta \, V_a \tag{4.1}$$

where

$$n_b = \frac{\ell^2}{3} \left(1 - \frac{\ell^2}{B} \right) \tag{4.2}$$

$$V_a = \ell \left(\theta_{l_1} - \theta_{f_1} - \frac{l^2}{B} \pm \Delta \right) \left(\frac{1}{3} - \beta_1 \right) \tag{4.3}$$

$$\beta = \frac{\frac{1}{3}\left(1 - \frac{l^2}{B}\right) - \left(\theta_{l_1} - \theta_{f_1} - \frac{l^2}{B} \pm \Delta \right) \left(\frac{1}{3} - \beta_1 \right)}{\left(\theta_{l_1} - \theta_{f_1} - \frac{l^2}{B} \pm \Delta \right) \left(\frac{1}{3} - \beta_1 \right)}. \tag{4.4}$$

Here n_b the growth rate coincides with the one given by Babchin et. al. [4] in the absence of roughness, laser radiation and applied electric field called classical growth rate, β is a constant and V_a is the normal velocity of the surface. The growth rate given by eqn. (4.1) is numerically computed for different values of ℓ, B, β_1, $\theta_{l_1} - \theta_{f_1}$, and Δ and the results are depicted in figures 2 to 5 and conclusions are drawn below.

Setting n=0 in eqn. (4.1), the cutoff wave number l_{ct} above which RTI mode is stabilized, is found to be

$$\ell_{ct} = \sqrt{B \left(\theta_{l_1} - \theta_{f_1} \pm \Delta \right)} \tag{4.5}$$

The maximum wave number ℓ_m obtained from eqn. (4.1) by setting $\frac{\partial n}{\partial \ell} = 0$ is

$$\ell_m = \sqrt{\frac{B \left(\theta_{l_1} - \theta_{f_1} \pm \Delta \right)}{2}} = \frac{\ell_{ct}}{\sqrt{2}} \tag{4.6}$$

The maximum value of n, namely n_{max}, after using ℓ_m given by eqn.(4.6), is

$$n_{max} = \left(\theta_{l_1} - \theta_{f_1} \pm \Delta \right)^2 \left(\frac{1}{3} - \beta_1 \right) \frac{B}{4} \tag{4.7}$$

From eqn. (4.7), the following three particular cases follow

Case (i) : For $\beta_1 = 0$, $\Delta = 0$, implying absence of roughness of the boundary and electric field, we get the maximum growth rate n_{1max} from eqn. (4.7) in the form

$$n_{1\max} = \frac{B\left(\theta_{l_1} - \theta_{f_1}\right)^2}{12} \tag{4.8}$$

From eqns. (4.7) and (4.8), we get

$$G_{1\max} = \frac{n_{\max}}{n_{1\max}} = \frac{\left(\theta_{l_1} - \theta_{f_1} \pm \Delta\right)^2 \left(1 - 3\beta_1\right)}{\left(\theta_{l_1} - \theta_{f_1}\right)^2} \tag{4.9}$$

Case (ii) : For $\beta_1 = 0$, $\Delta \neq 0$, implying absence of roughness of the boundary and in the presence of electric field, we get, from eqn.(4.7) the maximum growth rate, n_{2max} in the form

$$n_{2\max} = \frac{B}{12}\left(\theta_{l_1} - \theta_{f_1} \pm \Delta\right)^2 \tag{4.10}$$

From eqns.(4.7) and (4.10), we get

$$G_{2max} = \frac{n_{max}}{n_{2max}} = 1 - 3\beta_1 \tag{4.11}$$

Case (iii): Similarly, from eqns.(4.8) and (4.10), we get

$$G_{3\max} = \frac{n_{2\max}}{n_{1\max}} = \frac{\left(\theta_{l_1} - \theta_{f_1} \pm \Delta\right)^2}{\left(\theta_{l_1} - \theta_{f_1}\right)^2} \tag{4.12}$$

To know the behavior of the ratio of growth rates, G_{imax} (i = 1 to 3), it is computed for i = 1 from eqn. (4.9) , i = 2 from eqn. (4.11) and i =3 from eqn. (4.12) and the results are tabulated in the Table 1 and also depicted graphically in figs. (2) to (5) for different values of Δ, B, β_1 and N_l taking negative sign in $\pm\,\Delta$ which means voltage is applied opposing gravity.

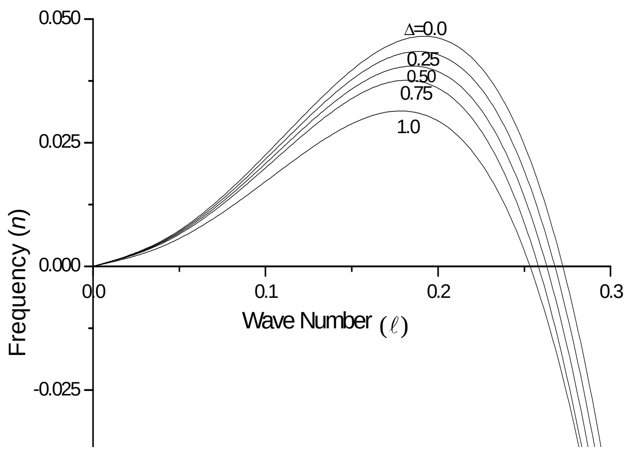

Fig 2: The growth rate *n* versus wave number ℓ for *B = 0.01, β_1 = 0, N_l = 0.01, B_i = 1.3, Ra = 1100, Ω_0=0.001* and for different electric numbers Δ

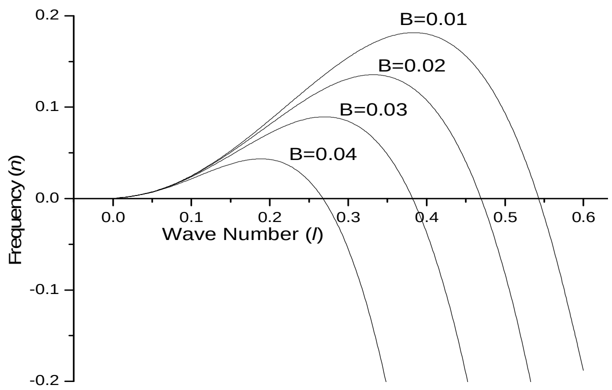

Fig 3: The growth rate *n* versus wave number ℓ for *Δ = 0.25, β_1 = 0, N_l = 0.01, B_i = 1.3, Ra = 1100, Ω_0=0.001* and for different Bond numbers *B*

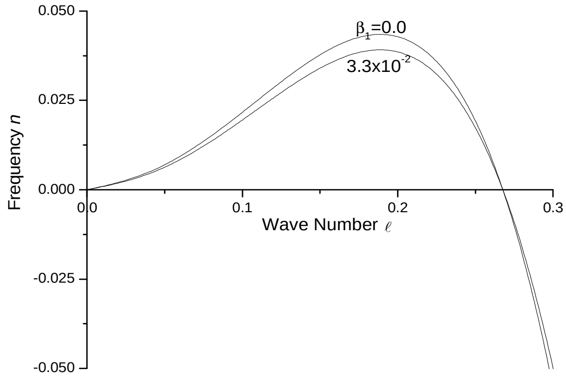

Fig 4:The growth rate *n* versus wave number ℓ for *Δ = 0.25, B = 0.01, N_l = 0.01, B_i = 1.3, Ra = 1100, Ω_0=0.001* and for different roughness parameter β_1

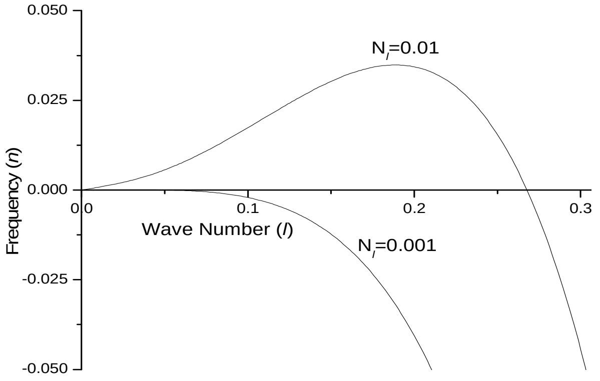

Fig 5: The growth rate *n* versus wave number ℓ for *Δ = 0.25, B = 0.01, β_1= 6.6x10^{-2}, B_i = 1.3, Ra = 1100, Ω_0=0.001* and for different laser intensity N_l

Table 1: Ratio G_{1max} (= n_{max}/n_{1max}) and the percentage of reduction in the maximum growth rate

Δ \ β_1	0	3.3x10^{-2}
0.0	1.00	0.9010
	100 %	**90.10 %**
0.25	0.9359	0.8433
	93.59 %	**84.33 %**
0.50	0.8741	0.7875
	87.41 %	**78.75 %**
0.75	0.8143	0.7337
	81.43 %	**73.37 %**
1.00	0.7566	0.6817
	75.66 %	**68.17 %**

Table 2: Comparison of our results with the existing literature

Authors	G_m	Percentage of reduction
Takabe et. al. (1985)	0.45	45% (for compressible fluid)
Rudraiah (2003 a)	0.79	79% (α_p = 0.1, σ_p = 0.1) (for porous lining)
Rudraiah et. al. (2004) (for MHD)	0.9960	99.60% for M = 10^{-1}
	0.7152	71.52 % for M = 10^{0}
	0.027	2.7 % for M = 10^{1}
	0.0003	0.03 % for M = 10^{2}
Rudraiah et. al. (2007)	Table 3	(for EHD)
Present paper	Table 1	(for EHD)

Table 3: % of reduction of growth rate

Δ \ β_1	**0**	**3.3×10^{-6}**	**3.3×10^{-5}**	**3.3×10^{-4}**	**3.3×10^{-3}**
0	100	99.999	99.9901	99.901	99.01
0.25	56.25	56.25	56.24	56.19	55.69
0.50	25	24.9998	24.9975	24.975	24.7525
0.75	6.25	6.2499	6.2494	6.2438	6.188
1.0	0	0	0	0	0

Figure 2 depicts the effect of applied transverse electric field in the direction opposing gravity represented by $\Delta = 0$ to 1.0 for fixed values of *B* = 0.01 ,R_a = 1100, B_i = 1.3, Ω_0 = 0.001, N_l = 0.01 and $\beta_1 = 0$. This figure reveals that an increase in *Δ* decreases the growth rate of RTI. From this we conclude that the effect of applied electric field is to reduce the growth rate, and hence makes the interface stable.

Figure 3 reveals the effect of varying surface tension represented by *B* = 0.01 to 0.04 for fixed values of *Δ* = 0.25, R_a = 1100, B_i = 1.3, Ω_0 = 0.001, N_l = 0.01 and β_1=0. It shows that a decrease in *B* implying an increase in surface tension (because B is the reciprocal of surface tension γ) decreases the growth rate of RTI. This implies that the increase in surface tension makes the interface more stable as expected on physical grounds.

Figure 4 shows the effect of varying roughness coefficient $\beta_1 = 0$, $3.3\text{x}10^{-2}$ for fixed values of $B = 0\ .01$, $\Delta = 0.25$, $R_a = 1100$, $B_i = 1.3$, $\Omega_0 = 0.001$ and $N_l = 0.01$. This figure reveals that an increase in roughness decreases the growth rate of the RTI. Hence, the effect of increase in roughness makes the interface stable.

Figure 5 shows that an increase in laser intensity N_l= 0.001, 0.01 for the fixed values of $B = 0\ .01$, $\Delta = 0.25$, $R_a = 1100$, $B_i = 1.3$, $\Omega_0 = 0.001$ and $\beta_1 = 6.6\text{x}10^{-2}$, increases the growth rate of RTI and hence makes the system unstable because an increase in laser intensity increases the energy. From figures 2 – 5 we note that all the three modes of instability namely stable, neutrally stable and unstable modes are possible for certain values of the parameters in the dispersion relation given by eqn. (4.1).

From Table 1 for $\Delta = 0.75$ and $\beta_1 = 3.3\text{x}10^{-2}$, we find $G_m = 0.7337$ that is the maximum growth rate is reduced to 73.37% of the classical value. Also, $G_m = 0.8741$ for $\Delta = 0.5$ and $\beta_1 = 0$, so that the maximum growth rate is reduced to 87.41% of the classical value. Therefore, Table 1 gives the amount of reduction in the maximum growth rate for different values of Δ and $\beta_{1.}$ Table 2 gives the amount reduction in maximum growth rate compared to those exist in the literature.

CONCLUSION

Finally, we conclude that with a proper choice of the strength of applied voltage, laser intensity and suitable roughness of the rigid surface in the film, it is possible to reduce the growth rate of the RTI. This is useful in efficient extraction of IFE by maintaining the symmetry of the target and also favorable to reduce the side effects like haemolysis in biomedical engineering problems.

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