Effect of Electromagnetic field on Rayleigh-Taylor instability in a power-law fluid in presence of boundary roughness

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Abstract: In the present study, the linear analysis of electrodynamic Rayleigh-Taylor instability (ERTI) in a thin layer of an incompressible two fluids with a poor conducting fluid confined above by an interface with heavier fluid and below with a rigid boundary subjected to boundary roughness is analyzed. A dispersion that accounts for the growth rate is derived using the approximations defined by Rudraiah et al. [1996] and stability is discussed theoretically as well as numerically. The influence of the combined effect of electromagnetic fields, surface tension, power-law fluid, boundary roughness and layer thickness on the ERTI is investigated and shown graphically for above various physical parameters on the stability of the system. It is observed that electric field, magnetic field, power-law fluid, porous parameter and boundary roughness have stabilizing effect on the system whereas Bond number and layer thickness destabilizes the interface.

Keywords: ERTI, Power-law fluid, porous layer, magnetic field, boundary roughness

1. Introduction

The problem of interfacial stability of superposed fluids has been investigated since the turn of the century by Rayleigh[1], Taylor[2] and Lewis[3]. A boundary between fluids with density difference is unsteady whenever there is external acceleration and density gradient are in the reverse direction. This phenomenon is illustrated as the Rayleigh-Taylor instability (RTI). The instability plays a vital role in many areas, namely plasmas [4], astrophysics [5], inertial confinement fusion [6], and many more.

This instability has attracted considerable interest both theoretically (see Chandrasekhar [7] and Sharp [8]) and experimentally (see Kull[9]) because of the importance of understanding the control and exploitation of many of the basic physical, chemical
and biological processes. The non-linear RT instability in a thin Newtonian fluid film when the wavelength is much higher than the film thickness was Babchin et al.[10]. Later, Brown[11] relaxed this assumption on the wavelength and studied the RT instability in a finite thin layer of a viscous fluid using the combined Stokes and lubrication approximations[10]. Rudraiah et al.[12] have extended the work of Brown[11] to include the viscosity stratification and oblique magnetic fields effect in Newtonian fluids. The above mentioned are mainly concerned with Newtonian fluid. Further, Rudraiah et. al,[13] studied the RTI of finite thickness layer of a non-Newtonian fluid. They concluded that the nature of the dispersion curve is influenced by both the reciprocal of the characteristic length and the non-Newtonian parameter, while film thickness just affects the nature of the growth rate of RTI. However, there has been less attention is paid to non-Newtonian fluid. Ram and Sharma[14] have studied the effect of magnetic field-dependent viscosity (MFD) along with porosity on the revolving Axi-symmetric steady ferrofluid flow with rotating disk by solving the boundary layer equations using Neur-inger-Rosensweig (NR) model. The work of Ram and Sharma[15] deals with the theoretical investigation of the effect of Magnetic Field-Dependent (MFD) viscosity on the revolving axi-symmetric steady laminar flow of viscous incompressible electrically non-conducting ferrofluid with rotating disk by solving the boundary layer equations. An attempt has been made by Ram et al [16] to describe the effects of geothermal viscosity with viscous dissipation on the three dimensional time dependent boundary layer flow of magnetic nanofluids due to a stretchable rotating plate in the presence of a porous medium.

Rudraiah et al[17] deliberated the electrorheological RTI at interface of thin shell and porous media with poor conducting couple-stress fluid. At the interface of superposed couple-stress Casson fluids flow, Agoor and Eldabe[18] presented the RTI in a porous medium under the influence of a magnetic field. Awasthi and Srinivastava[19] discussed using linear stability analysis of the interface between two viscous and dielectric fluids in the presence of a tangential electric field has been analyzed when there are a heat and mass transfer across the boundary. Garai et al[20] examined the RTI stabilization in a non-Newtonian unmagnetized dusty plasma with an experimentally tested model of shear flow rate dependent viscosity. It has been established, that non-Newtonian property also has an important role in RTI stabilization besides velocity shear stabilization in the short wavelength regime. The consequence of non-Newtonian parameters is more intense in the higher velocity shear rate system. The presence of an electric field may change the fluid behavior and its flow. The study of effects resulting from electric fields on fluid flows is called electrohydrodynamics(EHD). The impact of electric field on the stability of two fluid systems is one of the important problems in electrohydrodynamics. The discontinuity of the electric properties of the fluid across the interface effects the force balance at the fluid-fluid saturated porous layer interface, which may either stabilize or destabilize the interface. The study of electrohydrodynamic Rayleigh-Taylor instability of two inviscid fluids in the presence of tangential electric field was considered by Eldabe[21]. He found that the tangential electric field has stabilizing effect.
The influence of electric field on RTI in a non-Newtonian fluid-layer is studied by Rudraiah et al[22]. Doludenko et al[23] concerned with the study of RTI in pseudo-plastic fluids. Based on the basic properties of the shear-thinning liquids and the Atwood number, their work envisages that a direct 3-dimensional numerical simulation of the mixing of two media with several rheologies and conquer the width of the mixing layer and kinetic energy spectra. Recently, Chavaraddi et al[24] have analyzed influence of a magnetic field on RTI in a couple-stress fluid.

Through in view of various applications and keeping in mind the importance of non-Newtonian fluids also known as power-law fluid in modern technology and industries, the influence of magnetic field and electric field on RTI in a poor conducting power-law fluid confined above by a porous layer and below by rigid surface is investigated by Chavaraddi et al[25] very recently using the approximations defined by Rudraiah et al[11]. The present paper is extension of this work in presence of boundary roughness at the rigid surface. These approximations streamline the power law equation and pave the way to obtain the solution analytically for velocity distribution. This solution is used in Eq.(3.11) found subjected to constraints (3.1-3.4). The overall objective of this study is to observe stability and instability variations by altering the direction of magnetic field and electric field with reference to boundary roughness. Also, the effects of porosity, electromagnetic fields surface tension, boundary roughness and viscosity on ERTI are discussed. The condition of stability, instability as well as the growth rate is thoroughly analyzed by varying these parameters.

2. Mathematical Model

In a physical configuration, a system of two-dimensional medium of width $h$ consisting of different fluid layers of finite thickness separated by a plane interface $y=h$ is considered, as demonstrated in Figure 1. The external force $g$ in the opposite direction of $y$. The less dense fluid($\rho$) occupies the lower region, having thickness $h$, density, $\rho_f$, viscosity($\mu$) and is bounded by the rigid plane surface while the upper(heavy dense) fluid occupies the outer region, having thickness, density($\rho_p$), viscosity($\mu_p$)
and is bounded by the rigid plane surface. The density of lower fluid is lighter than the density of upper fluid \((\rho_p > \rho_f)\). This composite system comprises two incompressible power-law fluid and fluid-saturated porous layer separated by plane \(y=h\). Due to gravity, resultant acceleration is upper fluid (positive y-direction) and hence lighter fluid pushes the denser fluid. As long as the interface between fluids remains uniform, i.e., entirely horizontal and vertical to the resultant acceleration, the lighter (power-law) fluid enough pressurize to control the dense fluid in opposition to the ceiling. Nonetheless, to study the stability of the system small perturbations are imposed on the equilibrium state. When asymmetry takes place, the segments of the interface lie higher than normal, hence experience additional force from less dense fluid as it is essential to support for which interface remains to raise in the spots. In the parts where the interface let fall by tiny quantities below the normal, more stress is required to support. Further, even the instability is caused by the slightest perturbations. If the pressure gradient is reversed i.e., heavier fluid is on the floor supporting the lighter fluid, then the parts of the interface have risen, the dense fluid will lower back to normal while lowered portions will rise again. This qualitative study gives rise to a revealing statement that the system is steady if the heavy fluid pushes the lighter fluid and unsteady if the lighter fluid thrust the heavy fluid. In the present study(analysis), the fluids are taken as irrotational and incompressible.

Then the governing equations for non-Newtonian fluid with poor electrical conductivity for a thin film considered is given by (See Rudraiah and Kaloni[26]):

\[
\nabla \cdot \vec{q} = 0 \tag{2.1}
\]

\[
\rho \frac{D\vec{q}}{Dt} = -\nabla p + \nabla \cdot \vec{\tau} + \rho_e \vec{E} + \mu_0 (\vec{J} \times \vec{H}) \tag{2.2}
\]

\[
\frac{\partial \rho_e}{\partial t} + (\vec{q} \cdot \nabla) \rho_e + \nabla \cdot \vec{J} = 0 \tag{2.3}
\]

Maxwell’s equations

\[
\nabla \cdot \vec{E} = \frac{\rho_e}{\varepsilon_e}, \nabla \times \vec{E} = 0 \quad \text{or} \quad \vec{E} = -\nabla \phi, \vec{J} = \sigma \vec{E}, \sigma = \sigma_0 \left[1 + \alpha_h (C - C_0) \right] \tag{2.4}
\]

Where \(\vec{q} = (u, v)\) velocity, \(\vec{E}\) electric field, \(\vec{J}\) current density, \(\phi\) electric potential, \(\rho\) fluid density, \(p\) pressure, \(\rho_e\) is density of charges, \(\varepsilon_e\) is dielectric constant, \(C\) is concentration, and \(\sigma\) is electrical conductivity, \(\sigma_0\) the electrical conductivity with reference to concentration \(C_0\), \(\alpha_h\) is the volumetric expansion coefficient of \(\sigma\), \(\mu_0\) fluid viscosity and stress tensor \(\vec{\tau}_i\) expressed as
\[ \tau_i = k_i \left( \frac{1}{2} \left( \frac{1}{2} \gamma_j : \gamma_j \right) \right)^{n-1} \gamma_j . \]  

(2.5)

Here \( k_i \) is the consistency index and \( \gamma \) is the rate of strain given by

\[ \dot{\gamma}_{i,j} = \left( \frac{\partial q_i}{\partial x_j} + \frac{\partial q_j}{\partial x_i} \right) \dot{\gamma} . \]  

(2.6)

The \( \sigma \) differs from concentration \( C \) of deuterium-tritium as in Eq. (2.3). By considering minor advection of concentration, we will have

\[ \frac{d^2 C}{dy^2} = 0 \]  

(2.7)

with

\[ C = C_0 \quad \text{about} \quad y = 0 \]  

(2.8a)

\[ C = C_1 \quad \text{about} \quad y = h. \]  

(2.8b)

Solving Eq. (2.7) employ the given constraint’s and this solution in Eq.(2.4d), we obtain

\[ \sigma = \sigma_0 \left[ 1 + \alpha y \right] \approx \sigma_0 e^{\alpha y} \]  

(2.9)

where \( \alpha = \alpha_h \Delta C / h \) and \( \Delta C = C_1 - C_0 \). Suppose corresponding relaxation frequency of the electric field is more than the frequency of charge distribution, thus the time derivative \( \rho_e \) is less than \( \nabla \cdot (\sigma E) \) in Eq. (2.3), which leads to

\[ \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \alpha \frac{\partial \phi}{\partial y} = 0 . \]  

(2.10)

This equation has to be solved by employing conditions

\[ \phi = \frac{v_0 x}{h} \quad \text{at} \quad y = 0 \]  

(2.11)

\[ \phi = v_0 \left( \frac{x - x_0}{h} \right) \quad \text{at} \quad y = h \]  

(2.12)

These conditions appear because of embedded electrodes about \( y = 0 \) with \( y = h \) and permit a linear variation of \( \phi \) and \( x \).
By using Stokes and lubrication approximations[10], presuming the dense fluid in the porous lining is almost stationary due to creeping flow approximation, which leads the basic equations in the thin film region in the following form:

$$0 = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \quad (2.13)$$

$$0 = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial y} \left( k \left| \frac{\partial u}{\partial y} \right|^{n-1} \frac{\partial u}{\partial y} \right) + \mu \sigma_f H_0^2 u + \rho_e E_x \quad (2.14)$$

$$0 = -\frac{\partial p}{\partial x} + \rho_e E_y \quad . \quad (2.15)$$

For fully developed flow, Eq. (2.10) becomes

$$\frac{\partial^2 \phi}{\partial y^2} + \alpha \frac{\partial \phi}{\partial y} = 0 \quad . \quad (2.16)$$

The solution of this equation using the boundary conditions (2.11) and (2.12) is

$$\phi = \frac{v}{h} \left[ x - \frac{x_0}{1 - e^{-\alpha y}} (1 - e^{-\alpha y}) \right] \quad . \quad (2.17)$$

Equations (2.4a), using Eq.(2.17), reduces to

$$\rho_e = -\frac{v x_0 \alpha^2 e^{-\alpha y}}{h \left( 1 - e^{-\alpha h} \right)} \quad (2.18)$$

and hence

$$\rho_e E_x = -\rho_e \frac{\partial \phi}{\partial x} = \frac{v^2}{h^2} x_0 \alpha^2 e^{-\alpha y} \quad . \quad (2.19)$$

3. Dispersion Relation

To compute a dispersion relation, initially determine the velocity distribution beginning with Equation (2.14) work with the succeeding boundary and surface conditions are

$$-\beta \frac{\partial u}{\partial y} = u \quad \text{at} \quad y = 0 \quad (3.1)$$

$$\frac{\partial u}{\partial y} = -\frac{\alpha_p u}{\sqrt{k}} \quad \text{at} \quad y = h \quad (3.2)$$
\[ v = \frac{\partial \eta}{\partial t} \text{ at } y = h \quad (3.3) \]

\[ p = -\delta \eta - \gamma \frac{\partial^2 \eta}{\partial x^2} \pm \varepsilon_0 \frac{E^2 \eta}{h} \text{ at } y = h. \quad (3.4) \]

where \( \eta = \eta(x, y, t) \) is the height of the interface. The from equation (2.14) with respect to the above constraints we get

\[ u = C_1 \cos \theta y + C_2 \sin \theta y + \frac{1}{M^2 k_1 b(n)} \frac{\partial p}{\partial x} - \frac{\nu}{\alpha^2 + M^2} \frac{\partial^2 \eta}{\partial x^2} + \frac{\alpha^2 e^{-\alpha y}}{h} \quad (3.5) \]

where

\[ C_1 = - \frac{1}{M^2 k_1 b(n)} \frac{\partial p}{\partial x} + \frac{\nu}{\alpha^2 + M^2} \frac{\partial^2 \eta}{\partial x^2} \quad (3.6) \]

\[ C_2 = \frac{1}{(M \cos \theta y - \alpha \sin \theta y) - \sin \theta y (M \alpha^2 + \alpha \sigma p)} \left\{ \frac{1}{M^2 k_1 b(n)} \frac{\partial p}{\partial x} + \frac{\nu}{\alpha^2 + M^2} \frac{\partial^2 \eta}{\partial x^2} \right\} \quad (3.7) \]

To find the growth rate \( \omega \), we assume the solution of Eq.(3.7) in the following form \( \eta = \eta(y) e^{i\xi x + \omega t} \quad (3.8) \)

Here, wavenumber is \( \xi \) with amplitude of perturbation of the interface is \( \eta(y) \).
Exchanging Eq.(3.8) into (3.7), we get the following dispersion relation

\[
\omega = \frac{1}{M^3 k_1 b(n)} \left[ \frac{1 - \beta M (\alpha \sigma_p p (\cos \theta + 1) - M \sin \theta)}{M \cos \theta (\beta \alpha \sigma_p p - 1) - \sin \theta (\beta M^2 + \alpha \sigma_p p)} \right] \sin \theta
\]

\[
\left( 1 - \left( \frac{\delta + \varepsilon v^2}{h^2} \right) \left( \frac{1}{B} \right) \Delta_1 \right)
\]

Making Eq.(3.9) dimensionless using the quantities

\[
\omega^* = \frac{\omega k_1}{\sqrt{\gamma \delta}}, \quad h^* = \frac{h}{\sqrt{\gamma / \delta}}, \quad \ell^* = \ell \sqrt{\gamma / \delta}, \quad v^* = \frac{v}{h}, \quad M^* = M h, \quad \sigma_p^* = \frac{\sigma_p}{h}
\]

we obtain

\[
\omega = \ell^2 \left( 1 \pm \frac{1}{B} \right) \Delta_1
\]

where

\[
\Delta_1 = -\frac{h^3}{M^3 k_1 b(n)} \left[ \frac{1 - \beta M (\alpha \sigma_p p (\cos \theta + 1) - M \sin \theta)}{M \cos \theta (\beta \alpha \sigma_p p - 1) - \sin \theta (\beta M^2 + \alpha \sigma_p p)} \right] \sin \theta
\]

\[
\left( 1 - \left( \frac{\delta + \varepsilon v^2}{h^2} \right) \left( \frac{1}{B} \right) \Delta_1 \right)
\]

We = \varepsilon v^2 / \delta h^3 denotes electric parameter, \( M = \frac{\mu k_1 H_0^2}{b(m)} \) the Hartmann number

\( b(m) \) is a fitting constant, and \( B = \delta \alpha^2 / \gamma \) is the Bond number. The positive or negative sign in front of \( We \) in the above equation will depend, on whether the potential difference is along or opposing the gravity. Since the potential difference is opposing the gravity, we have chosen the negative sign and Eq. (3.11) takes the form

\[
\omega = \ell^2 \left( 1 - \frac{1}{B} \right) \Delta_1
\]

The fitting constant \( b(m) \) should be chosen in such a way that \( b(1) = 1 \). Thus, we consider the following cases for discussion

Case (i) : \( b(m) = \frac{m + 1}{2} \).

Case (ii) : \( b(m) = \frac{1}{2} + \frac{m}{4} + \frac{m^2}{4} \).
In the present work, we have discussed only case(i). The dispersion relation (3.12) is
work on for dissimilar values of \( m, h, We, M, B, \beta \) and \( \sigma_p \) suitable for shear thinning
and shear thickening flows and the results are shown in Figures 2-7 for case(i).

4. Results and Discussion

In this section, the numerical computation has been carried out using expressions
presented in dimensionless Eq.(3.12). Here we have discussed only case(i) approximations for fitting constants \( b(m) \) among cases(i) and (ii). The numerically evaluated
the dispersion relation (3.12) for different values of power-law index \( m \), film thickness \( h \), electric parameter \( We \), Hartmann number \( M \), Bond number, \( B \), and porous
parameter, \( \sigma_p \), roughness parameter, \( \beta \) and the results are depicted in Figures 2-8.
We found that the nature of the dispersion is influenced by both the reciprocal of the
characteristic length \( \gamma / \delta \) and the non-Newtonian index parameter \( m \). That is an in-
crease in the power-law index \( n \) decreases the growth rate as shown in Figure 2 for the
case(i). Figure 3 depicts the film thickness \( h \) affecting the nature of the growth
rate of instability in the sense that an increase in the film thickness parameter \( h \) in-
creases the growth rate. The \( \omega \) in Eq. (3.12) is evaluated on for various values of an
electric parameter, \( We \), and the results are represented graphically in Fig. 4. It is clear
that the growth rate reduces as compared to classical results is very sharp for \( We \) in
the span of 0.5 to 1.0.
Figure 5 illustrate the effect of the magnetic field on the instability for different ratios of
Hartmann number in keeping other parameters as constant. In other words, the
ERTI can be suppressed by the magnetic field, and thereby increasing the Hartmann
ratio results in slightly increasing the critical wave number and decreasing the maxi-
mum expansion rate. We have noticed that the magnetic field has a stabilize the RT
instability for the selected values of input parameters due to the increased Hartmann
ratio (Lorentz force to viscous force).

Figure 6 represents \( \omega \) versus \( \ell \) for values of the Bond number \( B \) from .01 to 0.04
using relation(3.12). From our results, it is clear that the instability between fluids having \( \ell \) slighter than the critical wavenumber \( \ell_{ct} \) are amplified when \( We>0 \), and the
instability reduces with a decrease in \( B \). This implies a rise in the surface tension since \( B \) is the reciprocal of it. Further, it is found that an increase in surface tension de-
creases the growth rate and accordingly makes the system more stable. Therefore,
small Bond number refers to the situation in which the surface tension force is ba-
anced by the gravity force.

The variation of wavenumber \( \ell \) with respect to frequency, \( n \) for different values po-
rous parameter, \( \sigma_p \) is shown in Figure 7. It is also observed that, as the porous pa-

ter, \( \sigma_p \) increases, the stable region increases, which depicts that the porous pa-
rameter phenomenon is stabilizing the classically unstable system and the growth rate can be greatly reduced.

In Figure 8, stability curves for growth rate, $n$ for different values of roughness parameter, $\beta$ have been drawn when fixed other physical parameters. It has been observed that stable region increases as boundary roughness increases. Hence it is concluded that boundary roughness has stabilizing effect on the stability of the system.

5. Conclusion

We have studied the effect of electromagnetic fields in power-law fluid subject to the boundary roughness at the rigid surface. The dispersion relation is obtained which is terms of wavenumber and frequency, $n$ with reference to all above said physical parameters in growth rate. The system is stable when the electric and magnetic fields are increases. The magnetic and electric fields were found to have a significant effect that decreases the growth rate of Rayleigh Taylor instability. It is observed that the physical parameters namely Hartmann number, electric parameter, power-law index, roughness parameter and porous parameter have stabilized the system whereas fluid film thickness and a Bond number have destabilized the system.

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Variation of power-law index $m$ for $h = 5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $M = 5$, $\beta = 0.33$, $We = 0.25$ and $B = 0.02$.

Figure 2: Variation of power-law index $m$

Variation of film thickness $h$ for $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $M = 5$, $\beta = 0.33$, $We = 0.25$ and $B = 0.02$.

Figure 3: Variation of film thickness $h$ for $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $M = 5$, $\beta = 0.33$, $We = 0.25$ and $B = 0.02$.

Varied the electric parameter $We$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $M = 5$, $\beta = 0.33$ and $B = 0.02$.

Figure 4: Varied the electric parameter $We$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $M = 5$, $\beta = 0.33$ and $B = 0.02$.

Effect of Hartmann number $M$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $We = 0.25$, $\beta = 0.33$ and $B = 0.02$.

Figure 5: Effect of Hartmann number $M$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $We = 0.25$, $\beta = 0.33$ and $B = 0.02$.

Influence of Bond number $B$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $We = 0.25$, $\beta = 0.33$ and $M = 5$.

Figure 6: Influence of Bond number $B$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $\sigma_p = 4.0$, $We = 0.25$, $\beta = 0.33$ and $M = 5$.

Different values of porous parameter $\sigma_p$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $B = 0.02$, $We = 0.25$, $\beta = 0.33$ and $M = 5$.

Figure 7: Different values of porous parameter $\sigma_p$ with $h = 5$, $m = 0.5$, $\alpha = 0.1$, $B = 0.02$, $We = 0.25$, $\beta = 0.33$ and $M = 5$. 
Figure 8: Varied the roughness parameter, $\beta$
with $h = 5, m = 0.5, \alpha_p = 0.1, B = 0.0, 2, We = 0.25, \sigma_p = 4.0$ and $M = 5$. 