Indian J. pure appl. Math., **35**(7) : 905-913, July 2004

STABILITY OF TWO SUPERPOSED VISCO-ELASTIC (MAXWELL) FLUIDS IN A VERTICAL MAGNETIC FIELD

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(*Received* 16 *April* 2002; *after final revision* 11 *March* 2003; *accepted* 19 *April* 2004)

The instability of the plane interface separating two superposed visco-elastic (Maxwell) conducting fluids in a uniform vertical magnetic field has been investigated. Upon application of normal mode technique, the dispersion equation is obtained. The equation is solved numerically and it is found that both viscosity and visco-elasticity of fluid have stabilizing influence while permeability of porous medium has mostly destabilizing effect on the growth rate of unstable mode of disturbance.

Key Words: Rayleigh-Taylor Instability; Visco-elastic fluid; Porous Medium; Superposed Fluids

1. INTRODUCTION

The account of instability at the plane interface separating two fluids when the lighter one is accelerated towards the heavier has been studied by several authors. A good contribution in this field is due to Chandrasekhar[1]. He studied the effect of vertical magnetic field on the Rayleigh-Taylor instability arising at the plane interface between two fluids. Other investigators, namely Ariel[2], Wobig[3], Srivastava[4] and Bhakta[5] have also investigated Rayleigh-Taylor instability under various operative conditions such as Coriolis force, Hall current and resistivity. Among relevant investigations on the Rayleigh-Taylor instability of superposed fluids, we may refer to the papers of Bhatia and Chhonkar[6], Obied-Allah[7], Bhatia and Sharma[8], Daval Osorozco[9] and others[8-11]. The authors have discussed the instabilities due to superposed viscous fluids under various operative forces such as rational force, finite Larmor radius (FLR) and magnetic field. The flow through porous medium is of considerable interest to geophysicists and engineers in recent years in view of its importance in the rocks and heavy oil recovery. We also refer to the relevant papers on stability of superposed viscous and viscoelastic fluids through porous medium, namely Khan and Bhatia[2], Ali and Bhatia[3], Chin[14], El-Sayeed[15], Sharma and Sharma[16] and others[17-19]. The presence or absence of magnetic field and suspended particles in the medium are also considered in the investigations.

Since, viscoelastic fluids play a significant role in industrial application, it would be of much interest to examine the stability condition for two superposed viscoelastic fluids with suspended particles in porous medium. With this motivation, we discuss the Rayleigh Taylor instability of two visco-elastic (Maxwell) superposed conducting fluids in porous medium. The fluids are permeated by vertical magnetic field. The effect of surface tension at the plane interface between two fluids has also been taken into account. We have carried out the stability analysis for two fluids of different viscosities and different densities.

PERTURBATION EQUATIONS

We consider the motion of an infinitely conducting visco-elastic Maxwell fluid (of variable viscosity) through a porous medium. The fluid is assumed to be immersed in a uniform vertical magnetic field $\vec{H} = (0, 0, H_0)$.

The constitutive equation for Maxwell visco-elastic fluid is given by

$$T_{ij} = -p\delta_{ij} + \tau'_{ij} \quad \text{... (1)}$$

$$\left[1 + \lambda\frac{\partial}{\partial t}\right]\tau_{ij} = 2\mu e_{ij} \quad \text{... (2)}$$

$$e_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad \text{... (3)}$$

where T_{ij} is the stress tnesor, τ'_{ij} is the deviatoric stress tensor, e_{ij} the rate of strain tensor, p the pressure, λ the stress relaxation time parameter, μ the coefficient of viscosity and u, the velocity components.

The linearised perturbation equation relevant to the problem is

$$\frac{\rho}{\varepsilon}\left(1 + \lambda\frac{\partial}{\partial t}\right)\frac{\partial \vec{u}}{\partial t} = -\left(1 + \lambda\frac{\partial}{\partial t}\right)\vec{\nabla}\delta p + \left(1 + \lambda\frac{\partial}{\partial t}\right)$$

$$\vec{g}\,\delta p + \left(1 + \lambda\frac{\partial}{\partial t}\right)(\vec{\nabla}\times\vec{h})\times\vec{H} + \frac{1}{\varepsilon}[(\vec{\nabla}\mu\vec{\nabla})\vec{u} + \vec{\nabla}\,\vec{u}.\,\vec{\nabla}\,\vec{u}]$$

$$+\frac{\mu}{\varepsilon}\vec{\nabla}^2\vec{u} - \frac{\mu}{\lambda}\vec{u} + \sum\left[T_s\left(1 + \lambda\frac{\partial}{\partial t}\right)\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right]\delta zs\right]\delta(z - z_s) \quad \text{... (4)}$$

$$\varepsilon\frac{\partial \vec{h}}{\partial t} = \vec{\nabla}\times(\vec{u}\times\vec{H}) \quad \text{... (5)}$$

$$\varepsilon\frac{\partial}{\partial t}\partial\rho + (\vec{u}.\,\vec{\nabla})\rho = 0 \quad \text{... (6)}$$

$$\varepsilon\frac{\partial}{\partial t}(z_s) = w_s \quad \text{... (7)}$$

$$\vec{\nabla}.\,\vec{u} = 0 \quad \text{... (8)}$$

$$\vec{\nabla}.\,\vec{h} = 0 \quad \text{... (9)}$$

where $\vec{u} = (u, v, w)$, $\vec{h} = (h_x, h_y, h_z)$. $\delta\rho$ and δp are respectively the perturbations in Darcian velocity, magnetic field $\vec{H}$, density ρ and pressure p; T, $\mu(z)$, $\vec{g} = (0, 0, -g)$ and ε are respectively the surface tension, variable coefficient of viscosity, acceleration due to gravity and medium porosity. Also, in eq. (4), $\hat{\lambda}$, $\delta(z - z_s)$ and λ denote permeability of the porous medium. Dirac's δ-function and viscoelastic parameter respectively.

DISPERSION EQUATION

Analyzing the disturbances in terms of normal modes, we seek solutions assuming the perturbed quantities have the space (x, y, z) and time (t) dependence of the form

$$F(z)\, e^{(ik_x x + ik_y y + nt)} \qquad \ldots (10)$$

where $F(z)$ is some function of z; k_x, k_y are the horizontal wave number $\left(k^2 = k_x^2 + k_y^2\right)$ and n is the growth rate of harmonic disturbance.

Upon using expression (10) in eqs. (4) to (9) and eliminating some of the variables, we finally obtain an equation in w

$$(1+\lambda n)\left[-\frac{n}{\varepsilon}D(\rho Dw) + \frac{n}{\varepsilon}\rho k^2 w + k^2 g\delta\rho + \frac{H_0^2}{\varepsilon n}(D^2-k^2)D^2 w\right]$$

$$+\frac{1}{\varepsilon}D^2\mu(D^2+k^2)w$$

$$+\frac{k^4 T}{n}\delta(z-z_s)w + \frac{1}{\hat{\lambda}}\left[\mu w k^2 - D(\mu D w)\right]$$

$$+\frac{\mu}{\varepsilon}(D^2-k^2)^2 w + \frac{2}{\varepsilon}(D\mu)(D^2-k^2)Dw = 0 \qquad \ldots (11)$$

where $\qquad D = \frac{d}{dz}.$

TWO SUPERPOSED VISCO-ELASTIC MAXWELL FLUIDS OF UNIFORM DENSITIES

We consider now the situation when two superposed electrically conducting viscoelastic Maxwell fluids of uniform densities ρ_1 and ρ_2 and uniform viscosities μ_1 and μ_2 are separated by the horizontal plane boundary $z = 0$ and the fluids with densities ρ_1 and ρ_2 occupy the regions $z < 0$ and $z > 0$ respectively. With the aforesaid assumption, the stability eq. (11) takes the form

$$(D^2-k^2)\left[-(1+\lambda n)\frac{n\rho w}{\varepsilon} + (1+\lambda n)\frac{H_0^2}{\varepsilon n}D^2 w - \frac{1}{\hat{\lambda}}\mu w + \frac{\mu}{\varepsilon}(D^2-k^2)w\right] = 0. \qquad \ldots (12)$$

For both the regions, eq. (12) reduces to the form

$$(D^2-k^2)(D^2-M^2)w = 0 \qquad \ldots (13)$$

where

$$M^2 = \frac{(1+\lambda n)\frac{n\rho}{\varepsilon} + \frac{1}{\hat{\lambda}}\mu + \frac{\mu k^2}{\varepsilon}}{(1+\lambda n)\frac{H_0^2}{\varepsilon n} + \frac{\mu}{\varepsilon}} \qquad \ldots (14)$$

The general solution of eq. (13) is $w = P_1 e^{kz} + P_2 e^{-kz} + Q_1 e^{Mz} + Q_2 e^{-Mz}$. Since, for the lower fluid $z \rightarrow -\infty$ and for the upper fluid $z \rightarrow \infty$ and w must vanish at both the ends, the solutions appropriate to the two regions are

$$w = P_1 e^{kx} + Q_1 e^{M_1 z}, \quad z < 0 \qquad \text{... (15)}$$

$$P_2 e^{-kz} - Q_2 e^{-M_2 z}, \quad z > 0 \qquad \text{... (16)}$$

where P_1, P_2, Q_1, Q_2 are constants and M_1, M_2 are positive square roots of (14) for the two regions. In writing the solutions (15) and (16), it is assumed that M_1 and M_2 are so defined that their real parts are positive.

We are to utilise the boundary conditions for determining the four constants P_1, P_2, Q_1 and Q_2. The conditions require that at the interface $z = 0$,

$$w, Dw \text{ and } \mu (D^2 + k^2) w \qquad \text{... (17}a,b,c\text{)}$$

must be continuous (Chandrasekhar[1]).

In order to obtain fourth condition, we integrate eq. (20) across $z = 0$ and obtain the relation

$$\left[(1 + \lambda n) \left\{ \rho_2 n D w_2 - \frac{H_2^2}{n} (D^2 - k^2) D w_2 \right\} - \mu_2 (D^2 - k^2) D w_2 + \frac{\mu_2 \varepsilon}{\hat{\lambda}} D w_2 \right]_{z=0}$$

$$- \left[(1 + \lambda n) \left\{ \rho_1 n D w_1 - \frac{H_1^2}{n} (D^2 - k^2) D w_1 \right\} - \mu_1 (D^2 - k^2) D w_1 + \frac{\mu_1 \varepsilon}{\hat{\lambda}} D w_1 \right]_{z=0}$$

$$= -(1 + \lambda n) \frac{k^2}{n} \left[g(\rho_2 - \rho_1) - \frac{k^2 T}{(1 + \lambda n)} w_0 \right] - 2k^2 (\mu_2 - \mu_1) D w_0 \qquad \text{... (17}d\text{)}$$

whre the subscripts 1 and 2 denote the corresponding quantities at the lower and upper fluids respectively and w_0 and $(Dw)_0$ are the unique values of these quantities at $z = 0$.

We now apply the boundary conditions (17a,b,c) to the solutions (15) and (16) and obtain

$$P_1 + Q_1 = P_2 + Q_2 \qquad \text{... (18)}$$

$$p_1 k + M_1 Q_1 = -kP_2 - Q_{2M_2} \qquad \text{... (19)}$$

$$\mu_1 \left[2k^2 P_1 + (M_1^2 + k^2) Q_1 \right] = \mu_2 \left[2k^2 P_2 + (M_2^2 + k^2) Q_2 \right]. \qquad \text{... (20)}$$

Applying the boundary condition (25d) to the solutions (23) and (24).

$$\left[(1 + \lambda n) \left\{ \rho_2 n (-P_2 k - Q_2 M_2) - \frac{H_2^2}{n} (D^2 - k^2) (-P_2 k - Q_2 M_2) \right\} \right.$$

$$\left. - \mu_2 (D^2 - k^2) (P_2 k - Q_2 M_2) + \frac{\mu_2 \varepsilon}{\hat{\lambda}} (-P_2 k - Q_2 M_2) \right]$$

$$-\left[(1+\lambda n)\left\{\rho_1 n(\rho_1 k+Q_1 M_1)-\frac{H_1^2}{n}(D^2-k^2)(P_1 k+Q_1 M_1)\right\}\right.$$

$$\left.-\mu_1(D^2-k^2)(P_1 k-Q_1 M_1)+\frac{\mu_2\varepsilon}{\hat{\lambda}}(-P_1 k-Q_1 M_1)\right]$$

$$=-(1+\lambda n)\frac{k^2}{n}\left[g(\rho_2-\rho_1)-\frac{k^2 T}{(1+\lambda n)}\right]\frac{1}{2}(P_1+Q_1+P_2+Q_2)-k^2(\mu_2-\mu_1)$$

$$\times(kP_1+M_1 Q_1-kP_2-M_2 Q_2)]. \quad \ldots (21)$$

Eliminating P_1, Q_1, P_2, Q_2 from eqs. (18)-(21)

$$\begin{vmatrix} 1 & 1 & -1 & -1 \\ k & M_1 & k & M_2 \\ 2k^2\mu_1 & \mu_1(M_1^2+k^2) & -2k^2\mu_2 & -\mu_2(M_2^2+k^2) \\ \left[-(1+\lambda n)\alpha_1 - (1+\lambda n\frac{R}{2}-C\right] & \left[-\frac{kM_1^2 V_{A_1}^2}{n^2} - (1+\lambda n)\frac{R}{2}-\frac{M_1 C}{k}\right] & \left[-(1+\lambda n)\alpha_2 - (1+\lambda n)\frac{R}{2}+C\right] & \left[-\frac{kM_2^2 V_{A_2}^2}{n^2} - (1+\lambda n)\frac{R}{2}+\frac{M_2 C}{k}\right] \end{vmatrix} = 0 \quad \ldots (22)$$

where we have written the non-dimensional quantities

$$\left.\begin{aligned} &\alpha_1=\frac{\rho_1}{\rho_1+\rho_2};\quad \alpha_2=\frac{\rho_2}{\rho_1+\rho_2}; \qquad (\alpha_1+\alpha_2=1) \\ &R=-\frac{gk}{2n^2}\left[(\alpha_2-\alpha_1)-\frac{k^2 T}{g(\rho_1+\rho_2)}\right];\quad C=\frac{k^2(\alpha_2 \nu_2-\alpha_1 \nu_1)}{n} \end{aligned}\right\} \quad \ldots (23)$$

and also have used Alfv́en velocities and kinematic viscosities as

$$V_{A_1}^2=\frac{H_1^2}{\rho_1+\rho_2},\quad V_{A_2}^2=\frac{H_2^2}{\rho_1+\rho_2}\quad \nu_1=\frac{\mu_1}{\rho_1} \text{ and } \nu_2=\frac{\mu_2}{\rho_2}. \quad \ldots (24)$$

Evaluating determinant (22), we obtain the characteristic equation as

$$(M_1-k)\left[2k^2(\alpha_1\nu_1-\alpha_2\nu_2)\left\{(1+\lambda n)\alpha_2-C\left(1-\frac{M_2}{k}\right)-\frac{kM_2 V_{A_2}^2}{n^2}\right\}\right.$$

$$- (1 + \lambda n)(R+1) \times \nu_2 \alpha_2 \left(M_2^2 - k^2 \right) \Bigg]$$

$$+ 2k \left[- \nu_2 \alpha_2 \left(M_2^2 - k^2 \right) \left\{ (1 + \lambda n) \alpha_1 + C\left(1 - \frac{M_1}{k} \right) - kM_1 \frac{Va_{A_1}^2}{n^2} \right\} \right.$$

$$\left. - \nu_1 \alpha_1 \left(M_2^2 - k^2 \right) \times \left\{ (1 + \lambda n) \alpha_2 - C\left(1 - \frac{M_2}{k} \right) - \frac{kM_2 V_{A_2}^2}{n^2} \right\} \right]$$

$$+ (M_2 - k) \left[\nu_1 \alpha_1 \left(M_2^2 - k^2 \right) \times (1 + \lambda n)(R+1) - 2k^2 \right.$$

$$\left. (\alpha_1 \nu_1 - \alpha_2 \nu_2) \left\{ (1 + \lambda n) \alpha_1 - C\left(1 - \frac{M_1}{k} \right) - \frac{kM_1 V_{A_1}^2}{n^2} \right\} \right] = 0. \qquad \text{... (25)}$$

The dispersion relation (25) is quite complex mainly due to square root terms in M_1 and M_2. We now restrict ourselves to carry out the stability analysis of conducting superposed fluids with high viscosity. Thus neglecting square and higher order terms of $\frac{1}{\nu_{1,2}}$, from eq. (14), we can write

$$M_{1,2} = k + \frac{1}{2}, \frac{Q}{k} + \frac{(1 + \lambda n)\left[n^2 - (k^2 + Q) \frac{V_{A_1, A_2}^2}{\alpha_{1,2}} \right]}{2k \left[n \nu_{1,2} + \frac{V_{A_1, A_2}^2}{\alpha 1, 2} \lambda n + \frac{V_{A_1, A_2}^2}{\alpha_{1,2}} \right]} \qquad \text{... (26)}$$

where $Q = \frac{\varepsilon}{\lambda}$ is the porous parameter.

Substituting the values of M_1 and M_2 from eq. (26), considering the case of equal knematic viscosity i.e. $\nu - \nu_1 = \nu_2$ and writing $V_{A_1} = V_{A_2} = V$, the dispersion relation (25) in dimensionless form reduces to

$$\overline{A} n^9 + \overline{B} n^8 + \overline{C} n^7 + \overline{D} n^6 + \overline{E} n^5 + \overline{F} n^4 + \overline{G} n^3 + \overline{H} n^2 + \overline{I} n + \overline{J} = 0 \qquad \text{... (27)}$$

where

$$\overline{A} = \frac{\nu}{2k} \lambda^3 (R+1) \alpha_1 \alpha_2$$

$$\overline{B} = \frac{\nu}{k} \alpha_1 \alpha_2 \lambda [C\lambda (\alpha_1 - \alpha_2) + 3\lambda (R+1) - 2C]$$

$$\overline{C}=k\nu\,(a_1-a_2)+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)\,b_4+\frac{\nu}{2k}(\alpha_1\,c_5+\alpha_2\,c_6)+2k\nu\,\alpha_1\,\alpha_2\,a_7$$

$$\overline{D}=k\nu\,(b_1-b_2)+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)\,c_4+\frac{\nu}{2k}(\alpha_1\,d_5+\alpha_2\,d_6)+2k\nu\,\alpha_1\,\alpha_2\,b_7$$

$$\overline{E}=k\nu\,(c_1-c_2)+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)\,d_4+\frac{\nu}{2k}(\alpha_1\,ec_5+\alpha_2\,e_6)+2k\nu\,\alpha_1\,\alpha_2\,c_7$$

$$\overline{F}=k\nu\,(d_1-d_2)+k^3\,\nu\,V^2+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)\,e_4+\frac{\nu}{2k}(\alpha_1 f_5+\alpha_2 f_6)+2k\nu\,\alpha_1\,\alpha_2\,d_7$$

$$\overline{G}=k\nu\,(e_1-e_2)+2k^3\,\nu\,V^2\,a_3+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)f_4+\frac{\nu\alpha}{2k}(\alpha_1\,g_5+\alpha_2\,g_6)+2k\nu\,\alpha_1\,\alpha_2\,e_7$$

$$\overline{H}=k\nu\,(f_1-f_2)+k^3\,\nu\,V^2\,b_3+\frac{\nu}{k}C\,(\alpha_1-\alpha_2)\,g_4+\frac{\nu}{2k}(\alpha_1\,h_5+\alpha_2\,h_6)+2k\nu\,\alpha_1\,\alpha_2 f_7$$

$$\overline{I}=k^3\,\nu\,V^2\,c_3\;+\;\frac{\overline{\alpha}}{2k}\;(\alpha_1\,i_5+\alpha_2\,i_6)$$

$$\overline{J}=\frac{\alpha}{2k}\;(\alpha_1\,j_5+\alpha_2\,j_6).$$

The details of the coefficients $a_1, a_2, \ldots, f_7$ are calculated but not presented in the paper to avoid repetition and to save space.

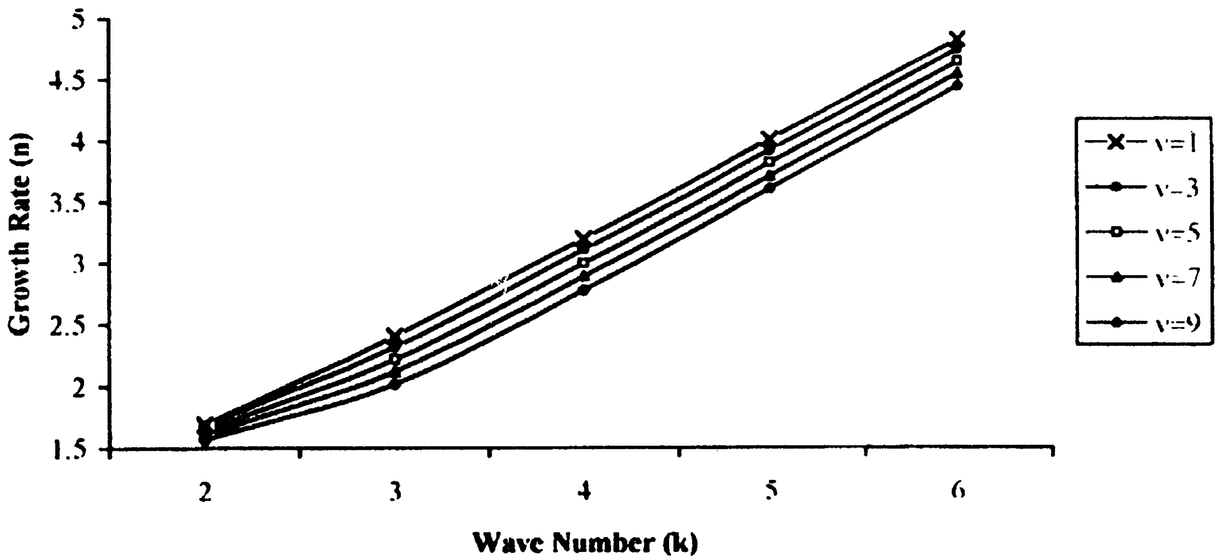

FIG. 1. Dependence of growth rate (real positive n) against wave number k for viscosity ν = 1, 3, 5, 7, 9 when α_1 = 0.25, α_2 = 0.75, V = 1.0, λ = 1.0, Q = 1.0, R = 1.0, C = 1.0.

CONCLUSION

The dispersion relaiton (27) is quite complex. We have performed numerical calculations of dispersion relation (27) for unstable configuration ($\alpha_2 > \alpha_1$) to locate the roots of n (growth rate) against k (wave number) for several values of the physical parameters namely, viscosity, visco-elasticity and

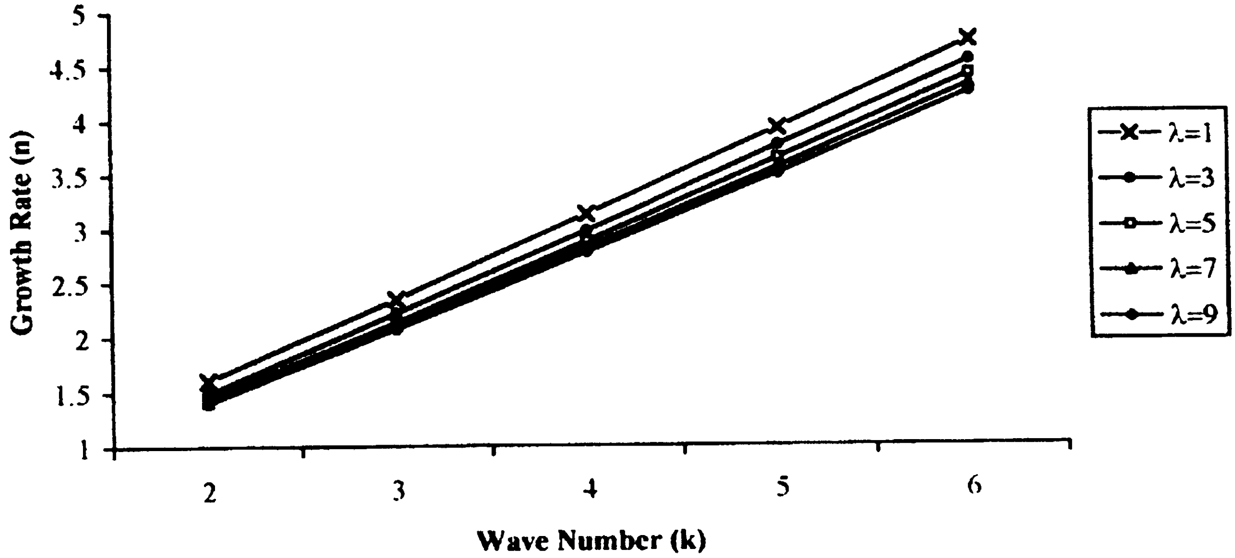

FIG. 2. Dependence of growth rate (real positive n) against wave number k for viscosity λ = 1, 3, 5, 7, 9 for α_1 = 0.25, α_2 = 0.75, V = 1.0, λ = 1.0, Q = 1.0, R = 1.0, C = 1.0.

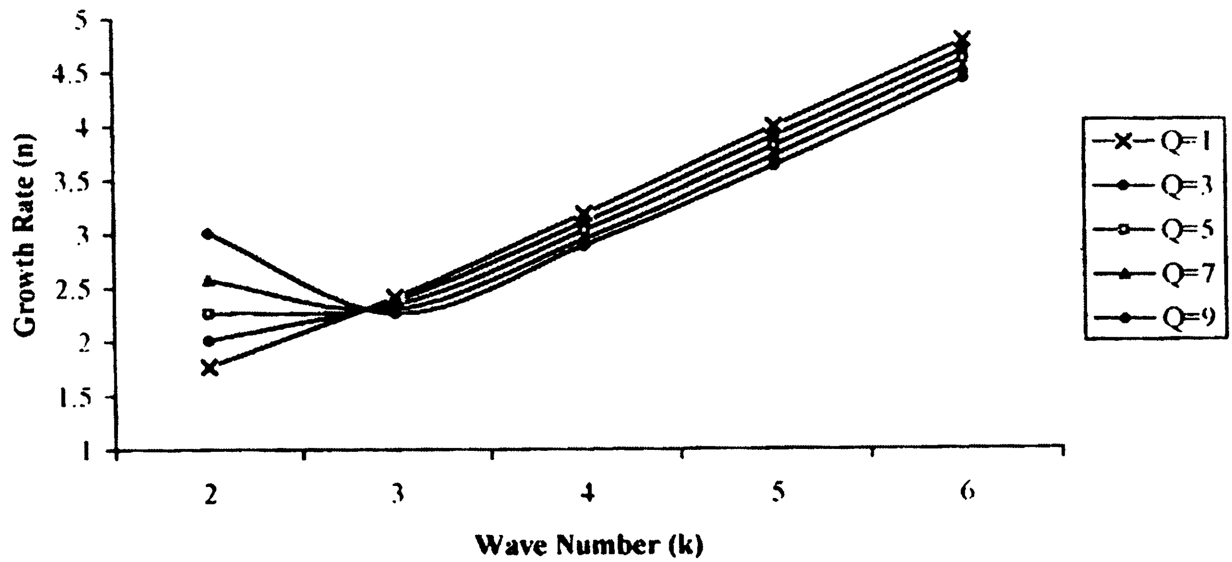

FIG. 3. Dependence of growth rate (real positive n) against wave number k for permeability Q = 1, 3, 5, 7, 9 for α_1 = 0.25, α_2 = 0.75, V = 1.0, λ = 1.0, Q = 1.0, R = 1.0, C = 1.0.

medium permeability. The numerical calculations are presented in Fig. 1-3 where we have taken $V = 1.0$, $R = 1.0$ and $C = 1.0$.

From Fig. 1, we see that for each wave number k, as ν (viscosity) increases, the growth rate n decreases showing stabilizing character of viscosity. Also, Fig. 2 shows that for each wave number k, the growth rate n decreases with the increment of visco-elasticity (λ). This indicates the stabilizing influence of visco-elasticity. Finally, Fig. 3 shows that for each wave number k (except $k = 2$), as permeability (Q) increases, the growth rate n increases with the increment of permeability of porous medium thereby showing mostly destabilizing influence of permeability of porous medium.

The stabilising influence for wave number 2 may have some indication of critical wave number.

Thus, we may conclude that viscosity and visco-elasticity have stabilizing influence and permeability of porous medium has destabilizing influence on the Rayleigh-Taylor instability of superposed visco-elastic Maxwell fluids.

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