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THERMAL DIFFUSION EFFECTS WITH INTERNAL HEAT SOURCE ON THE ONSET OF DDC IN A FLUID SATURATED POROUS LAYER

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ABSTRACT
In this paper, we have studied the effect of thermal diffusion with internal heat source on the onset of double diffusive convection (DDC) in a binary viscoelastic fluid-saturated sparsely packed porous layer using linear stability analysis. The onset criterion for stationary and oscillatory convection is derived analytically. The effect of different parameters on both the stationary and oscillatory system has investigated and the results have been shown graphically and discussed.

Keywords: *Double-diffusive convection, Viscoelastic fluid, Porous layer, Internal heat source, Thermal diffusion*

1. INDTRODUCTION

Double diffusive convection in porous media occurs in many systems, and this problem has attracted considerable interest over the years due to its numerous fundamental and industrial applications, such as high –quality crystal production, liquid gas storage, migration of moisture in fibrous insulation, transport of contaminants in saturated soil, solidification of magmas. Extensive reviews of the literature on this subject can be found in the books by Ingham (1998, 2005), Vafai (2000, 2005), Vadasz (2008) and Nield (2006).

With the growing importance of non-Newtonian fluids in modern technology and also due to their natural occurrence, the investigations on such fluids are quite desirable. In particular, the flow of viscoelastic fluid is of considerable importance in several fields of applications such as material processing, petroleum, chemical and nuclear industries, carbon dioxide-geologic sequestration, bioengineering, and reservoir engineering. Although the problem of Rayleigh Benard convection has been extensively investigated for Newtonian fluids, relatively little attention has been devoted to the thermal convection of viscoelastic fluids (Li and Khayat, 2005 and references therein).

A situation in which a porous medium has its own source of heat can occur through present perspective. A relatively weak exothermic reaction which can take place within the porous materials. Internal heat generation becomes very important in geophysics, reactor safety analysis, fire& combustion studies and storage of radioactive materials. The onset of convection in a horizontal layer of an anisotropic porous medium with internal heat source subjected to an inclined temperature gradient was studied by Parthiban and Parthiban (1997). An analytical solution for small Rayleigh number in a finite container with isothermal walls and uniform heat generation within the porous medium was given by Joshi *et al.*, (2006). Recently, the natural convection in a rotating anisotropic porous layer with internal heat generation using a weak nonlinear analysis is studied by Bhadauria *et al.*, (2012). The double diffusive natural convection in an anisotropic porous layer in the presence of internal heat source is studied by Bhadauria (2012).

If the cross diffusion terms are included in the species transport equations, then the situation will be quite different. Due to the cross diffusion effects, each property gradient has a significant influence on the flux of the other property. Aflux of salt caused by a special gradient of temperature is called the Soret effect. Similarly, aflux of heat caused by a spatial gradient of concentration is called the Dufour effects. The Dufour coefficient is of order of magnitude smaller than the Soret coefficient in liquids, and the corresponding contribution to the heat flux may be neglected. Many studies can be found in the literature concerning the

Soret and Dufour effects. A study by Rudraiah and Malashetty (1986) discussed the double diffusive convection in aporous medium in the presence of Soret and Dufour effects. In another study, Rudraiah and Siddheshwar (1998) investigated a weak nonlinear stability analysis of double diffusive convection with cross diffusion in a fluid saturated porous medium. Recently, the double diffusive convection in a fluid saturated anisotropic porous layer with Soret effect is investigated by Gaikwad and kamble (2012). Also, more recently Altawallbeh *et al.*, (2013) have investigated the linear and nonlinear double diffusive convection in a saturated anisotropic porous layer with Soret effect and internal heat source.

It is well known that Darcy's law is not valid for non-Newtonian fluid flows in porous media. Recently, the onset of Darcy-Brinkman convection in a binary viscoelastic fluid saturated porous layer is studied by Swamy *et al.*, (2012), where the modified Darcy-Brinkman-Oldroyd model has been developed. This model overcomes not only the shortcomings encountered in the modified Darcy-Oldroyd model but also the disadvantages encountered in the Jeffrey's model. By using a variable porous parameter *Da* (Darcy number), the modified Darcy-Brinkman-Oldroyd model bridges the gap between nonporous cases in which $Da \to \infty$ and very densely packed porous cases in which $Da \to 0$. A better understanding of the characteristics of the Darcy-Brinkman equation is therefore an important part of more practical problems and thus motivates the present report.

The objective of the present work is to study the onset of double diffusive convection in a horizontal binary viscoelastic fluid saturated porous layer with an internal heat source in the presence of thermal diffusion effect using a modified Darcy-Brinkman-Oldroyd model by linear stability theory which we intend to perform the onset criteria for stationary and oscillatory convection.

2. MATHEMATICAL FORMULATION

We consider an infinite horizontal sparsely packed, binary viscoelastic fluid saturated porous layer confined between the planes $z=0$ and $z=d$, with the vertically downward gravity force $\mathbf{g}$ acting on it. Constant temperatures $\Delta T + T_0$ and T_0 with stabilizing concentrations $\Delta S + S_0$ and S_0 respectively are maintained between the lower and upper surfaces. A Cartesian frame of reference is chosen with the origin in the lower boundary and the z-axis vertically upwards. The modified Darcy − Brinkman − Oldroyd model, which includes the time derivative, is employed as a momentum equation (see Swamy *et al.*, 2012). With the Oberbeck − Boussinesq approximation, the basic governing equations are

$$\nabla \cdot \mathbf{q} = 0, \tag{2.1}$$

$$\left(1+\bar{\lambda}_1 \frac{\partial}{\partial t}\right)\left(\frac{\rho_0}{\varepsilon}\frac{\partial q}{\partial t} + \nabla p - \rho \mathbf{g}\right) = \left(1+\bar{\lambda}_2 \frac{\partial}{\partial t}\right)\left(-\frac{\mu}{K} q + \mu_e \nabla^2 q\right), \tag{2.2}$$

$$\gamma \frac{\partial T}{\partial t} + \left(q \cdot \nabla\right) T = \kappa_T \nabla^2 T + Q\left(T - T_0\right), \tag{2.3}$$

$$\varepsilon \frac{\partial S}{\partial t} + \left(\mathbf{q} \cdot \nabla\right) S = \kappa_S \nabla^2 S + D_1 \nabla^2 T\,, \tag{2.4}$$

$$\rho = \rho_0\left[1 - \beta_T\left(T - T_0\right) + \beta_S\left(S - S_0\right)\right]. \tag{2.5}$$

Where, $\gamma = \dfrac{(\rho c)_m}{(\rho c_p)_f}$, $(\rho c)_m = (1-\varepsilon)(\rho c)_s + \varepsilon(\rho c_p)_f$.

2.1. Basic State:

The basic state is assumed to be quiescent and the variables except q_b are functions of z alone. To study the stability of the system we superpose infinitesimal perturbation on the basic state so that the equations governing the perturbed quantities are given by

$$\nabla.\mathbf{q}^{'} = 0, \tag{2.6}$$

$$\left(1+\frac{\partial}{\partial t}\overline{\lambda_1}\right)\left[\frac{\rho_0}{\varepsilon}\frac{\partial \mathbf{q}^{'}}{\partial t}+\nabla p'-\rho'\mathbf{g}\right]=\left(1+\frac{\partial}{\partial t}\overline{\lambda_2}\right)\left(\frac{\mu}{K}\mathbf{q}^{'}+\mu_e\nabla^2\mathbf{q}^{'}\right), \tag{2.7}$$

$$\gamma\frac{\partial T'}{\partial t}+\left(\mathbf{q}^{'}.\nabla\right)T'-\left(\frac{\Delta T}{d}\right)w^{'}=\kappa_T\nabla^2 T'+QT', \tag{2.8}$$

$$\varepsilon\frac{\partial S'}{\partial t}+\left(\mathbf{q}^{'}.\nabla\right)S'-\left(\frac{\Delta S}{d}\right)w^{'}=\kappa_S\nabla^2 S'+D_1\nabla^2 T^{'} \tag{2.9}$$

$$\rho' = -\rho_0\left[\beta_T T'-\beta_S S'\right]. \tag{2.10}$$

2.2. Perturbed State:

By operating curl twice on Eq. (7) we eliminate p' and then use the scaling

$$\left(x',y',z'\right)=\left(x^*,y^*,z^*\right)d,\ \left(u',v',w'\right)=\left(\kappa_T/d\right)\left(u^*,v^*,w^*\right),$$
$$t'=t^*\left(\gamma d^2/\kappa_T\right),\ T'=\left(\varDelta T\right)T^*,\ S'=\left(\varDelta S\right)S^*, \tag{2.11}$$

to non-dimensionalize equations (6)-(10)I in the form (on dropping the asterisks),

$$\left(1+\frac{\partial}{\partial t}\lambda_1\right)\left[\frac{1}{Pr_D}\frac{\partial}{\partial t}\nabla^2 w-Ra_T\nabla_h^2 T++Ra_S\nabla_h^2 S\right]-\left(1+\frac{\partial}{\partial t}\lambda_2\right)\left(Da\,\nabla^4 w-\nabla^2 w\right)=0, \tag{2.12}$$

$$\left[\frac{\partial}{\partial t}-\nabla^2-Ra_{\text{int}}+\left(q\cdot\nabla\right)\right]T-w=0, \tag{2.13}$$

$$\left[\lambda\frac{\partial}{\partial t}-\frac{1}{Le}\nabla^2+\left(q\cdot\nabla\right)\right]S-D_T\frac{Ra_T}{Ra_S}\nabla^2 T-w=0, \tag{2.14}$$

where $Ra_{\text{int}}=\dfrac{Qd^2}{\kappa_T}$ is the internal Rayleigh number. The thermal Rayleigh number characterizes the buoyancy due to the thermal gradient and that due to the solute gradient is indicated by the solute Rayleigh number. The viscoelastic character of the liquid mixture appears in the relaxation parameter λ_1 (which is also known as the Deborah number) and retardation parameter, λ_2. The Deborah number is a ratio of the relaxation time of the material to a characteristic time of the process. The parameter $\lambda_2=0$ for a Maxwell fluid while $\lambda_1=\lambda_2=0$ for a Newtonian fluid. For dilute polymeric solutions the value of Deborah number is most likely in the range [0.1, 2] and λ_2 in the range [0.1, 1]. It is worth mentioning here that the Darcy-Prandtl number Pr_D includes the Prandtl number, Darcy number, porosity and the specific heat ratio. It depends on the properties of the fluid and on the nature of the porous matrix. The Prandtl number affects the stability of the porous system through this combined dimensionless group. For the sparse porous media, $Da\in\left[10^{-2},1\right],\varepsilon\cong 0.5$ and a typical value for the Prandtl number for a viscoelastic fluid is $Pr=10.$ Since Pr_D is magnified by a factor $\varepsilon^{-1}Da$ the reasonable range for Pr_D will be [5, 500]. The ratio between thermal and solute diffusivities is characterized by the Lewis number and can be varied in the range of [1, 1000]. The normalized porosity λ is expressed in terms of the porosity of the porous medium ε and the solid to fluid heat capacity ratio, γ . Since $0<\varepsilon<1,$ it is clear that $0<\lambda<1.$

Since the boundaries are assumed to be stress free, isothermal and isohaline; the Eqs. $(2.12)-(2.14)$ are to be solved for the boundary conditions

$$w = \frac{\partial^2 w}{\partial z^2} = T = S = 0 \text{ at z = 0, 1} \tag{2.15}$$

3. LINEAR STABILITY ANALYSIS

In this section we predict the thresholds of both marginal and oscillatory convections. The Eigenvalue problem defined by Eqs. $(2.12)-(2.14)$ and subjected to the boundary conditions (2.15) is solved using the time-dependent periodic disturbances in a horizontal plane. Assuming that the amplitudes of the perturbations are very small, we write

$$\begin{pmatrix} w \\ T \\ S \end{pmatrix} = \begin{pmatrix} W(z) \\ \Theta(z) \\ \Phi(z) \end{pmatrix} exp\left[i\left(lx+my\right)+\sigma t\right]. \tag{3.1}$$

Infinitesimal perturbations of the rest state may either damp or grow depending on the value of the parameter σ. Substituting Eq. (3.1) into the linearized version of Eqs. $(2.12)-(2.14)$, we obtain

$$\begin{aligned}(1+\lambda_1\sigma)\left[\frac{\sigma}{Pr_D}\left(D^2-a^2\right)W + a^2 Ra_T\Theta - a^2 Ra_S\Phi\right] - (1+\lambda_2\sigma) \\ \times\left(D^2-a^2\right)\left[Da\left(D^2-a^2\right)^2-1\right]W = 0,\end{aligned} \tag{3.2}$$

$$\left[\sigma - \left(D^2-a^2\right) - Ra_{\text{int}}\right]\Theta - W = 0, \tag{3.3}$$

$$\left[\lambda\sigma - Le^{-1}\left(D^2-a^2\right)\right]\Phi - D_T\frac{Ra_T}{Ra_S}(D^2-a^2)\Theta - W = 0, \tag{3.4}$$

where $D \equiv d/dz$ and $a^2 = l^2 + m^2$. The boundary conditions (2.15) now becomes

$$W = \frac{\partial^2 W}{\partial z^2}\Theta = \Phi = 0 \text{ at } z = 0, 1. \tag{3.5}$$

We assume the solutions in the form

$$\begin{pmatrix} W(z) \\ \Theta(z) \\ \Phi(z) \end{pmatrix} = \begin{pmatrix} W_0 \\ \Theta_0 \\ \Phi_0 \end{pmatrix} \text{Sin}\, n\pi z, \; (n = 1, 2, 3, ...). \tag{3.6}$$

The most unstable mode corresponds to $n = 1$ (fundamental mode). Therefore substituting Eqs. $(3.2)-(3.4)$ and using the solvability condition we obtain

$$Ra_T = \left(\sigma + \delta^2 - Ra_{int}\right)\left\{\frac{\delta^2}{a^2}\left[\frac{\sigma}{Pr_D} + \frac{(1+\lambda_2\sigma)}{(1+\lambda_1\sigma)}\frac{\left(1+\delta^2 Da\right)}{\delta^2 D_T}\right] + \frac{Ra_S}{\left(\lambda\sigma + \delta^2 Le^{-1} + \delta^2 D_T\right)}\right\}. \tag{3.7}$$

3.1. Stationary State:

For the validity of the principle of exchange of stabilities (i.e., steady case), we have $\sigma=0$ (i.e., $\omega_r = \omega_i = 0$) at the margin of stability. Then the Rayleigh number at which the marginally stable steady mode exists becomes

$$Ra_T^{St} = \left(\delta^2 - Ra_{\text{int}}\right)\left[\frac{\delta^4\left(1+\delta^2 Da\right)}{a^2 D_T} + \frac{Le\,Ra_S}{\delta^2(1+D_T)}\right]. \tag{3.8}$$

The minimum value of the Rayleigh number Ra_T^{St} occurs at the critical wavenumber $a = a_c^{St}$ where $a_c^{St} = \sqrt{h}$ satisfies the equation

$$s_1 h^5 + s_2 h^4 + s_3 h^3 + s_4 h^2 + s_5 h + s_6 = 0. \tag{3.9}$$

In the absence of a heat source for the sparsely packed porous medium (i.e., when $Ra_{\text{int}} = 0$) Eq. (3.8) reduces to

$$Ra_T^{St} = \frac{\delta^4\left(1+\delta^2 Da\right)}{a^2 D_T} + \frac{Le\,Ra_S}{D_T}, \tag{3.10}$$

In the absence of Soret parameter (i.e., when $D_T = 0$) the above Eq. (3.10) reduces to

$$Ra_T^{St} = \frac{\delta^4\left(1+\delta^2 Da\right)}{a^2} + Le\,Ra_S, \tag{3.11}$$

This result exactly coincides with the one given by [8]. When $Da \to 0$, that is for densely packed porous medium Eq. (3.11) becomes

$$Ra_T^{St} = \frac{\left(\pi^2 + a^2\right)^2}{a^2} + Ra_S Le, \tag{3.12}$$

which is the classical result for double diffusive convection in a Darcy porous medium [see Nield and Bejan (2006)]. For a single component fluid ($Ra_S = 0$), the expression for stationary Rayleigh number reduces to the classical result

$$Ra_T^{St} = \frac{\left(\pi^2 + a^2\right)^2}{a^2} \tag{3.13}$$

which has the critical value $Ra_c^{St} = 4\pi^2$ for $a_c^{St} = \pi$ obtained by Horton and Rogers (1945) and Lapwood (1948).

3.2. Oscillatory state:

We now set $\omega = i\,\omega_i$ in Eq. (3.13) and clear the complex quantities from the denominator, to obtain

$$Ra_T = \Delta_1 + i\,\omega_i\,\Delta_2, \tag{3.14}$$

where Δ_1 and Δ_2 are as given in appendix. Since Ra_T is a physical quantity, it must be real. Hence, from Eq. (3.14) it follows that either $\omega_i = 0$ (steady onset) or $\Delta_2 = 0$ ($\omega_i \neq 0$, oscillatory onset). For oscillatory onset, setting $\Delta_2 = 0$ ($\omega_i \neq 0$) gives an expression for frequency of oscillations in the form (on dropping the subscript *i*)

$$a_0\left(\omega^2\right)^2 + a_1\omega^2 + a_2 = 0, \tag{3.15}$$

Now Eq. (3.14) with $\Delta_2 = 0$, gives

$$Ra_T^{Osc} = \frac{(-\delta^2 + Ra_{int})w^2\delta^6(1+LeD_T)(\lambda-\lambda_1-1)(1+w^2\lambda_1^2-(1+Da\delta^2)Pr_D(\lambda_1+\lambda_2)}{a^2(1+w^2\lambda_1^2)Pr_D(\delta^4+Le^2w^2\lambda_1^2+Le\delta^4D_T(2+LeD_T)} + \frac{Ra_S(\delta^2(Le^{-1}+D_T)(\delta^2-R_{int})+w^2\lambda_1)}{\delta^4(Le^{-1}+D_T)^2+w^2\lambda_1^2}. \quad (3.16)$$

The analytical expression for the oscillatory Rayleigh number given by Eq. (3.16) is minimized with respect to the wavenumber numerically, after substituting for $\omega^2 \left(>0\right)$ from Eq. (3.15), for various values of physical parameters in order to know their effects on the onset of oscillatory convection.

RESULTS AND DISCUSSION

The onset of double diffusive convection in a two-component viscoelastic fluid saturated sparsely packed porous layer in the presence of an internal heat source and thermal diffusion effect is investigated analytically using linear stability theory. In the linear stability theory the expressions for both stationary and oscillatory Rayleigh numbers are derived analytically along with the expression for frequency of oscillation. The stationary critical Rayleigh number is found to be independent of the viscoelastic parameters because of the absence of base flow in the present case. The critical Rayleigh number for the oscillatory mode is derived as a function of internal Rayleigh number, thermal diffusion, viscoelastic parameters, solute Rayleigh number, Darcy number, normalized porosity, Darcy-Prandtl number and Lewis number.

The neutral stability curves in the $Ra_T - a$ plane for various parameter values are as shown in Figs.1-7. We fixed the values for the parameters except the varying parameter. From these figures it is clear that the neutral curves are connected in a topological sense. This connection allows the linear stability criteria to be expressed in terms of the critical Rayleigh number Ra_{Tc}, below which the system is stable and unstable above.

In Fig. 1, the neutral stability curves for different values of thermal diffusion D_T are drawn. From this figure, we observed that with an increase in the value of negative thermal diffusion D_T, the stationary Rayleigh number increases, indicating that the negative thermal diffusion stabilizes the system. On the other hand, for positive thermal diffusion, the minimum of the stationary Rayleigh number decreases with an increase of the thermal diffusion, indicating that the positive thermal diffusion destabilizes the system in the stationary mode. In the case of oscillatory mode, we find that the negative thermal diffusion coefficient has destabilizing effect where as the positive thermal diffusion coefficient has a stabilizing effect. The effect of normalized porosity parameter on the neutral curves is shown in Fig. 2. We observe that the effect of increasing the normalized porosity parameter decreases the minimum of the Rayleigh number, indicating that the effect of normalized porosity parameter is to advance the onset of double diffusive convection. Further, it is important to note that the effect of normalized porosity parameter is significant for small λ.

Fig. 3 depicts the effect of solute Rayleigh number Ra_S on the neutral stability curves for stationary and oscillatory modes. We find that the effect of increasing Ra_S is to increase the value of the Rayleigh number for stationary mode while decreases for oscillatory mode. Fig. 4 depicts the neutral stability curves for different values of Lewis number Le. It is observed that with the increase of Le the critical values of Rayleigh number and the corresponding wave number for the over stable mode decrease while those for stationary mode increases. Therefore, the effect of Le is to advance the onset of oscillatory convection where as its effect is to inhibit the stationary onset.

The neutral stability curves for different values of Darcy-Prandtl number Pr_D are presented in the above Fig. 5. The point where the over stable solution bifurcates into the stationary solution is observed to be shifted towards a higher value of a with the increasing Pr_D. From this figure it is evident that for small and moderate values of Pr_D the critical value of oscillatory Rayleigh number decreases with the increase of Pr_D, however this trend is reversed for large values of Pr_D. Fig. 6 exhibits the effect of Darcy number Da on the neutral stability curves for the fixed values of other governing parameters. It is observed that the oscillatory convection sets in prior to the stationary convection for the values of the parameters chosen for this figure. We find that with the increase in the values of Darcy number Da the critical Rayleigh number and the corresponding wavenumber for the stationary and oscillatory mode increases. Therefore, the effect of Darcy numer Da is to stabilize the system.

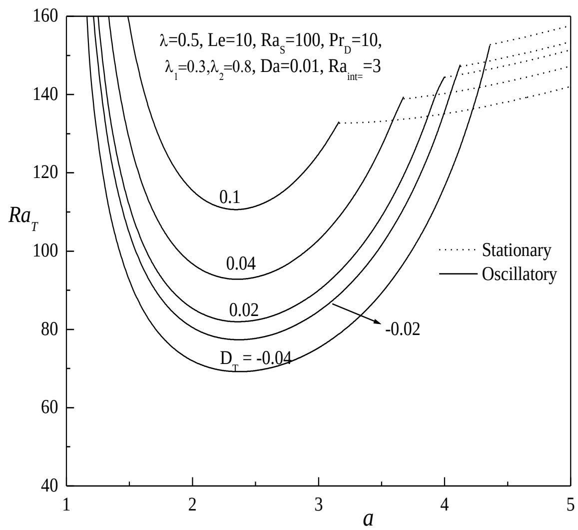

Fig.1 Neutral stability curves for different values of D_T.

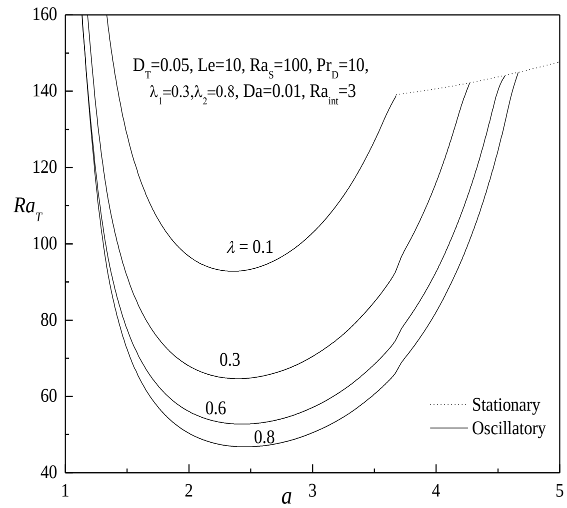

Fig.2 Neutral stability curves for different values of λ

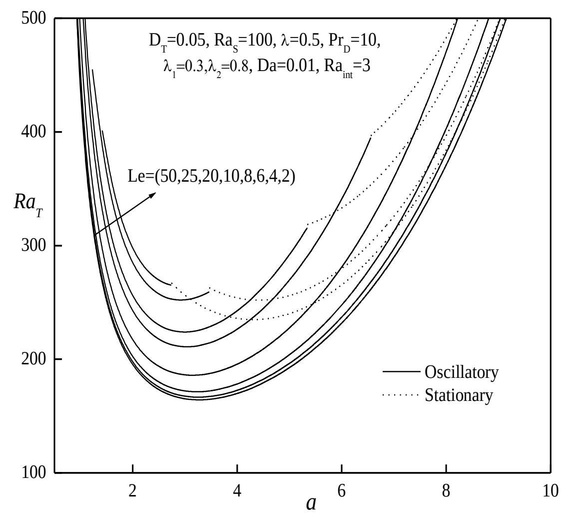

Fig.4 Neutral stability curves for different values of *Le*.

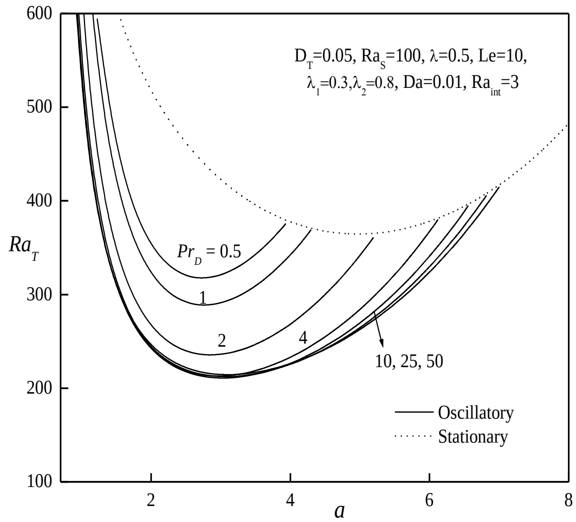

Fig.5 Neutral stability curves for different values of Pr_D.

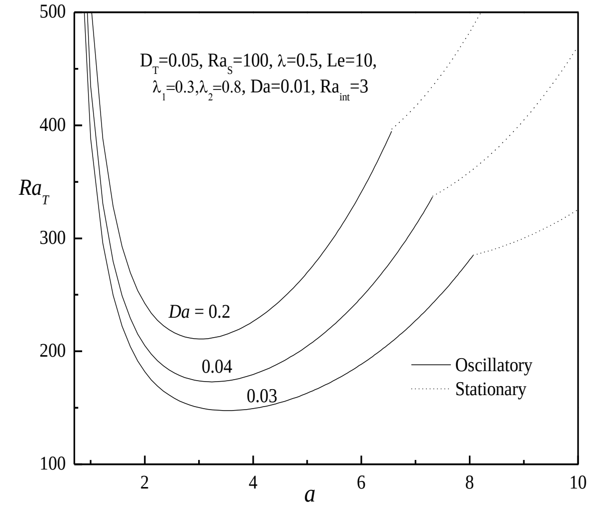

Fig. 6 Neutral stability curves for different values of *Da*.

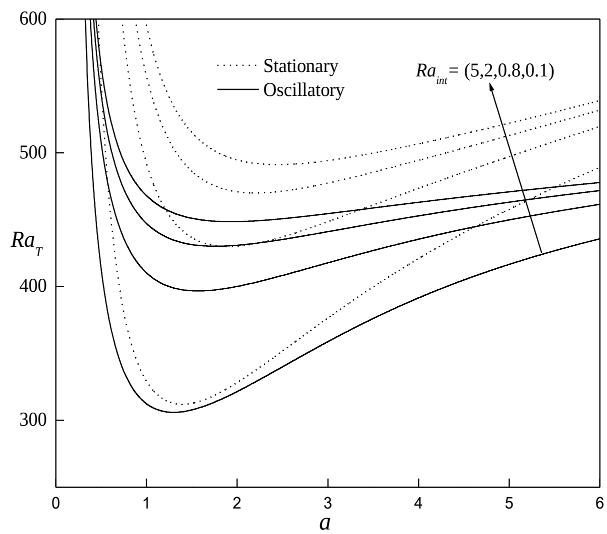

Fig. 7 Neutral stability curves for different values of Ra_{int}.

Fig. 7 shows the neutral stability curves for different values of the internal Rayleigh number Ra_{int} and for fixed values of other parameters. We observe from this figure that the minimum value of the Rayleigh number for both stationary and oscillatory modes decreases with an increase in the value of the internal Rayleigh number Ra_{int}, indicating that the effect of the internal Rayleigh number is to destabilize the system.

CONCLUSIONS

The onset of Darcy-Brinkman convection in a horizontal, sparsely packed porous layer saturated with a binary viscoelastic fluid with an internal heat source and Soret effect is studied analytically using linear stability theory. The following important conclusions are drawn:

- With increase in the negative value of thermal diffusion, the stationary Rayleigh number increases, that is the effect of thermal diffusion stabilizes the system. For the positive value of thermal diffusion, the stationary Rayleigh number decreases with increase of thermal diffusion, that is the effect of thermal diffusion destabilizes the system in the stationary mode.
- In oscillatory case, the negative value thermal diffusion has destabilizing effect where as positive thermal diffusion has stabilizing effect. Increase in the value of thermal diffusion decreases the critical Rayleigh number for stationary mode where as it increases the critical Rayleigh number for oscillatory mode.
- The effect of internal Rayleigh number is to destabilize the system for stationary and oscillatory modes. Increasing in internal Rayleigh number decreases the critical thermal Rayleigh number for stationary and oscillatory convection that is an internal Rayleigh number is to advance the onset of double diffusive convection.
- Effect of solute Rayleigh number to delay both the stationary and oscillatory modes.
- The effect of Lewis number is to advance the onset of oscillatory convection whereas its effect is to inhibit the stationary onset. Also it is observed that Lewis number is to advance the onset of oscillatory convection.
- The Darcy Prandtl number has a dual effect on the oscillatory mode in the sense that there is a critical value say Pr_D^* such that a strong destabilizing effect is observed when $Pr_D < Pr_D^*$, while for $Pr_D < Pr_D^*$ this effect is reversed and hence the system is stabilized. The stabilizing effect of Pr_D becomes less significant when $Pr_D >> Pr_D^*$. Hence effect of Darcy Prandtl number is to advance the onset of oscillatory convection.
- The effect of Darcy number is stabilizing the system for stationary and oscillatory modes.
- The effect of relaxation parameter is to advance the onset of double diffusive convection. The stability of the system in oscillatory mode becomes independent of the viscoelastic parameters when the values of relaxation and retardation parameters become same. The effect of retardation parameter stabilizes the system towards the oscillatory mode.

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