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DOUBLE DIFFUSIVE CONVECTION IN A BINARY VISCOELASTIC FLUID SATURATED POROUS LAYER WITH SORET EFFECT AND INTERNAL HEAT SOURCE

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ABSTRACT

In this paper, we have investigated the effect of Soret parameter on the onset of double diffusive convection in a binary viscoelastic fluid saturated porous layer with internal heat source using linear stability theory which is based on the normal mode technique. The effect of Soret parameter, normalized porosity, the Lewis number, internal Rayleigh number and the Darcy-Prandtl number on the stability of a system is shown graphically. From this study we find that the effect of negative Soret parameter stabilizes the system while destabilizes the system for positive Soret parameter for oscillatory mode. The Lewis number (Le), normalized porosity (ε_n), and internal Rayleigh number (R_i) have stabilizing effects. The effect of Darcy –Prandtl number (p_{r_D}) destabilizes the system for oscillatory convection.

Keywords: *Double-diffusive convection (DDC), Viscoelastic fluid, Porous layer, Internal heat source, Soret parameter.*

1. INTRODUCTION

The Soret effect is a mass flux due to a temperature gradient and appears in the species continuing equation when we have a multicomponent mixture where each species has its own diffusional velocity. The diffusion material is in an unevenly heated mixture of gases or a solution caused by the presence of temperature gradient in the system. The effect is named for the Swiss scientist J. Soret, who was the first to study thermodiffusion (1879). The study of thermohaline with thermodiffusion in a fluid saturated porous medium is of importance in geophysics, ground water hydrology; soil science, oil extraction etc. (see Parvathy and Patil, [15]). The reason is that the earth's crust is a porous medium saturated by a mixture of different types of fluids such as oil, water, gases and molten form of ores dissolved in fluids. Thermal gradient present between the interior and exterior of the earth's crust may help convection to set in and which causes the Soret effect. The Soret effect which make the larger molecule components to have a tendency to rise, while smaller molecule components go down to the bottom of the wall. However, gravity causes the heavy components in a given well is neither consistent nor readily predictable.

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 [14]. Recently, Bhadauria *et al.* [2] studied the natural convection in a rotating anisotropic porous layer with internal heat generation using a weak nonlinear analysis. Bhadauria [3] have studied double diffusive natural convection in an anisotropic porous layer in the presence of internal heat source.

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 and Pop [8, 9], Vafai [20, 21], Nield and Bejan [13], and Vadasz [19].

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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. A flux of salt caused by a special gradient of temperature is called the Soret effect. Similarly, a flux 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 [16] discussed the double diffusive convection in a porous medium in the presence of Soret and Dufour effects. In another study, Rudraiah and Siddheshwar [17] investigated a weak nonlinear stability analysis of double diffusive convection with cross diffusion in a fluid saturated porous medium. Recently, Gaikwad and Kamble[4] have investigated double diffusive convection in a fluid saturated anisotropic porous layer with Soret effect. Also more recently, Altawallbeh *et al.* [1] 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 the Darcy's law is not valid for non-Newtonian fluid flows in porous media. Recently, Swamy et al. studied the onset of Darcy-Brinkman convection in a binary viscoelastic fluid saturated porous layer, 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 (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.

More recently, Malashetty *et al.* [12] have investigated the onset of convection in a binary vicoelastic fluid saturated porous layer; Gaikwad and Kouser [6] have studied the onset of Darcy-Brinkman convection in a binary viscoelastic fluid saturated porous layer with internal heat source. Gaikwad and Kamble [5] have studied theoretically the cross diffusion effects on convective instability in porous media. Yaha *et al.* [23] and Yaha [22] have studied the presence of heat generation/absorption on boundary layer slip flow of nanofluid over a porous stretching sheet and also investigated the presence of pressure gradient on laminar boundary layer over a permeable surface with convective boundary condition respectively.

There are so many work is available on convective instabilities concerned to the investigation but a very little attention has been devoted to this study. Therefore, the main objective of the present work is to study the onset of double diffusive convection in a horizontal binary viscoelastic fluid saturated porous layer with internal heat source and Soret effect using linear stability analyses.

2. FORMULATION OF THE PROBLEM

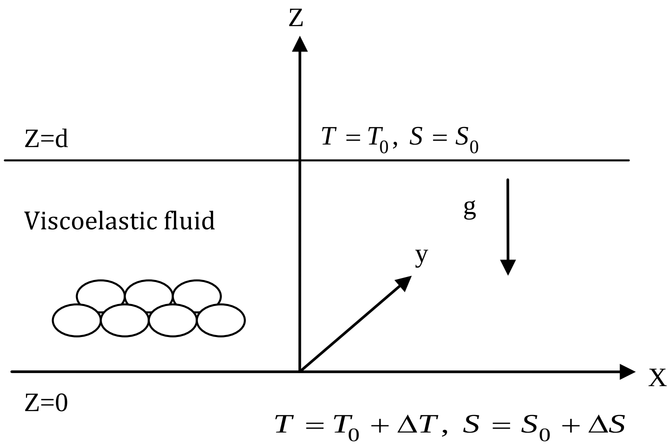

Figure A: Physical configuration of the problem.

The physical configuration of the problem is as shown in the above Fig. A. 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 **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. Here ΔT and ΔS are the temperature and salinity difference between the walls respectively. 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. With the Oberbeck − Boussinesq approximation, the basic governing equations are

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

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

$$\gamma \frac{\partial T}{\partial t} + \left(q \cdot \nabla\right) T = \kappa_T \nabla^2 T + Q\left(T - T_0\right), \tag{3}$$

$$\varepsilon \frac{\partial S}{\partial t} + \left(\mathbf{q} \cdot \nabla\right) S = \kappa_S \nabla^2 S + D_1 \nabla^2 T, \tag{4}$$

$$\rho = \rho_0 \left[1 - \beta_T \left(T - T_0\right) + \beta_S \left(S - S_0\right)\right], \tag{5}$$

Where $\mathbf{q}$ is the velocity vector, p is the pressure, $\overline{\lambda}_1$ and $\overline{\lambda}_2$ are the stress relaxation and strain retardation parameters respectively. ε the porosity, T is the temperature, S is the solute concentration, $\mathbf{g}$ is the gravitational acceleration, ρ the density, t is time, Q is internal heat source, μ is the dynamic viscosity, μ_e is the effective viscosity, κ_T and κ_S are the thermal and solute diffusivity, D_1 is the Soret coefficient, β_T and β_S are thermal and solute expansion coefficient respectively. Further, $\gamma = (\rho c)_m / (\rho c_p)_f$, $(\rho c)_m = (1-\varepsilon)(\rho c)_s + \varepsilon(\rho c_p)_f$, c is the specific heat of the solid, c_p is the specific heat of the fluid at constant pressure, the subscripts f, s and m denote fluid, solid and porous medium values respectively.

2.1. Basic State

The basic state of the fluid is assumed to be quiescent and is given by

$$\mathbf{q_b} = \left(0,0,0\right),\ p = p_b(z),\ T = T_b(z),\ S = S_b(z),\ \rho = \rho_b(z). \tag{6}$$

Using Eq. (6) into Eqs. (1) – (5) yields

$$\left.\begin{aligned} &\frac{dp_b}{dz} = -\rho_b g,\ \ \kappa_T \frac{d^2 T_b}{dz^2} + Q\left(T_b - T_0\right) = 0,\ \ \frac{d^2 S_b}{dz^2} = 0, \\ &\rho_b = \rho_0 \left[1 - \beta_T \left(T_b - T_0\right) + \beta_S \left(S_b - S_0\right)\right]. \end{aligned}\right\} \tag{7}$$

Then the conduction state temperature and concentration are given by

$$T_b\left(z\right) = \frac{\Delta T\, sin\left[\sqrt{R_i}\left(1 - \frac{z}{d}\right)\right]}{sin\sqrt{R_i}} + T_0, \quad S_b = \Delta S\left(1 - \frac{z}{d}\right) + S_0. \tag{8}$$

2.2. Perturbed State

On the basic state, we superpose small perturbations in the form

$$\mathbf{q} = \mathbf{q}_b + \mathbf{q}',\ T = T_b + T',\ S = S_b + S',\ p = p_b + p',\ \rho = \rho_b + \rho', \tag{9}$$

where the primes indicate perturbations. Substituting Eq.(9) into Eqs. (1) −(5) and using the equations (6)-(8), the perturbations are given in the form

$$\nabla . \mathbf{q}' = 0, \tag{10}$$

$$\left(1+\overline{\lambda}_1 \frac{\partial}{\partial t}\right)\left[\frac{\rho_0}{\varepsilon}\frac{\partial \mathbf{q}'}{\partial t} + \nabla p' + \rho_0(\beta_T T' - \beta_S S')g\right] = \left(1+\overline{\lambda}_2 \frac{\partial}{\partial t}\right)\left(\mu_e \nabla^2 \mathbf{q}' - \frac{\mu}{K}\mathbf{q}'\right), \tag{11}$$

$$\gamma \frac{\partial T'}{\partial t} + \left(\mathbf{q}'.\nabla\right) T' + w' \frac{\partial T_b}{\partial z} = \kappa_T \nabla^2 T' + Q T', \tag{12}$$

$$\varepsilon \frac{\partial S'}{\partial t} + \left(\mathbf{q}'.\nabla\right) S' + w' \frac{\partial S_b}{\partial z} = \kappa_S \nabla^2 S' + D_1 \nabla^2 T', \tag{13}$$

where $\rho' = -\rho_0\left[\beta_T T' - \beta_S S'\right]$.

By operating curl twice on Eq. (11) we eliminate p' and then use the scaling

$$\begin{aligned}&\left(x',y',z'\right)=\left(x^*,y^*,z^*\right)d,\ \left(u',v',w'\right)=\left(\kappa_T/d\right)\left(u^*,v^*,w^*\right),\\&t'=t^*\left(\gamma d^2/\kappa_T\right),\ T'=\left(\Delta T\right)T^*,\ S'=\left(\Delta S\right)S^*,\end{aligned}\tag{14}$$

to non-dimensionalize equations (10)-(13) in the form (on dropping the asterisks),

$$\left(1+\lambda_1\frac{\partial}{\partial t}\right)\left[\frac{1}{Pr_D}\frac{\partial}{\partial t}\nabla^2 w-Ra_T\nabla_1^2T++Ra_S\nabla_1^2S\right]-\left(1+\lambda_2\frac{\partial}{\partial t}\right)\left(Da\nabla^4w-\nabla^2w\right)=0,\tag{15}$$

$$\left[\frac{\partial}{\partial t}-\nabla^2-R_i+\left(q\cdot\nabla\right)\right]T-w=0,\tag{16}$$

$$\left[\varepsilon_n\frac{\partial}{\partial t}-\frac{1}{Le}\nabla^2+\left(q\cdot\nabla\right)\right]S-Sr\,\nabla^2T-w=0,\tag{17}$$

where $R_i=Qd^2/\kappa_T$ is the internal Rayleigh number , $\lambda_1=\dfrac{\bar{\lambda}_1\kappa_T}{\gamma d^2}$, relaxation parameter, $\lambda_2=\dfrac{\bar{\lambda}_2\kappa_T}{\gamma d^2}$, retardation parameter, $Da=\dfrac{\mu_eK}{\mu d^2}$, Darcy Number, $\Pr_D=\dfrac{\gamma\varepsilon\nu d^2}{\kappa_TK}$, Darcy-Prndtl number, $Le=\dfrac{\kappa_T}{\kappa_S}$, Lewis number, $Sr=\dfrac{D_1\beta_S}{\kappa_T\beta_T}$, Soret parameter, $Ra_T=\dfrac{\beta_Tg\Delta TdK}{\nu\kappa_T}$, thermal Rayleigh number, $Ra_S=\dfrac{\beta_Sg\Delta SdK}{\nu\kappa_T}$, solute Rayleigh number, $\varepsilon_n=\varepsilon/\gamma$, normalized porosity, $\nabla_1^2=\dfrac{\partial^2}{\partial x^2}+\dfrac{\partial^2}{\partial y^2}$, $\nabla^2=\nabla_1^2+\dfrac{\partial^2}{\partial z^2}$.

Since the boundaries are assumed to be stress free, isothermal and isohaline, the Eqs. (15-17).

$$w=\frac{\partial^2w}{\partial z^2}=T=S=0,\ at\ z=0,1.\tag{18}$$

3. LINEAR STABILITY ANALYSIS

In this section we predict the thresholds of both marginal and oscillatory convections. The Eigenvalue problem defined by Eqs. $(15)-(17)$ and subjected to the boundary conditions (18) is solved using the time-dependent periodic disturbances in a horizontal plane. Assuming that the amplitudes of the perturbations are very small, we write

$$\begin{pmatrix}w\\T\\S\end{pmatrix}=\begin{pmatrix}W(z)\\\Theta(z)\\\Phi(z)\end{pmatrix}exp\left[i\left(lx+my\right)+\sigma t\right],\tag{19}$$

where l,m are horizontal wave numbers and σ is the growth rate. Infinitesimal perturbations of the rest state may either dampen or grow depending on the value of the parameter σ .

Substituting Eq. (19) into the linearized version of Eqs. $(15)-(17)$, we obtain

$$\left(1+\lambda_1\sigma\right)\left[\frac{\sigma}{Pr_D}\left(D^2-a^2\right)W+Ra_Ta^2\Theta-Ra_Sa^2\Phi\right]-\left(1+\lambda_2\sigma\right)\left(D^2-a^2\right)\left[Da\left(D^2-a^2\right)^2-1\right]W=0,\tag{20}$$

$$\left[\sigma-\left(D^2-a^2\right)-R_i\right]\Theta-W=0,\tag{21}$$

$$\left[\varepsilon_n\sigma-Le^{-1}\left(D^2-a^2\right)\right]\Phi-W-S\ \ (D^2-a^2)\Theta-=0,\tag{22}$$

where $D\equiv d/dz$ and $a^2=l^2+m^2$,

The boundary conditions (18) now becomes

$$W=D^2W=\Theta=\Phi=0\ \text{at}\ z=0,1.\tag{23}$$

We assume the solutions in the form

$$\left(W(z),\Theta(z),\Phi(z)\right)=\left(W_0,\Theta_0,\Phi_0\right)\mathrm{Sin}\,n\pi z\,,\ (n=1,2,3,......). \tag{24}$$

Substituting Eq. (24) with $n=1$ (fundamental mode) into Eqs. (20)- (22), for non-trivial solution of W_0,Θ_0, and Φ_0 , we require

$$Ra_T=\left(\sigma+k_1^2-R_i\right)\left\{\frac{\left[\sigma\,Pr_D^{-1}+\Lambda\left(Da\,k_1^2+1\right)\right]k_1^2\left(\varepsilon_n\sigma+k_1^2Le^{-1}\right)-Srk_1^2a^2Ra_S}{a^2\left(\varepsilon_n\sigma+k_1^2Le^{-1}\right)}\right\} \tag{25}$$

where $k_1^2=\pi^2+a^2,\ \Lambda=\dfrac{1+\lambda_2\sigma}{1+\lambda_1\sigma}$.

3.1 Stationary Convection

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

$$Ra_T^{St}=\left(k_1^2-R_i\right)\left[\frac{k_1^2\left(Da\,k_1^2+1\right)}{a^2}-Sr\,LeRa_S\right]. \tag{26}$$

The critical cell size at the onset of instability is obtained from the condition $\left(\dfrac{\partial Ra_T^{St}}{\partial a}\right)_{a=a_c}=0$, which gives $a_c=\pi$ (for brevity we have skipped one step)

In the absence of a heat source (i.e., R_i = 0) Eq. (26) reduces to

$$Ra_T^{St}=k_1^2\left[\frac{k_1^2\left(Dak_1^2+1\right)}{a^2}-SrLeRa_S\right]. \tag{27}$$

In absence of the Soret parameter (i.e., $Sr=0$) the above Eq. (27) reduces to

$$Ra_T^{St}=\frac{k_1^4\left(Dak_1^2+1\right)}{a^2}. \tag{28}$$

when $Da\to 0,$ that is for densely packed porous medium Eq. (28) becomes

$$Ra_T^{St}=\frac{\left(\pi^2+a^2\right)^2}{a^2}, \tag{29}$$

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 Convection

We now set $\sigma=i\,w_i$ in Eq. (25) and clear the complex quantities from the denominator and rearrange the real and complex parts. Since Ra_T is a physical quantity, it must be real. Hence, it follows that either $\omega_i=0$ (steady onset) or complex part equals to zero ($\omega_i\neq 0$, oscillatory onset). For oscillatory onset we have

$$Ra_T^{Osc}=\frac{1}{a^2}\left\{\frac{\omega^2}{Pr_D\left(\varepsilon_n\omega\right)^2+\left(k_1Le^{-1}\right)^2}+\frac{\omega^2\left(\lambda_2-\lambda_1\right)+k_1^2\left(k_1^2-R_i\right)\left(Dak_1^2+1\right)}{\left(1+\lambda_2{}^2\omega^2\right)}-k_1^2SrRa_S\left(k_1^2-R_i\right)\right\}. \tag{30}$$

The analytical expression for the oscillatory Rayleigh number given by Eq. (30) is minimized with respect to the wavenumber numerically to know their effects on the onset of oscillatory convection.

4. RESULTS AND DISCUSSION

We have studied the Soret effect on the onset of convection in a binary viscoelastic fluid saturated porous layer with internal heat source using linear stability analysis. The expressions for stationary and oscillatory Rayleigh numbers are derived analytically and the graphs are plotted for different values of different parameters and the results are discussed here.

The figures (1-5) show the effect of oscillatory Rayleigh number with the solute Rayleigh number for different values of various parameters. Fig. 1 depicts the effect of Soret parameter Sr on oscillatory Rayleigh number with Ra_S . From this figure we observe that an increase in the values (positive) of the Soret parameter decreases the oscillatory Rayleigh number indicating that the effect of the Soret parameter destabilizes the system for oscillatory mode. On the other hand, for increasing in the negative Soret parameter increases the oscillatory Rayleigh number indicating that the effect of negative Soret parameter stabilizes the system for oscillatory convection. From Fig. 2, we find that increasing the values of normalized porosity ε_n increases the oscillatory Rayleigh number indicating that the effect of normalized porosity stabilizes the system for oscillatory mode.

Fig. 3 displays the effect of the Lewis number Le on the oscillatory Rayleigh number with the solute Rayleigh number. From this figure we observe that an increase of the Lewis number increases the oscillatory Rayleigh number implying that the effect of Lewis number stabilizes the system. Fig. 4 depicts the effect of Dracy-Prandtl number Pr_D on oscillatory convection. From this figure we find that an increase in the values of Dracy-Prandtl number decreases the oscillatory Rayleigh number indicating that the Darcy- Parndtl number advances the onset of double diffusive convection. The effect of an internal Rayleigh number R_i on oscillatory convection is depicted in the Fig. 5. From this figure we observe that an increase in the value of internal Rayleigh number R_i increases the oscillatory Rayleigh number indicating that the effect of R_i stabilizes the system for oscillatory convection.

5. CONCLUSIONS

The Soret effect on the onset of convection in a binary viscoelastic fluid saturated porous layer with internal heat source is studied using linear stability analysis which is based on the usual normal mode technique and the following important conclusions are drawn:

1. The effect of Soret parameter stabilizes the system for negative values of Sr while destabilizes the system for positive values of the Soret parameter for oscillatory convection.
2. The normalized porosity, the Lewis number and an internal Rayleigh number have stabilizing effects in the system of oscillatory convection.
3. The Darcy –Prandtl number has destabilizing effect for oscillatory mode.

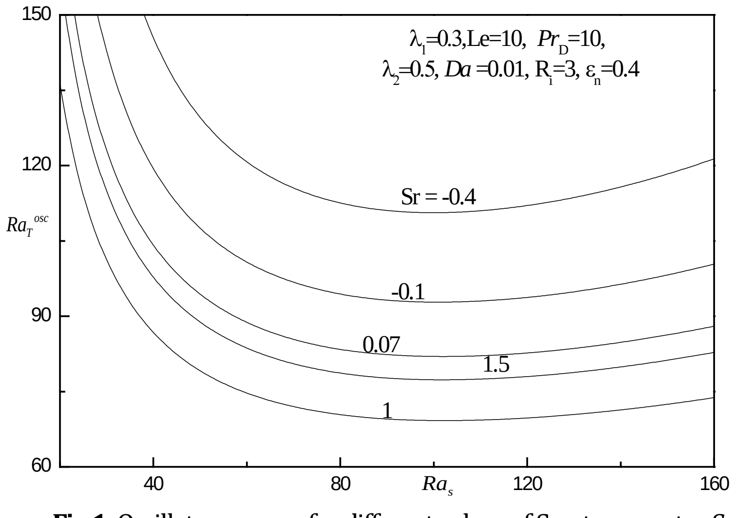

Fig.1. Oscillatory curves for different values of Soret parameter *Sr*.

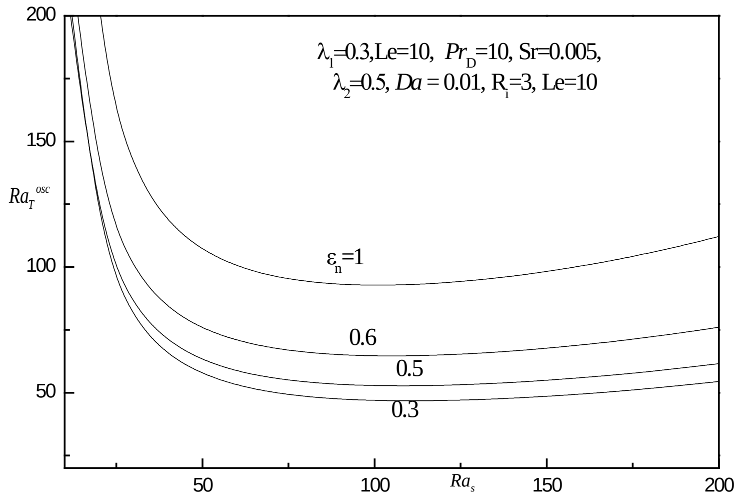

Fig.2. Oscillatory curves for different values of normalized porosity ε_n.

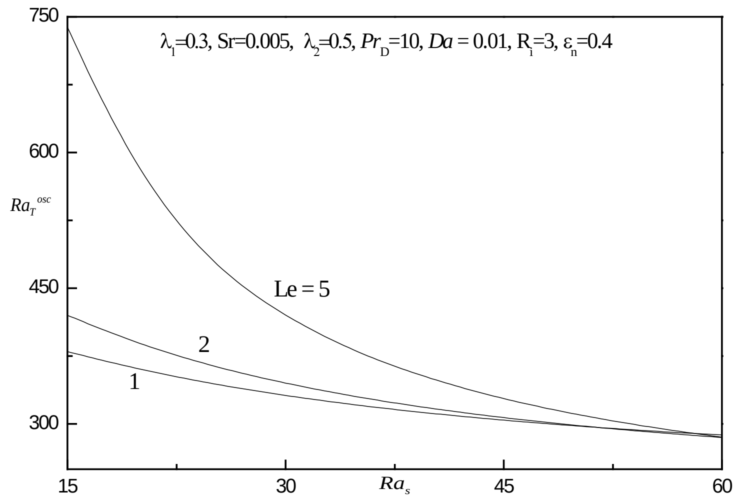

Fig.3. Oscillatory curves for different values of Lewis number *Le*.

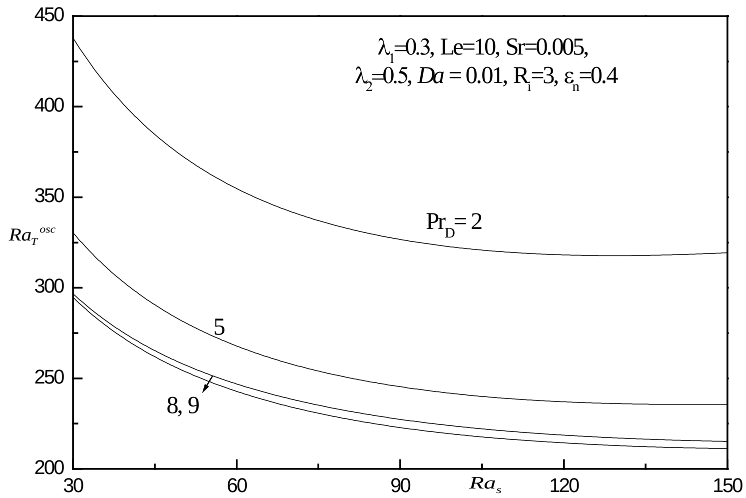

Fig.4. Oscillatory curves for different values of Darcy-Prandtl number Pr_D.

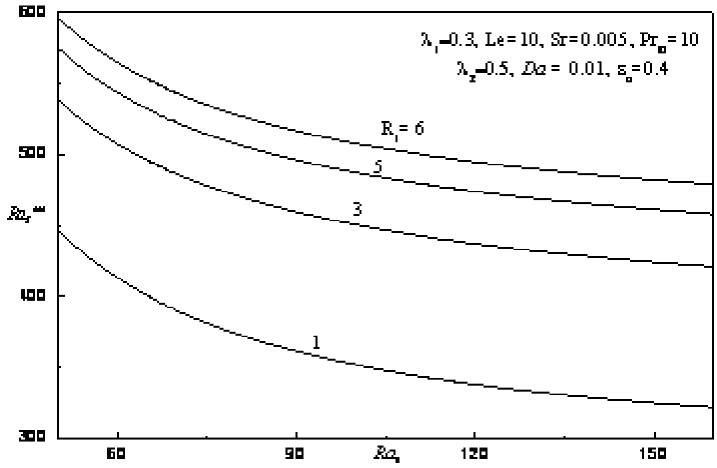

Fig.5. Oscillatory curves for different values of internal Rayleigh number R_i.

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