A Study of Linear Double Diffusive Convection in Fluid-Saturated Anisotropic Rectangular Porous Channels with Cross-Diffusion Effects

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Abstract

Dufour and Soret effects on flow in a fluid-saturated anisotropic porous media are studied in this paper. A two dimensional Darcy model without time derivative is employed for the momentum equation. Walls of the channels heated and salted from below in the presence of Soret and DuFour effects, is studied using linear stability analysis. The effects of anisotropy parameter, solute Rayleigh number and Soret and DuFour effects on onset of convection are discussed.

Keywords: Double diffusive convection, Anisotropy, Double Fourier series, Rayleigh number Soret/DuFour parameter.

1.1 Introduction

The double diffusive convection in porous media has become important in recent years because of its many applications in geophysics, particularly in saline geothermal fields where hot brines remain beneath less saline, cooler ground water. In a system where two diffusing properties are present, instabilities can occur only if one of the components are destabilizing. When heat and mass transfer occur simultaneously in a moving fluid, the relation between the fluxes and the driving potentials are of more intricate in nature. It has been found that an energy flux can be generated not only by temperature gradient but also by composition gradients as well. The energy flux caused by a composition gradient is called the Dufour or diffusion-thermo effect. On the other hand, mass fluxes can also be created by temperature gradients and this is the Soret or thermal- diffusion effect. If the cross-diffusion terms are included in the species transport equations, then the situation will be quite different. Due to cross-diffusion effects, each property gradient has a significant influence on the flux of the other property.

There are many studies available on the effect of cross diffusions on the onset of double diffusive convection in a porous medium.

Heat and mass transfer by natural convection at a stagnation point in a porous medium considering Soret and DuFour effects, recently studied by Adrain Postelnicu (2010). Ahmed and Afify (2007) have investigated effects of temperature-dependent viscosity with soret and dufour numbers on non-darcy MHD free convective heat and mass transfer past a vertical surface embedded in a porous medium. Alam et al., (2006) have investigated by Dufour and Soret effects on steady free convection and mass transfer flow past a semi-Infinite vertical porous plate in a porous medium. Gaikwad et.al.,(2009) discussed linear and non-linear double diffusive convection in a fluid-saturated anisotropic porous layer with cross diffusion effects (2009). Hassan (2009) have studied Soret and DuFour effects on natural convection flow past a vertical surface in a porous medium with variable surface temperature. Mojtabi A. Charrier-Mojtabi M.C. (2000 & 2005) discussed double diffusive convection in porous media. The book available on the effects of cross diffusions on the onset of double diffusive convection in a porous medium by Nield and Bejan (2006). Nilesen T. and Storesletton L. (1990) studied an analytical study of natural convection in isotropic and anisotropic porous channels. Balagondar P.M and Pranesha Setty A., (2012).discussed a study of natural convection in anisotropic porous rectangular channels using a thermal non-equilibrium model. The double diffusive convection in a porous medium in the presence of Soret and DuFour coefficients has been analyzed by Rudraiah and Malashetty (1996) extended to weak non-linear analysis by Rudraiah and siddheshwar (1998). Trevisan O.V.., Bejan A. (1999). Have studied Combined heat and mass transfer by natural convection in a porous media. A study of convective instability in a fluid mixture heated from above with negative separation ratio (Soret coefficient) was performed experimentally by La Porta and Surko (1998). J. Wang., etal (2014), investigated onset of double-diffusive convection in horizontal cavity with Soret and Dufour effects. A. Lagra., etal, discussed (2015) Double diffusive convection in a shallow horizontal binary fluid in the presence of Soret and Dufour effects.

1.2 Mathematical Formulation

We consider two-dimensional free convection in a horizontal porous media heated and salted from below is considered (see figure 1). A constant gradient of temperature ΔT and salinity ΔS is maintained between the boundaries. The Darcy model without time derivative is employed for the momentum equation and the both the cross-diffusion terms are included in the temperature and concentration equations. The channel is rectangular with height h and width a, we choose a cartesian co-ordinate system with z-axis is in the vertical direction and x-axis is the horizontal direction perpendicular to the channel axis. The horizontal channel walls are z = 0 and z = h and the vertical walls at $x = -\frac{a}{2}$ and $x = \frac{a}{2}$. On assuming that the Prandtl-Darcy number is large, so that inertia term may be neglected and invoking Boussinesq approximation, the governing equations are

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0, \qquad (1.2.1)$$

$$0 = -\frac{\partial p}{\partial x} - \frac{\mu}{k_x} u, \tag{1.2.2}$$

$$0 = -\frac{\partial p}{\partial z} - \frac{\mu}{k_z} w - \rho g, \tag{1.2.3}$$

$$\gamma \frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + w \frac{\partial T}{\partial z} = \kappa_{11} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) + \kappa_{12} \left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial z^2} \right), \tag{1.2.4}$$

$$\varepsilon \frac{\partial S}{\partial t} + u \frac{\partial S}{\partial x} + w \frac{\partial S}{\partial z} = \kappa_{21} \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} \right) + \kappa_{22} \left(\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial z^2} \right), \tag{1.2.5}$$

$$\rho = \rho_0 \left[1 - \beta_T (T - T_0) + \beta_s (S - S_0) \right], \tag{1.2.6}$$

where u and v are the Darceian velocity vector, p the pressure, g the acceleration due to gravity .T the temperature, S the concentration , ε the porosity, κ_x *and* κ_z are the anisotropic permeability tensor, $\gamma = (\rho c_p)_m / (\rho c_p)_f$ with $(\rho c_p)_m = (1-\varepsilon)(\rho c_p)_s + \varepsilon(\rho c_p)_f$, $k_x, k_z, \rho, \mu, \gamma, \beta_T$ and β_s denote the permeability horizontal direction, permeability in z direction, density , viscosity , specific heat ratio, thermal and solute expansion coefficients respectively, κ_{11} thermal diffusivity κ_{12} cross diffusion due to S component, κ_{21} cross diffusion due to T component and κ_{22} is the mass diffusivity.

1.2.1. Basic State

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

$$(u, v, w) = (0, 0, 0),\ p = p_b(z),\ T = T_b(z),\ S = S_b(z),\ \rho = \rho_b(z), \tag{1.2.7}$$

using the equation (1.2.7) in (1.2.1) – (1.2.6) we get

$$\frac{d p_b}{d z} = -\rho_b(z),\ \frac{d^2 T_b}{d z^2} = 0,\ \frac{d^2 S_b}{d z^2} = 0,\ \rho_b = \rho_0 \left[1 - \beta_T (T_b - T_0) + \beta_s (S_b - S_0) \right],$$

$$T_b = T_0 + \Delta T \left(1 - \frac{z}{d} \right),\ S_b = S_0 + \Delta S \left(1 - \frac{z}{d} \right). \tag{1.2.8}$$

1.2.2. Perturbed State

Applying a small perturbations in the form

$$\left. \begin{aligned} q &= q_b(z) + q'(x, y, z, t), \\ T &= T_b(z) + \theta'(x, y, z, t), \end{aligned} \right\} \tag{1.2.9}$$

$S = S_b(z)+\phi\,(x,y,z,t),$

$p\ = p_b(z)+p'\,(x,y,z,t),$

$\rho\ = \rho_b\,(z)+\rho'\,(x,y,z,t)\,.$

Where $'$ indicate perturbations. Introducing (1.2.9) in equations (1.2.1)-(1.2.6) and using the basic state (1.2.8), we get

$$\frac{\partial u'}{\partial x}+\frac{\partial w'}{\partial z}=0 \tag{1.2.10}$$

$$0=-\frac{\partial p'}{\partial x}-\frac{\mu}{k_x}u', \tag{1.2.11}$$

$$0=-\frac{\partial p'}{\partial z}-\frac{\mu}{k_z}w'-\rho' g, \tag{1.2.12}$$

$$\gamma\frac{\partial\theta'}{\partial t}+u'\frac{\partial\theta'}{\partial x}+w'\frac{\partial\theta'}{\partial z}=\kappa_{11}\left(\frac{\partial^2\theta'}{\partial x^2}+\frac{\partial^2\theta'}{\partial z^2}\right)+\kappa_{12}\left(\frac{\partial^2 S'}{\partial x^2}+\frac{\partial^2 S'}{\partial z^2}\right), \tag{1.2.13}$$

$$\varepsilon\frac{\partial\phi'}{\partial t}+u'\frac{\partial\phi'}{\partial x}+w'\frac{\partial\phi'}{\partial z}=\kappa_{21}\left(\frac{\partial^2\theta'}{\partial x^2}+\frac{\partial^2\theta'}{\partial z^2}\right)+\kappa_{22}\left(\frac{\partial^2\phi'}{\partial x^2}+\frac{\partial^2\phi'}{\partial z^2}\right), \tag{1.2.14}$$

$$\rho'=-\rho_0(\beta_T T'-\beta_s S'). \tag{1.2.15}$$

Since the flow is two dimensional, we introduce stream function ψ in the form:

$$(u',\,w')=\left(\frac{\partial\psi}{\partial z},-\frac{\partial\psi}{\partial x}\right). \tag{1.2.16}$$

Eliminating pressure from (1.2.2)-(1.2.3), applying stream functions and non dimensionalsing using following non-dimensional parameters in (1.2.1) – (1.2.5)

$$(x^*,z^*)=\left(\frac{x}{d},\frac{z}{d}\right),\ t^*=\frac{t}{d^2/\kappa_{11}},\ \psi^*=\frac{\psi}{\kappa_{11}},\ \theta^*=\frac{\theta}{\Delta\theta},\ \phi^*=\frac{\phi}{\Delta\phi},$$

we obtain

$$\xi\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial z^2}=-\xi\,Ra_T\frac{\partial\theta}{\partial x}+\xi\,Ra_s\frac{\partial\phi}{\partial x}, \tag{1.2.17}$$

$$\left(\frac{\partial}{\partial t}-\nabla^2\right)\theta=-\frac{\partial\psi}{\partial x}+\frac{\partial(\psi,\theta)}{\partial(x,z)}+Du\frac{Ra_S}{Ra_T}\nabla^2\phi, \tag{1.2.18}$$

$$\left(\varepsilon\frac{\partial}{\partial t}-\tau\nabla^2\right)\phi=-\frac{\partial\psi}{\partial x}+\frac{\partial(\psi,\phi)}{\partial(x,z)}+Sr\frac{Ra_T}{Ra_S}\nabla^2\theta. \tag{1.2.19}$$

where

$Ra_T = \dfrac{\beta_T \, g \, \Delta T \; d \, k_z}{\nu \, \kappa_{11}}$ Thermal Rayleigh number

$Ra_S = \dfrac{\beta_S \, g \, \Delta S \; d \, k_z}{\nu \, \kappa_{11}}$ Solutal Rayleigh number

$Du = \dfrac{\kappa_{12}}{\kappa_{11}} \dfrac{\beta_T}{\beta_S}$ DuFour parameter

$Sr = \dfrac{\kappa_{21}}{\kappa_{11}} \dfrac{\beta_S}{\beta_T}$ Soret parameter

$\xi = \dfrac{k_z}{k_x}$ anisotropy parameter

$\nu = \dfrac{\mu}{\rho_0}$ kinematic viscosity

The asterisks have been dropped and setting $\gamma = 1$ to restrict the number of parameters.

1.3 Linear Stability analysis and numerical solution

The linearised forms of the governing equations are

$$\xi \frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} = -\xi \, Ra_T \, \frac{\partial \theta}{\partial x} + \xi \, Ra_s \, \frac{\partial \phi}{\partial x} , \tag{1.3.1}$$

$$\left(\frac{\partial}{\partial t} - \nabla^2 \right) \theta = -\frac{\partial \psi}{\partial x} + Du \, \frac{Ra_S}{Ra_T} \, \nabla^2 \phi \quad , \tag{1.3.2}$$

$$\left(\varepsilon \frac{\partial}{\partial t} - \tau \nabla^2 \right) \phi = -\frac{\partial \psi}{\partial x} + Sr \, \frac{Ra_T}{Ra_S} \, \nabla^2 \theta . \tag{1.3.3}$$

The boundary conditions used are

$$\psi = \theta = \phi = 0 \quad \text{at} \quad \left\{ \begin{array}{l} x = -\frac{1}{2}, \quad x = \frac{1}{2}, \quad 0 < z < 1 \\ z = 0, \quad z = 1 \; , \; -\frac{1}{2} < x < \frac{1}{2} \end{array} \right\} . \tag{1.3.4}$$

$$\psi = e^{\sigma t}\left[\frac{1}{2}C_0 + \sum_{n=1}^{\infty} C_n(x)\, con\, n\pi z + \sum_{n=1}^{\infty} D_n(x)\, \sin n\pi z\right], \qquad (1.3.5)$$

$$\theta = e^{\sigma t}\left[\frac{1}{2}F_0 + \sum_{n=1}^{\infty} F_n(x)\cos n\pi z + \sum_{n=1}^{\infty} G_n(x)\, \sin n\pi z\right], \qquad (1.3.6)$$

$$\phi = e^{\sigma t}\left[\frac{1}{2}H_0 + \sum_{n=1}^{\infty} H_n(x)\cos n\pi z + \sum_{n=1}^{\infty} I_n(x)\, \sin n\pi z\right]. \qquad (1.3.7)$$

Where C_n, D_n, F_n, G_n, H_n and I_n are function of x only and σ is growth rate. The boundary conditions (1.3.4) are satisfied if $C_n = F_n = H_n = 0$ for all x. Comparing the $\sin n\pi z$ terms for ψ, θ and ϕ, for marginal stability $\sigma = 0$, with single-mode component then the above equations is reduces in the form

$$\psi = D(x)\, \sin \pi z\,, \qquad (1.3.8)$$

$$\theta = G(x)\, \sin \pi z\,, \qquad (1.3.9)$$

$$\phi = I(x)\, \sin \pi z\,. \qquad (1.3.10)$$

These satisfy the boundary conditions (1.3.4) on the horizontal boundary.
In terms of D, G and I the boundary conditions are

$$D\left(\pm\frac{1}{2}\right) = 0,\ G\left(\pm\frac{1}{2}\right) = 0 \text{ and } I\left(\pm\frac{1}{2}\right) = 0. \qquad (1.3.11)$$

By eliminating D(x) and I(x) from (1.3.1) – (1.3.3) we get sixth order differential equation in the form:

$$[(\tau\xi - \xi S_1 S_2)\, D^6 - (\pi^4\tau + Ra_S\,\xi + 2\pi^2\tau\xi - Ra_T\,\tau\xi + Ra_T\,\xi\, S_1 - Ra_S\,\xi S_2 - \pi^2 S_1 S_2$$
$$- 2\pi^2\xi S_1 S_2 + \pi^4\xi S_1 S_2) D^4 + (2\pi^4\tau + \pi^2 Ra_S\,\xi + \pi^4\tau\xi - \pi^2 Ra_T\,\tau\xi + \pi^2 Ra_T\,\xi S_1$$
$$- \pi^2 Ra_S\,\xi S_2 - 2\pi^4 S_1 S_2) - \pi^6(\tau - S_1 S_2)]G(x) = 0. \qquad D = \frac{d}{dx}$$

(1.3.12)

Where $S_1 = Du\,\dfrac{Ra_s}{Ra_T}$, $S_2 = Sr\,\dfrac{Ra_T}{Ra_s}$ (1.3.13)

with boundary conditions

$$G_n\left(\pm\frac{1}{2}\right) = G'\left(\pm\frac{1}{2}\right) = G''\left(\pm\frac{1}{2}\right) = 0\,. \qquad (1.3.14)$$

The general solution of equation (6.3.12) is

$$G(x) = c_1 e^{m_1 x} + c_2 e^{m_2 x} + c_3 e^{m_3 x} + c_4 e^{m_4 x} + c_5 e^{m_5 x} + c_6 e^{m_6 x}\,, \qquad (1.3.15)$$

where c_i 's are arbitrary constants and m_i 's roots of the auxiliary equation of (1.3.12). Since the auxiliary equation involves cubic in D^2, put $m_2 = -m_1,\ \ m_4 = -m_3,\ \ m_6 = -m_5,$

where

$$m_1 = \frac{1}{6\,\delta_1^{\,2}}\left[2\delta_2^{\,2} + \left(2^{\frac{4}{3}}\,\frac{k_1}{k_3}\right) + \left(2^{\frac{2}{3}}\,k_3\right)\right], \tag{1.3.16}$$

$$m_3 = \frac{1}{12\delta_1^{\,2}}\left[4\,\delta_2^{\,2} - \left(2^{\frac{4}{3}}\left(1+\sqrt{-3}\right)\frac{k_1}{k_3}\right) + \left(2^{\frac{2}{3}}\left(-1+\sqrt{-3}\right)k_3\right)\right], \tag{1.3.17}$$

$$m_5 = \frac{1}{12\,\delta_1^{\,2}}\left[4\,\delta_2^{\,2} + \left(2^{\frac{4}{3}}\left(-1+\sqrt{-3}\right)\frac{k_1}{k_3}\right) - \left(2^{\frac{2}{3}}\left(1+\sqrt{-3}\right)k_3\right)\right]. \tag{1.3.18}$$

$$\left.\begin{aligned}
&\delta_1^{\,2} = \tau\,\xi - \xi\,S_1\,S_2, \\
&\delta_2^{\,2} = \pi^4\,\tau + Ra_S\,\xi + 2\pi^2\,\tau\,\xi - Ra_T\,\tau\,\xi + Ra_T\,\xi\,S_1 - Ra_S\,\xi\,S_2 - \pi^2 S_1\,S_2 \\
&\qquad - 2\pi^2\,\xi\,S_1\,S_2 + \pi^4\,\xi\,S_1\,S_2 \\
&\delta_3^{\,2} = 2\pi^4\,\tau + \pi^2\,Ra_S\,\xi + \pi^4\,\tau\,\xi - \pi^2\,Ra_T\,\tau\,\xi + \pi^2\,Ra_T\,\xi\,S_1 - \pi^2\,Ra_S\,\xi\,S_2 - 2\pi^4 S_1 S_2 \quad . \\
&\delta_4^{\,2} = \pi^6\,(\tau - S_1 S_2),\ \ k_1 = \delta_2^{\,4} - 3\delta_1^{\,2}\,\delta_3^{\,2}\ ,\ k_2 = 2\delta_2^{\,6} - 9\delta_1^{\,2}\delta_2^{\,2}\delta_3^{\,2} + 27\delta_1^{\,4}\,\delta_4^{\,2}, \\
&k_3 = \left(k_2 + \sqrt{-4(k_1)^3 + (k_2)^{\,2}}\right)^{\frac{1}{3}}
\end{aligned}\right\} . \tag{1.3.19}$$

For a non-trivial solution of the system of equations (3.8), (4.0) and (4.1), we require:

$$\begin{vmatrix}
e^{0.5\,m_1} & e^{-0.5\,m_1} & e^{0.5\,m_3} & e^{-0.5\,m_3} & e^{0.5\,m_5} & e^{-0.5\,m_5} \\
e^{-0.5 m_1} & e^{0.5\,m_1} & e^{-0.5\,m_3} & e^{0.5\,m_3} & e^{-0.5\,m_5} & e^{0.5\,m_5} \\
m_1 e^{0.5\,m_1} & -m_1 e^{-0.5\,m_1} & m_3 e^{0.5\,m_3} & -m_3 e^{-0.5\,m_3} & m_5 e^{0.5\,m_5} & -m_5 e^{-0.5\,m_5} \\
m_1 e^{-0.5\,m_1} & -m_1 e^{0.5\,m_1} & m_3 e^{-0.5\,m_3} & -m_3 e^{0.5\,m_3} & m_5 e^{-0.5\,m_5} & -m_5 e^{0.5\,m_5} \\
(m_1)^2 e^{0.5\,m_1} & (m_1)^2 e^{-0.5\,m_1} & (m_3)^2 e^{0.5\,m_3} & (m_3)^2 e^{-0.5\,m_3} & (m_5)^2 e^{0.5\,m_5} & (m_5)^2 e^{-0.5\,m_5} \\
(m_1)^2 e^{-0.5\,m_1} & (m_1)^2 e^{0.5\,m_1} & (m_3)^2 e^{0.5\,m_3} & (m_3)^2 e^{-0.5\,m_3} & (m_5)^2 e^{0.5\,m_5} & (m_5)^2 e^{-0.5\,m_5}
\end{vmatrix} = 0. \tag{1.3.20}$$

The left hand side of (1.3.20) may be viewed as a function of Ra, say $f(Ra_c)$, with Ra_c depending on Ra_s, Sr and Du hence equation (1.3.20) can be written as $f(Ra_c)=0$. Using Newton-Raphson method for various values of Ra_s, Sr, D_u and Ra_c can be calculated numerically.

$$[Ra_C]_{k+1} = (Ra_C)_k - \frac{f(Ra_C)_k}{f'(Ra_C)_k},$$

$$\text{where} \quad f'((Ra_c)_k) = \underset{\delta Ra_c \to 0}{Lt}\left[\frac{f((Ra_c)_k + \delta Ra_c) - f((Ra_c)_k)}{\delta Ra_c}\right] \tag{1.3.21}$$

1.4 Results and Discussion

The variation of small critical Rayleigh number Ra_c with solute Rayleigh number Ra_s for different values of mechanical anisotropy parameter ξ and for fixed values of $Sr=1.0$, $Du=0.03$ and $\tau=0.9$ is shown in figure 1. We observe that critical Rayleigh number decreases with increasing anisotropy parameter ξ indicating that the effect of increasing ξ is to advance the onset of convection. The effect of increasing ξ on the Rayleigh number diminishes as ξ becomes large.

Figure 2 shows the variation of the critical Rayleigh number Ra_c with solute Rayleigh number Ra_s for different values of Soret parameter and for fixed values of $\xi=0.2$, $Du=0.03$ and $\tau=0.9$. We find that as the Soret parameter increases positively, the critical Rayleigh number decreases. However, we find that the effect of increasing negative Soret number is to increase the Rayleigh number. This is due to fact that, for negative Soret number, the heavier component migrate towards the hotter region, thus counteracting the density gradient caused by temperature.

The effect of DuFour parameter on the critical Rayleigh number for fixed values of $Sr=1.0$, $\xi=0.2$ and $\tau=0.9$ is shown in figure 3. We observe from this figure that for small values of solute Rayleigh number, the effect of increasing DuFour parameter is to decrease the critical Rayleigh number.

In figure 4 the effect of diffusivity ratio on the critical Rayleigh number for fixed value of $\xi=0.2$, $Du=0.03$ and $Sr=1.0$. We observe that when Ra_s small, an increase in τ increases the critical Rayleigh number, indicating that the effect of increasing τ is to stabilize the system. However, for large value of the solute Rayleigh number, the trend reverses.

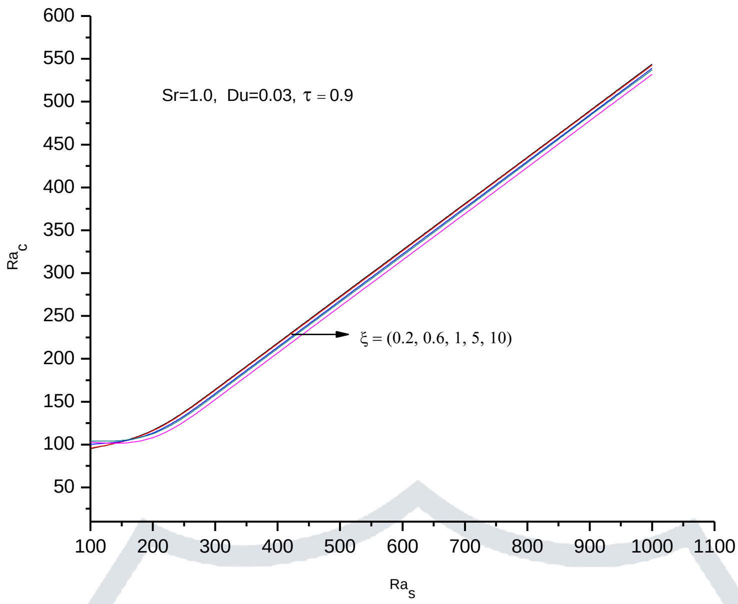

Figure1. Variation of critical Rayleigh number Ra_c with solutal Rayleigh number Ra_s for different values of mechanical anisotropy parameter ξ .

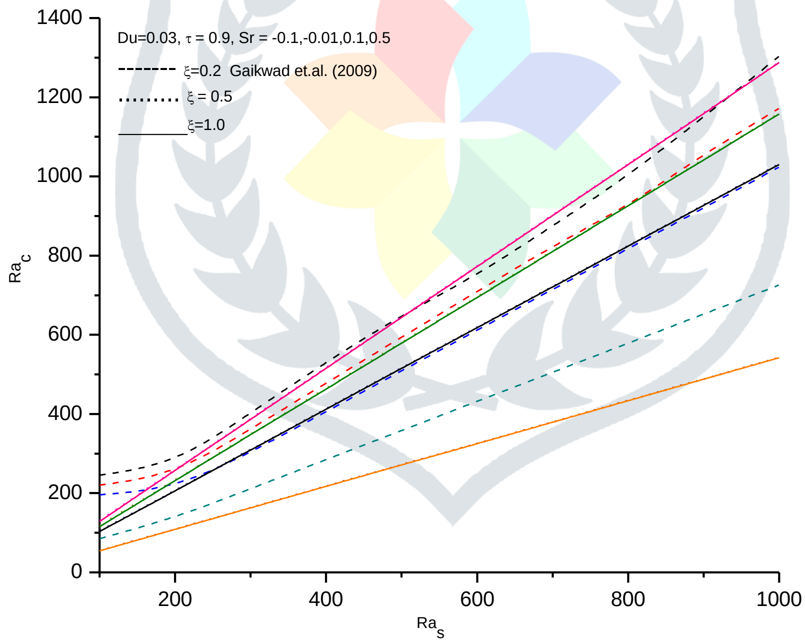

Figure 2. Variation of critical Rayleigh number Ra_c with solutal Rayleigh number Ra_s for different values of Soret parameter Sr

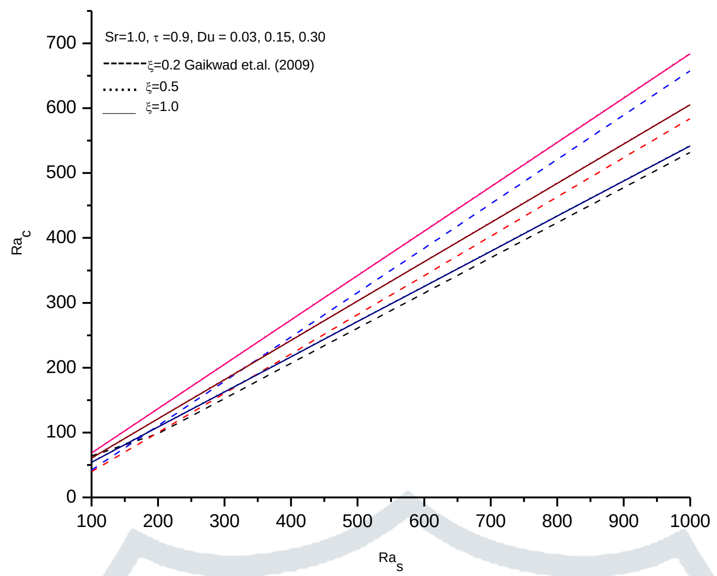

Figure 3. Variation of critical Rayleigh number Ra_c with solutal Rayleigh number Ra_s for different values of Soret parameter Du

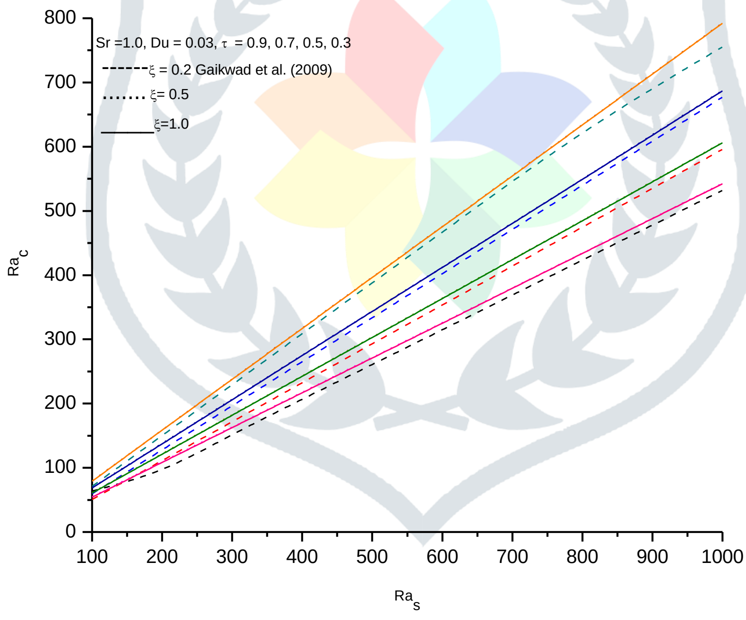

Figure 4. Variation of critical Rayleigh number Ra_c with solutal Rayleigh number Ra_s for different values of Soret parameter τ

1.5 Conclusion

The cross-diffusion effect on double diffusive convection in a horizontal rectangular channel saturated anisotropic porous media which is heated and salted below, is studied numerically. The effect of anisotropy parameter, solute Rayleigh number, Soret and DuFour parameters are shown graphically and the conclusions are the positive Soret parameter destabilizes the system, while the negative Soret parameter stabilizes the sysytem. The DuFour parameter destabilizes the system in stationary modes. The ratio of diffusivity stabilizes the system for small values of Ra_s and it destabilizes for large Ra_s.

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