International Journal of Research in Engineering and Applied Sciences(IJREAS)
Available online at http://euroasiapub.org
Vol. 8 Issue 12, December-2018,
ISSN (O): 2249-3905, ISSN(P): 2349-6525 | Impact Factor: 7.196 |

Thermosolutal instability caused by coupled molecular diffusion in a densely packed porous medium

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Abstract

The "Thermosolutal instability Caused by coupled molecular diffusion in a packed porous medium". The characteristic feature of this model is that, the flux of the solute depends not only on its own spatial gradient but also on the in situ temperature gradient. Here, the linear stability analysis of double-diffusive convection has been extended to include two cross-diffusion flux terms. It is found that even in the case of two-phase-system, for a sufficiently large coupled diffusion effect fingers are formed even when the concentration of both the components make The flu's density gradient statically stable. Finite amplitude analysis is carried out and the results are presented through graphs and are discussed.

1. Introduction

In past decades, the investigation on the phenomenon of the convective process in a horizontal fluid/porous layer has gained huge attention owing to its very large applications in science, engineering and industrial areas. Convection can be the dominant mode of heat and mass transport in many processes that involve the freezing and melting of the storage material. Natural convection is an omnipresent transport phenomenon in saturated porous geological structures. In fact, the study of convection is of most importance in geophysical, astrophysical and heat transfer problems. For example, the extraction of energy from geothermal sources is the most promising one among the other methods and it is believed that the fluid in these reservoirs are highly permeable and consists of multi-components rather than a single component. Therefore, buoyancy driven convection in a porous medium with water as the working fluid is an important mechanism of energy transport. In fact, the key feature of a major geothermal system while on the land or beneath the sea floor is a high intrinsic heat transport. In fact, the local thermal conditions and the physical properties of media are directly of great importance on the characteristics of the heat and mass transfer in such real configurations. Moreover, the nature of the fluid flow (2D, 3D, pattern and range) is drastically dependent on the complexity of geophysical sites, i.e., the geometry, heterogeneity and anisotropy of the domains. Fluid motions induced by free convection have tangible effects in geothermal areas, on the diffusion of pollutants or on the mineral diagenesis processes.

Technically, the phenomenon is important as it may occur in porous insulation of buildings thereby increasing the loss of heat. In the stellar atmosphere also, certain heavenly bodies may be considered to be porous material and the study has relevance to that also. Also, convection in planetary cores and stellar interiors often occurs in the presence of strong rotational and magnetic constraints. Over the past four decades, there has been an increasing concern about soil and water contamination from industrial and agricultural chemicals. In such cases, thermal and chemical interactions between a rotating porous layer and an overlying fluid layer can be considered. Such a study has many engineering and environmental applications also.

The study of convection in a fluid saturated porous layer is also of interest since it provides a convenient means for experimentally determining the nonlinear effects such as, the preferred cell pattern, heat transport etc. In the case of Rayleigh- Benard Convection, it is necessary to consider a thin fluid layer to detect these phenomena whereas in porous media, the depth of the fluid can be greatly increased since the frictional force is much larger. The study of porous convection has attracted the attention of considerable research workers because of its natural occurrence and its intrinsic importance in many industrial problems, particularly in petroleum exploration, chemical and nuclear industries. The mechanism of transfer of heat from the deep interior of the earth to a small depth in the geophysical region is of vital importance. These studies also help in power generation. More specifically, the results of the study of natural convection in a porous medium are useful in nuclear industries in the evaluation of the capability of heat removal from a hypothetical accident in a nuclear reactor.

As the fluid in the aquifers consists of multi-components rather than just a single component, there exists two sources of buoyancy. Further, multi-component onset of convection is important in many naturally occurring phenomena and technological processes. Examples include: Convection in stars, dynamics within the earth's core, oceanography, solar ponds, coating/drying processes and crystallization/solidification.

The Coriolis force caused by earth's rotation plays a significant role in the determination of the qualitative and quantitative features of the system. The effect of geomagnetic field and earth's rotation on the stability of geophysical flows is of great interest to geophysicists. While studying the stability of earth's core, the role of magnetic field becomes important, where the earth's mantle consisting of molten conducting fluid, behaves like a porous medium and can become convectively unstable as a result of differential diffusion. The reason for the occurrence of this phenomenon is that the stabilizing effect of one component is reduced by diffusion in the presence of a magnetic field, thereby releasing the potential energy of the unstable component. In geophysical problems, the effect of earth's rotation is considerable and distorts the boundaries of a hexagonal convective cell in a fluid / porous layer and this distortion plays an important role in the process of extraction of energy.

The multi-component onset of convection is important in many naturally occurring phenomena and technological processes. In double diffusive convection, heat and solute diffuse at different rates, as a result of which complex flow structures may form which have no counterpart in buoyant flows driven by a single component. Extensive literature pertaining to this phenomenon is available (Fujita and Gosting (1956); Stem (1960);Miller (1966); Miller et al. (1967);Nield (1968);Hurle and Jakeman (1971): Huppert and Manins (1972);Schechter et al (1972);Velarde and Schechter (1972); Vitagliano et al. (1972); Caldwell (1974);Turner (1974, 1985);Griffiths (1979); Antoranz and Venard (1979);Leaist and Lyons (1980); Placsek and Toomre

(1980);Narusawa and Suzukawa (1981); Srimani (1981). Takao, Tsuchiya and Narasuwa (1982); McTaggart (1983); Srimani (1984,1990); Torrones and Pearlstein (1989),Anamika (1990); Chen and Su (1992); Zimmermann Muller and Davis (1992);Tanny, Chen and Chen (1995);Shivakumar (1997); Skarda, Jacqmin and McCaughan (1998);).But in Type III, considered in this investigation, an additional effect viz., the effect of the coupled fluxes of the two properties due to irreversible thermodynamic effects is considered. This is termed as the effect of Coupled diffusion or Cross-diffusion and Soret effect is an example of this cross-diffusion where a flux of salt is caused by a spatial gradient of temperature. In fact, Dufour effect is the corresponding flux of heat caused by a spatial gradient of temperature.

Some literature (Hurle and Jakeman (1971); Skarda, Jacqmin and McCaughan (1998); Zimmermann et al (1992); Chen and Chen (1994)) in this direction are useful. Recently McDougall (1983) has made a detailed study of Double-diffusive convection caused by coupled molecular diffusion. The results of his linear stability analysis, predicts that for a sufficiently large coupled diffusion effect, fingers can form even when the concentrations of both the components make the fluid's density gradient statically stable. The conditions for the occurrence of finger as well diffusive instabilities are predicted. The results of his finite amplitude analysis reveal that for sufficiently large cross-diffusion effect, fingers do exist.

The effect which we considered in this investigation is that of the coupled fluxes of the two properties due to irreversible thermodynamic effects. The Soret effect is a familiar example of this cross diffusion where the flux of the solute depends not only on its own spatial gradient but also on the in situ temperature gradient. Linear as well as finite amplitude analyses are carried out

The present investigation aims at answering the following questions which arise in the study:

i) What is the effect of the porous parameter on the equivalent Rayleigh numbers in the presence of cross-diffusion?

ii) What are the conditions for the onset of 'finger' instability in the case of a densely packed porous medium?

iii) Do fingers form, when the concentrations of both the components makethe fluid's density gradient statically stable in a densely packed layer?

iv) Is it possible to predict the conditions under which double diffusive instability and finger instability occur? What is the role played by the porous parameter in these situations ?

v) Are there any similarities between the results pertaining to the study of double diffusive convection with cross-diffusion in ordinary fluid and in a densely packed porous layer?

vi) Is it possible to recover the results pertaining to double diffusive convection phenomenon in a densely packed medium in the absence of cross-diffusion, from the present results ?

vii) What is the role played by the porous parameter in the finite-amplitude analysis with the cross-diffusion terms?

viii)What additional features are introduced into the behaviour of a double diffusive convective system in a densely packed porous layer by the presence of cross-diffusion terms ?

2. Formulation and solution of the problem

$$\rho = \rho_0 - (1 + \alpha T + \beta S)$$

The set of dimensionless Boussinesq equations is

$$\frac{\partial T}{\partial t} - \nabla^2 T - \frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T}\nabla^2 S = -\psi_x \quad (1)$$

$$\frac{\partial S}{\partial t} - \frac{D_{22}}{D_{11}}\nabla^2 S - \frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S}\nabla^2 T = -\psi_x \quad (2)$$

$$\left(\frac{\partial}{\partial t} - \frac{\sigma}{P_l}\right)\nabla^2\psi = \sigma\left(R\frac{\partial T}{\partial x} + R_s\frac{\partial S}{\partial x}\right) \quad (3)$$

Where, $R = \alpha g \Delta T d^3/\nu\, D_{11}$ is the Rayleigh number,

$R_s = \beta g \Delta S d^3/\nu\, D_{11}$ is the solute Rayleigh number,

$\tau = D_{22}/D_{11}$ is the diffusivity parameter,

$\sigma = \nu/D_{11}$ is the Prandtl number,

$P_L = \frac{1}{P_l} = \frac{d^2}{K}$ is the porous parameter.

The boundaries are assumed to have free-slip boundary conditions.

We seek solutions to (1) to (3) of the form

$$\psi = \psi_0[\sin\pi\alpha x \, \sin n\pi z]e^{pt} \tag{4}$$

$$\begin{bmatrix} T \\ S \end{bmatrix} = \begin{bmatrix} T_0 \\ S_0 \end{bmatrix} \cos\pi\alpha x \sin n\pi z e^{pt} \quad (5)$$

Substituting (4) and (5) into (1) to (3) we obtain

$$\psi_0 = -\frac{(p+k^2)}{\pi a} T_0 + \left(-\frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T}\frac{k^2}{\pi a}\right) S_0 \tag{6}$$

$$\psi_0 = \left(-\frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S}\frac{k^2}{\pi a}\right) T_0 - \frac{(p+\tau k^2)}{\pi a} S_0$$
(7)

$$\psi_0 k^2 (p - \sigma P_L) = \sigma\pi a (RT_0 + R_s S_0) \tag{8}$$

where $\tau = \frac{D_{12}}{D_{11}} < 1,\ k^2 = \pi^2(a^2 + n^2)$

From (6) and (7) expressions for T_0 and S_0 are obtained.Substituting T_0 and S_0 in (8) yields a cubic equation for the growth rate p:

$$p^3 + p^2[k^2(1+\tau) - \sigma P_L] + p\left[k^2\left(\tau k^2 - \sigma P_L(1+\tau)\right) + \frac{\sigma\pi^2 a^2}{k^2}\left\{R + R_s - k^6 \frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}}\frac{1}{\sigma\pi^2 a^2}\right\}\right]$$

$$+\sigma\left[-P_L \tau k^4 + \pi^2 a^2 \left\{\tau R + R_s + P_L \frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}}\frac{k^4}{\pi^2 a^2} - \frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T} R - \frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S} R_s\right\}\right] = 0 \tag{9}$$

In the absence of cross-diffusion (i.e.,$D_{12} = D_{21} = 0$)an equivalent Rayleigh and solute Rayleigh numbers R^e and R_s^e formed such that the curly backrests in (9) are equal to the expressions

$$R^e + R_s^e = R + R_s - \frac{k^6}{\sigma\pi^2 a^2}\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}} = R + R_s - A \tag{10}$$

$$\tau R^e + R_s^e = \tau R + R_s + \frac{k^4}{\pi^2 a^2}\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}} P_L - \frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T} R - \frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S} R_s = \tau R + R_s - B \tag{11}$$

Solving (10) and (11) we get

$$R^e = R + \frac{B-A}{1-\tau}\,;\; R_s^e = R_s + \frac{\tau A - B}{1-\tau}$$

where,

$$A = \frac{k^6}{\sigma\pi^2 a^2}\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}} \text{and} B = -\frac{k^4}{\pi^2 a^2}\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{11}}P_L + \frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T}R + \frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S}R_s$$

Conditions for the onset of 'finger instability'

In a double diffusive convective system, the required conditions for the onset of finger instability (Srimani 1981)are

$$R_s^e < 0,\, R^e > 0,\, -R_s^e > \tau(R^e - 4\pi^2 P_L)$$

$$-R_s^e > \tau(R^e - 4\pi^2 P_L) - B$$

which on simplification yields

$$\frac{1}{\tau}\left[\frac{D_{21}}{D_{11}}\frac{\Delta T}{\Delta S}\frac{R_s}{R} - \frac{R_s}{R} + \frac{D_{12}}{D_{11}}\frac{\Delta S}{\Delta T}\right] > \left[1 + 4\pi^2 P_L\left(\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{22}} - 1\right)\right] \quad (12)$$

From the definition of R and R_s, we have the following results

$$\frac{R_s}{R} = \frac{\beta}{\alpha}\frac{\Delta S}{\Delta T} \quad (13)$$

$$\frac{\Delta T}{\Delta S} = \frac{\beta}{\alpha}\frac{R}{R_s} = \frac{T_z}{S_z} \quad (14)$$

From (12), (13) and (14) we get

$$\left(\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} - 1\right) + \frac{1}{\tau}\left[\frac{\beta}{\alpha}\frac{S_z}{T_z}\left(\frac{\alpha}{\beta}\frac{D_{12}}{D_{11}} - 1\right)\right] > \frac{4\pi^2 P_L}{R}\left(-1 + \frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{22}}\right) \quad (15)$$

Clearly, for $R < 0$, i.e., $\alpha T_z > 0$ the above inequality is reversed. Further, the hydro static stability is assured by $R + R_s > 0$. i.e., $\alpha T_z + \beta S_z < 0$.

$$\beta S_z > 0,\, \alpha T_z < 0 \text{and} \left|\frac{\beta}{\alpha}\frac{S_z}{T_z}\right| > \tau$$

In the presence of cross-diffusion effect the criteria is given by

$$\left|\frac{\beta}{\alpha}\frac{S_z}{T_z}\right|\left(1 - \frac{\alpha}{\beta}\frac{D_{12}}{D_{11}}\right) > \tau\left(1 - \frac{\beta}{\alpha}\frac{D_{21}}{D_{22}}\right) \text{ with } \beta S_z > 0, \text{and} \alpha T_z < 0 \quad (16)$$

If D_{21}>0(16) suggests that the formation of fingers is encouraged otherwise is discouraged.

Condition for 'specialised initial' conditions

The specialised initial condition is considered. In this situation, the two horizontal boundaries are impervious to the S-property and a constant difference of the T-property is maintained between the plates. The vertical flux of S is at all depths, then from the definition

$$\frac{R_s}{R} = \frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} \qquad (17)$$

Substituting (17) into (15), we obtain

$$\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} > \frac{\tau}{1+\tau} + \frac{1}{1+\tau}\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{22}} + 4\pi^2 P_L\left(\frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{22}} - 1\right)(18)$$

which is a condition for a particular type of finger perturbation to grow. For large R, (18) reduces to

$$\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} \geq \tau\left[1 + \tau - \frac{\beta}{\alpha}\frac{D_{12}}{D_{11}}\right]^{-1} \qquad (19)$$

This is identical to that of the fluid layer (McDougall 1983).

In fact, conditions (18) and (19) are not the very accurate conditions for instability, since the impervious boundary conditions lead to the S-gradient when perfectly permeable boundary conditions are assumed for instability. The situation when both T and S are stably stratified. That is

$$\alpha T_z < 0; \beta S_z < 0$$

From (15) the minimum condition for the formation of fingers as

$$\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} > 1 \ \text{ or } \frac{\alpha}{\beta}\frac{D_{12}}{D_{11}} > 1$$

Conditions for the onset of 'diffusive instability'

The conditions for the onset of 'diffusive' instability in a densely packed porous layer under the cross-diffusion effect is derived. Only steady motions ensue during finger instability while in the case of diffusive instability, steady as well as oscillatory instabilities occur. The relevant conditions are derived from the cubic equation (9) for the growth rate p, corresponding to infinitesimal perturbations. In the case of normal double diffusive convection, the well-known condition for the diffusive instability is

$R_s^e < 0, R^e > 0, -R_s^e > R_s^e \left[\frac{\sigma+\tau}{\sigma+1}\right] + \frac{4\pi^2 P_L}{\sigma}(1+\tau)(\sigma+\tau)$

Subject tot the T and S properties being fixed at the free slip horizontal boundaries, which are in terms of the equivalent Rayleigh numbers. The last inequality can be expressed in terms of the physical Rayleigh numbers as

$$-R > R_s \left[\frac{\sigma+\tau}{\sigma+1}\right] + \frac{B-A(\sigma+1+\tau)}{(\sigma+1)} + \frac{4\pi^2 P_L}{\sigma}(1+\tau)(\sigma+\tau) \quad (20)$$

From (20) it is possible to recover the condition for the double diffusive convection in a densely packed porous layer by setting $A = B = 0$. If the special conditions

$\frac{R_s}{R} = -\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}}$and $R < 0$ are taken into consideration, then (20) transforms to

$$\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} < \left(1+\frac{1}{\sigma}\right) - \frac{D_{12}}{D_{11}}\frac{D_{21}}{D_{22}}\frac{1}{\sigma} - \frac{4\pi^2 P_L}{D_{11}^2 \sigma R} D_{12} D_{21}(2+\tau) + \frac{4\pi^2 P_L}{\sigma^2 \sigma}(\sigma+1)(1+\tau)(\sigma+\tau)$$

In the above inequality, the cross-diffusion terms play a significant role along with the porous parameter and we can get a result where$\alpha\alpha T_z$ and βS_z are considered to be independent. Neglecting the terms containing$4\pi^2 P_L$, we obtain

$$\tau \propto T_z \left(\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} + \frac{(\sigma+1)}{\tau}\right) + \beta S_z \left(\frac{\alpha}{\beta}\frac{D_{12}}{D_{11}} + \sigma + \tau\right) > 0$$

This condition is independent of the nature of the layer considered.

Finite amplitude finger analysis under the influence of cross-diffusion terms

Under the assumption that the motion is vertical, the horizontal velocities are zero and this leads to the following

$$\frac{dw}{dz} = 0; \quad \nabla^2 \mathrm{w} = \nabla_1^2 w = \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}$$

From the horizontal momentum equation, we find that $p = p(z)$we have

$$\alpha T(x,y,z) = \alpha \bar{T}(z) + \alpha T^*(x,y) \quad (21)$$

$$\beta S(x,y,z) = \beta \bar{S}(z) + \beta S^*(x,y) \quad (22)$$

The overbar means the horizontal average. From (21), (22) and conservation equation for T and S we obtain

$$D_{11}D_{22} - D_{12}D_{21} = 0$$

or $D^2\bar{T} = 0 = D^2\bar{S}$

The horizontal average of vertical conservation momentum equation, we get

$$\alpha T^* + \beta S^* = -\frac{v}{k}\frac{1}{g}w \quad (23)$$

Again, fromconservation equation for T and S we obtain

$$w\bar{T}_z = D_{11}\nabla_1^2 T^* + D_{12}\nabla_1^2 S^* \quad (24)$$

$$w\bar{S}_z = D_{22}\nabla_1^2 S^* + D_{21}\nabla_1^2 T^* \quad (25)$$

We seek solutions 0f(23) to (25) in the form

$$[w, T^*, S^*] = [w_0, T_0, S_0]\cos mx \cos ny$$

$$\alpha T_0 + \beta S_0 = -\frac{v}{k}\frac{1}{g}w_0 \quad (26)$$

$$S_0 = \frac{w_0(\bar{T}_z D_{21} - \bar{S}_z D_{11})}{(D_{11}D_{22} - D_{12}D_{21})(m^2 + n^2)}$$

$$T_0 = \frac{w_0(\bar{T}_z D_{22} - \bar{S}_z D_{12})}{(D_{21}D_{12} - D_{11}D_{22})(m^2 + n^2)}$$

Substitution of S_0 and T_0 values into (26) yields

$$\alpha\bar{T}_z\left(\frac{\beta}{\alpha}D_{21} - D_{22}\right) + \beta\bar{S}_z\left(\frac{\alpha}{\beta}D_{12} - D_{11}\right) = \frac{v}{k}\frac{(m^2 + n^2)}{g}(D_{11}D_{22} - D_{12}D_{21})$$

For finger instability $(m^2 + n^2) > 0$ and $(D_{11}D_{22} - D_{12}D_{21}) > 0$ implies that

$$\left(\frac{\beta}{\alpha}\frac{D_{21}}{D_{22}} - 1\right) + \frac{1}{\tau}\frac{\beta\bar{S}_z}{\alpha\bar{T}_z}\left(\frac{\alpha}{\beta}\frac{D_{12}}{D_{11}} - 1\right) > 0$$

If T is unstably stratified (i.e., $\alpha\bar{T}_z > 0$) and the inequality is reversed if T is stably stratified (i.e., $\alpha\bar{T}_z < 0$). From the above inequality, it is observed that the conditions are opposite in the case of fluid and porous layers.

3. Results and Discussion

In this chapter, the effect of molecular diffusion on thermos solutal convection is studied for the case of a densely packed porous layer.

i) The results of the analytical investigation show that the porous parameter has a strong influence on the equivalent Rayleigh numbers.

ii)In predicting the regions of diffusive instability and the finger instability. the cross-diffusion parameters as well as the porous parameter play a very significant role.

iii) It is interested to note that the results are in excellent agreement with those of porous convection in the absence of cross-diffusion.

iv) The stability boundaries are exactly the same as for small values of the diffusion parameters satisfying the conditions.

v) Zeroth order solution for temperature, concentration and velocity are derived and the parameters have a significant effect in a specific range of P_L.

vi) The conditions for the onset of diffusive and finger instabilities are discussed.

vii) The interesting and remarkable difference between the results pertaining to fluid and porous layers is that, in the present case, the condition for the formation of fingers is less restrictive and favourable. The results are interesting.

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