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On the thermal anisotropy affecting transfers in a multilayer porous medium

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Abstract

An analytical model for studying double-diffusive natural convection within a multilayer anisotropic porous medium is developed and validated with respect to a direct numerical simulation. The studied domain is composed of two horizontal porous layers where the lower one is thermally anisotropic and is submitted to a uniform horizontal heat flux and a vertical mass flux. The assumption of parallel flow is validated and the effect of anisotropy on dynamic transitions is investigated. *To cite this article: R. Bennacer et al., C. R. Mecanique 332 (2004).*

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Résumé

Sur l'effet de l'anisotropie thermique sur les transferts dans un milieu poreux multicouches. Un modèle analytique est développé pour l'étude de la convection double diffusive dans un milieu poreux multicouche thermiquement anisotrope et comparé à un modèle de simulation numérique directe. Le domaine composé de deux couches poreuses horizontales est soumis à un flux thermique horizontal et à un flux massique vertical, la couche inférieure est thermiquement anisotrope. L'hypothèse d'un écoulement parallèle est validée et l'effet de l'anisotropie sur les transitions dynamiques est qualifié. *Pour citer cet article: R. Bennacer et al., C. R. Mecanique 332 (2004).*

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La convection double diffusive en milieu poreux est présente dans des processus naturels ou industriels induisant des écoulements complexes en présence d'instabilités et de bifurcations [1–5].

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Le présent travail présente une approche analytique et numérique de la double diffusion en milieu poreux. Le modèle comporte un milieu de hauteur H à deux couches celle d'en bas étant thermiquement anisotrope (Fig. 1) soumis horizontalement à un flux thermique (q) et verticalement à un flux massique (j). Le fluide saturant le milieu est considéré incompressible vérifiant l'hypothèse de Boussinesq.

Le problème est réduit en utilisant les quantités H , H^2/α , $1/\alpha$, qH/λ_y et jH/D pour l'espace (x, y) , le temps t , la fonction de courant ψ , la température T et la concentration S . α étant la diffusivité thermique effective du milieu poreux, D sa diffusivité massique et λ_m la conductivité thermique dans la direction m . Le problème est gouverné par les variables adimensionnelles R_T , N , Le , λ^r , A_a et A (définies dans les Éqs. (5)). Les nombres de Nusselt (Nu) et de Sherwood (Sh) quantifiant le transfert de chaleur et de masse sont utilisés dans cette étude.

L'approche analytique dans l'hypothèse, $A \gg 1$, permet d'utiliser une approximation d'écoulement parallèle et de chercher des solutions analytiques.

Pour la simulation numérique, les équations sont résolues dans le cadre d'une approximation de type volumes finis [10]. L'approche numérique a déjà été validée dans le cas d'une cavité rectangulaire occupée par un milieu poreux anisotrope [11]. Pour le présent problème, le rapport de forme est fixé à $A = 4$, en particulier, ce rapport de forme est la valeur nécessaire pour que l'écoulement s'établisse dans la direction horizontale pour la valeur du nombre de Rayleigh considéré. Le maillage 151×51 a été retenu car il permet un bon compromis entre la précision souhaitée et le temps de calcul. Le nombre de Prandtl est également fixé à $Pr = 0,71$.

A titre de généralité, le diagramme de stabilité marginale, d'existence d'écoulement pour un milieu isotrope est donné sur la Fig. 2 pour les nombre de Rayleigh thermique et solutal et le nombre de Lewis. Pour centrer l'étude sur l'influence de la géométrie du milieu et de l'anisotropie, le nombre de Lewis et R_T sont également fixés ($Le = 10$ et $R_T = 5$). Les résultats sont présentés pour un milieu monocouche puis étendus à un milieu bicouche. A titre indicatif, des propriétés thermophysiques correspondant à $Pr = 1$ et $Le = 10$ peuvent tout à fait correspondre à un problème concret : celui de la naissance d'écoulement dans un sol sablonneux à proximité d'un puits de forage. Les infiltrations d'hydrocarbures couvrent des distances importantes et les substances volatiles diffusent verticalement donnant lieu à une situation de stratification stable en concentration. Une source d'énergie (incendie) même très lointaine pourra parcourir de grandes distances si une déstabilisation de cette couche stratifiée se produit et donne lieu à une onde progressive.

La Fig. 3 montre le changement du type de solution, transfert de masse et intensité de l'écoulement (Sh et ψ_c), en fonction du rapport des forces de flottaison thermiques et solutales (N) pour différents taux d'anisotropie λ^r . Pour l'ensemble des résultats un bon accord est observé entre les solutions analytique et numérique.

Pour $N > 0$, les forces de flottaison thermique et solutale s'associent pour intensifier la convection. La courbe représentée pour le cas isotrope ($\lambda^r = 1,0$), montre une croissance de l'intensité de convection avec N . On distingue dans l'ensemble deux régimes évoluant de la solution diffusive à la solution convective. Pour des valeurs de N élevées, la convection est principalement d'origine solutale. Pour des forces de flottaison opposées ($N < 0$), le gradient vertical de concentration stabilisant réduit l'intensité de l'écoulement. A la limite $N \rightarrow -\infty$, le gradient stabilisant solutal domine le gradient thermique. L'écoulement demeure stable en dessous de $N = -3$.

L'augmentation de l'anisotropie thermique (décroissance du paramètre λ^r) intensifie les transferts, et une solution asymptotique est atteinte pour $1/\lambda_x < 0,1$ (Fig. 3). Ceci est essentiellement du aux conditions aux limites imposées (Fig. 1). Le flux thermique étant imposé, l'augmentation de la conductivité horizontale induit de faibles gradients thermiques horizontaux. La force d'Archimède décroît avec le gradient thermique et ne demeure que les forces solutales qui suivent le comportement classique de la convection de type Rayleigh Bénard. Les configurations discutées précédemment montrent un écoulement dans le sens trigonométrique ($\psi_c < 0$) cohérent avec le moteur de convection thermique. En absence d'échauffement pariétal, l'écoulement est induit par le gradient solutal vertical déstabilisant, au-delà d'une valeur critique du nombre de Rayleigh solutal, le sens de rotation est obtenu d'une manière équiprobable. Pour une faible anisotropie ($\lambda^r \gg 1$) une branche asymétrique est obtenue et correspond aux forces déstabilisantes [3].

Pour un gradient stabilisant ($N = -1$), l'écoulement est d'origine à la fois thermique et solutale. Avec les conditions aux limites choisies (Fig. 1) les résultats numériques indiquent l'existence de solution dans le sens des aiguilles d'une montre.

La Fig. 3 montre également que le nombre de flottaison critique est fonction de l'anisotropie. Comme précisé précédemment, l'anisotropie thermique favorise la transition du régime conductif au régime convectif.

La présence d'une couche d'anisotropie de rapport de forme A_a est examinée. La Fig. 4 représente l'effet de A_a sur l'écoulement et les transferts. Sur cette figure est reporté le cas isotrope de référence ($A_a = 0$). En observation générale, l'augmentation du rapport A_a ou la diminution de l'anisotropie intensifient les transferts (Fig. 4). Il est aussi observé que la transition du régime diffusif au régime convectif intervient pour une valeur faible de A_a . L'effet déstabilisant est dû à l'intensification des forces d'Archimède et aussi à l'augmentation de la température de la couche inférieure.

La capacité du modèle analytique à prédire la dynamique du système est confirmée par le bon accord constaté en comparaison aux simulations. Les résultats montrent aussi que l'anisotropie d'une seule couche du système confère à ce dernier un comportement comme s'il était totalement anisotrope particulièrement pour des rapports d'anisotropie thermique importants. Pour un faible rapport, le couplage entre les deux couches est plus complexe particulièrement pour des gradients de température importants.

1. Introduction

Double-diffusive natural convection occurs in many systems and in nature including the disposal of waste material, groundwater contamination, and chemical transport in packed-bed reactors and others. This field, cover numerous porous media potential applications. Such problems refer to complex flows, involving bifurcations, and unsteadiness [1–5].

The double-diffusive natural convection was analysed chronologically for the onset of motion in a horizontal porous layer heated and salted from below then within cavities differentially heated from the vertical sides with adding or opposing horizontal solutal gradients in isotropic or anisotropic porous media [6,7]. Many practical applications involve configurations subject to either vertical or horizontal gradients of heat and mass [8].

This article reports an analytical model compared to numerical simulation of double-diffusive natural convection in a fluid-saturated multilayer porous domain with thermal anisotropy under cross constant fluxes of heat and mass along the vertical and the horizontal boundaries respectively. General Bifurcation diagram is given and particular value are chosen for the study. The main purpose is to delineate the effect of multilayer porous domain and thermal anisotropy on the obtained solutions and extend the previous isotropic homogeneous results [9]. The study concerns the analytical solutions obtained in a tall horizontal cavity and the corresponding direct numerical investigation. The thermal anisotropy in homogeneous domain is firstly investigated and extended to the multilayer domain.

2. Problem statement

2.1. Problem definition

The physical system is sketched in Fig. 1 and consists of a two-dimensional horizontal enclosure of height H and width L . An uniform heat flux per unit area q is applied on the two vertical walls while the top and the bottom are subject to vertical uniform fluxes of mass j . The cavity is filled with two superposed homogeneous porous layer (fluid-saturated). The lower one of height e is thermally anisotropic.

It is assumed that the resulting flow is incompressible and the binary fluid saturating the porous matrix is Newtonian modelled as a Boussinesq one. Variables are reduced using H , $1/\alpha$, qH/λ_y and jH/D for space, stream function, temperature and species respectively λ_x , α and D are the effective porous medium horizontal

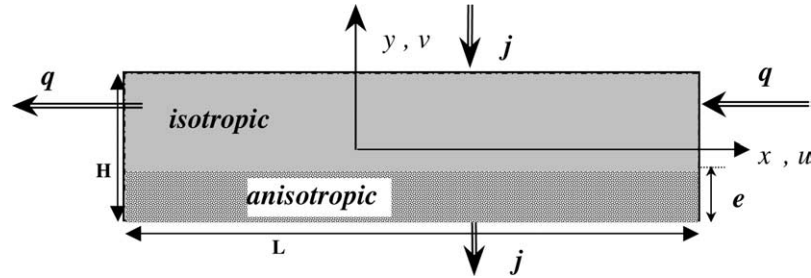


Fig. 1. Geometry of the anisotropic multiplayer media, submitted to an horizontal heat flux q and a vertical mass flux j .

Fig. 1. Géométrie du milieu poreux anisotrope et multicouche soumis à un flux thermique vertical q et à un flux massique horizontal j .

thermal conductivity, thermal and mass diffusivities respectively and λ_y the thermal conductivity along the y direction. For the sake of simplicity, reduced variables keep the same notation as dimensionless one and governing dimensionless equations are expressed in terms of temperature, concentration and stream-function, in steady state:

$$\nabla(\overline{\overline{\mathfrak{K}}}_{\lambda^r}^{-1} \nabla T) = u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \quad (1)$$

$$\frac{1}{Le} \nabla^2 S = u \frac{\partial S}{\partial x} + v \frac{\partial S}{\partial y} \quad (2)$$

$$\nabla^2 \Psi = -R_T \frac{\partial}{\partial x} (T + NS) \quad (3)$$

Velocity components u and v are classically linked to the stream function with $u = \partial \Psi / \partial y$ and $v = -\partial \Psi / \partial x$ to satisfy the continuity equation. The thermal anisotropy is accounted by the dimensionless second order tensor involving the thermal conductivity in x and y directions (i.e., λ_x and λ_y):

$$\overline{\overline{\mathfrak{K}}}_{\lambda^r} = \begin{bmatrix} \lambda^r & 0 \\ 0 & 1 \end{bmatrix} \quad \text{where } \lambda^r = \lambda_x / \lambda_y$$

The dimensionless boundary conditions are

For vertical walls:

$$\Psi \left(x = \pm \frac{A}{2}, y \right) = 0, \quad \frac{\partial S}{\partial x} \left(x = \pm \frac{A}{2}, y \right) = 0, \quad \frac{\partial T}{\partial x} (x, y) = -\frac{1}{\lambda^r} \quad \text{for } y \in \left[-\frac{1}{2}, -\frac{1}{2} + A_a \right] \quad \text{and} \\ \frac{\partial T}{\partial x} (x, y) = -1 \quad \text{for } y \in \left[-\frac{1}{2} + A_a, \frac{1}{2} \right] \quad (4a)$$

For horizontal surfaces:

$$\Psi \left(x, y = \pm \frac{1}{2} \right) = 0, \quad \frac{\partial T}{\partial y} \left(x, y = \pm \frac{1}{2} \right) = 0, \quad \frac{\partial S}{\partial y} \left(x, y = \pm \frac{1}{2} \right) = 1 \quad (4b)$$

The present problem is governed by six dimensionless parameters, namely Rayleigh number R_T , buoyancy ratio N , Lewis number Le , thermal anisotropy λ^r , relative height of the anisotropic layer A_a and the aspect ratio A defined as:

$$R_T = \frac{Kg\beta_T q H^2}{\lambda \alpha \nu}, \quad N = \frac{\beta_S \Delta S}{\beta_T \Delta T}, \quad Le = \frac{\alpha}{D}, \quad \lambda^r = \frac{\lambda_x}{\lambda_y}, \quad A_a = \frac{e}{H}, \quad A = \frac{L}{H} \quad (5)$$

where ν , β_T and β_S are the kinematics viscosity, the coefficient of volumetric thermal expansion and the density change due to concentration.

The Nusselt (Nu) and Sherwood (Sh) numbers related to the heat and mass transfers, which are of interest in engineering applications, are based on the average temperature difference $\overline{\Delta T}$ between the two vertical walls and on the average concentration difference $\overline{\Delta S}$ between the two horizontal walls:

$$Nu = \frac{qH}{\lambda \overline{\Delta T}} = \frac{1}{\Delta T} \quad \text{and} \quad Sh = \frac{jH}{D \overline{\Delta S}} = \frac{1}{\Delta S}$$

2.2. Methods of solution

An analytical model based on the parallel flow assumption is developed. In the limit of a shallow cavity ($A \gg 1$), the model can be simplified by using the parallel flow approximation enabling analytical solution. The main assumption is $\Psi(x, y) \approx \Psi(y)$, $\varphi(x, y) = C_\varphi x + \theta_\varphi(y)$ for temperature ($\varphi \equiv T$) or concentration ($\varphi \equiv S$) in the central part of the cavity, where C_φ is unknown gradient assumed constant. Eqs. (1)–(3) in the central part become independent from the anisotropy and can be reduced to the following set of ordinary differential equations:

$$\frac{d^2\theta_T}{dy^2} = C_T \frac{d\Psi}{dy} \tag{6}$$

$$\frac{d^2\theta_S}{dy^2} = Le C_S \frac{d\Psi}{dy} \tag{7}$$

assuming constant $d^2\Psi/dy^2 = E$ for parallel flow. Inner thermal and solutal fields result only from the flow field where

$$E = -R_T(C_T + NC_S) \tag{8}$$

The set of Eqs. (6) and (7) and boundary conditions (4), can be solved to yield the temperature and concentration distributions:

$$\theta_T(y) = \frac{EC_T}{2} \left(\frac{y^3}{3} - \frac{y}{4} \right) \quad \text{and} \quad \theta_S(y) = \frac{EC_S Le}{2} \left(\frac{y^3}{3} - \frac{y}{4} \right) + y \tag{9}$$

The energy and species conservation at each vertical section of the enclosure taking into account the multilayer configuration in the integrating equation yield to the determination of C_T and C_S . The combination of Eqs. (8) and (9) results on a 5-degree polynomial equation on E with coefficients depending on Le , λ' , N , R_T and A_a . Exhibiting roots of this polynomial equation for given coefficients, it yield the values of E , i.e., of C_T and C_S and consequently to the Sherwood number $Sh = 6(120 + Le^2 E^2)/(Le^2 E^2 + 720)$.

For the direct numerical simulation, governing equations (1)–(3), subject to boundary conditions (4) are solved under a finite volume approximation [10]. Convective and diffusive fluxes are respectively approximated by using a second order centred scheme. The accuracy of the numerical method has been established with a reference solution concerning pure thermal and thermosolutale convection within a rectangular anisotropic porous cavity [11]. For the calculations presented, a 151×51 grid was used, allowing a good compromise between accuracy and CPU time.

3. Results and discussion

The general stability diagram for the isotropic case is given on Fig. 2. The effect of anisotropy and heterogeneity on such a problem are still open questions. To focus mainly on the anisotropy effects, parameters are fixed to a near model of two inter gas diffusions ($A = 4$, $Pr = 0.71$, $Le = 10$, $R_T = 5$). The considered aspect ratio is the minimum one ensuring the parallel flow establishment for the considered Rayleigh number. Results are presented for monolayer medium ($A_a = 0$) and extended to multilayer one (Fig. 1).

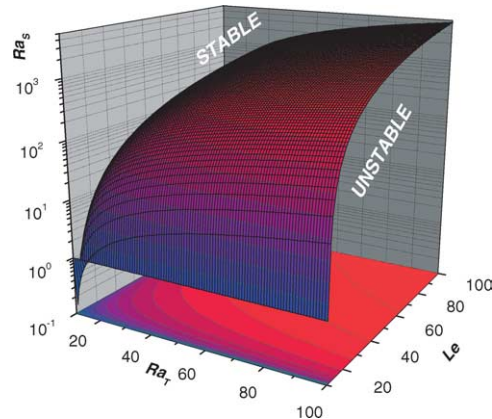


Fig. 2. Marginal stability diagram for the monolayer isotropic case.

Fig. 2. Diagramme de stabilité marginale pour le cas monocouche isotrope.

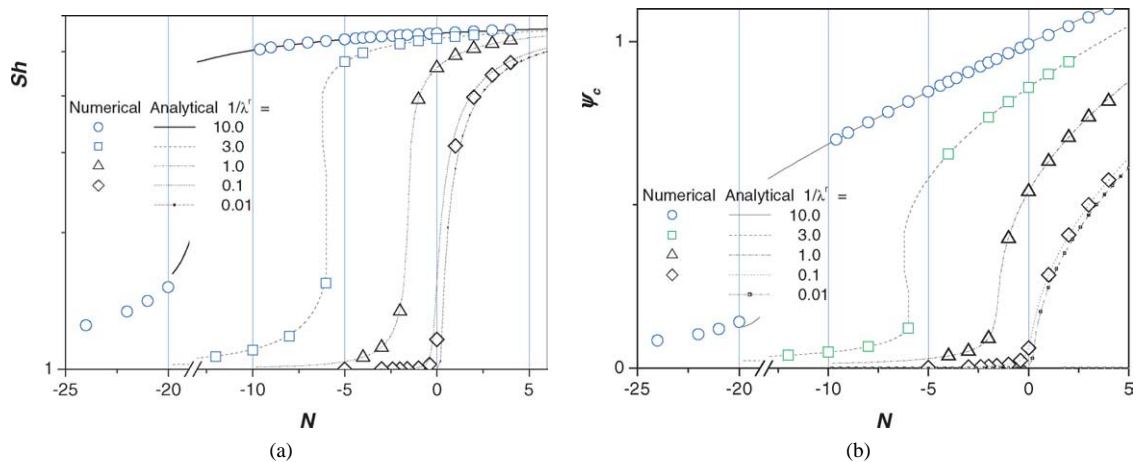
Fig. 3. Comparison of analytical and numerical results for mono-layer domain, effect of the buoyancy ratio N and λ' on (a) ψ_c and (b) Sh , for $R_T = 5$, $Le = 10$ and $A = 4$.Fig. 3. Comparaison des solutions analytique et numérique, effet des paramètres N et λ' sur (a) ψ_c et (b) Sh pour $R_T = 5$, $Le = 10$ et $A = 4$.

Fig. 3 shows analytically and numerically the effect of the buoyancy ratio N on mass transfer Sh and stream function ψ_c . Results concerns also the anisotropy effects. The agreement is good and is even excellent, particularly for lower thermal anisotropy level.

All the obtained results show solutions evolving from a diffusive to a convective state. For isotropic case and $N > 0$ both the solutal and the thermal buoyancy forces combine to increase convection given by the clockwise circulation flow patterns ($\psi_c > 0$). For high N , the solutal buoyancy forces principally drives the flow. For negative N , solutal and thermal buoyancy forces operate in an opposite way. The strength of flow circulation is progressively annihilated due to the imposition of an increasingly strong stable vertical concentration gradient. For $N \rightarrow -\infty$, a strong stabilising vertical solutal gradient prevails within the porous layer for which the fluid within the layer is expected to remain at rest with diffusive temperature and concentration fields. For isotropic case the flow remains stable (at rest) up to $N = -3$.

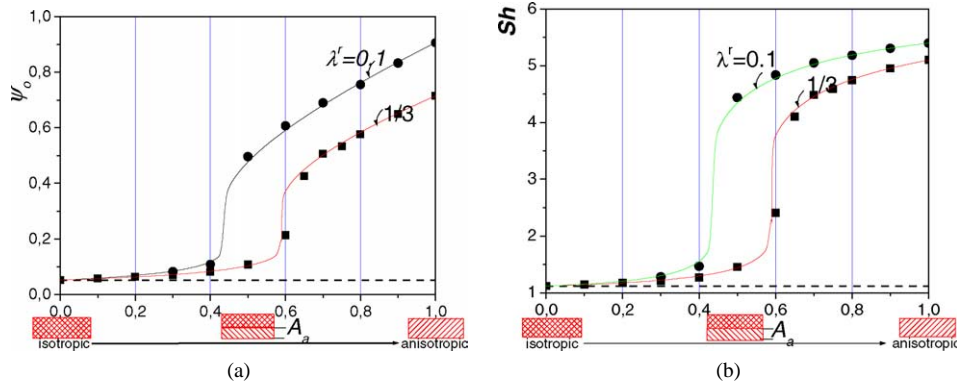


Fig. 4. Comparison of analytical and numerical results for mono-layer domain, effect of the relative height of the anisotropic layer A_a on (a) ψ_c (b) and Sh for different λ^r , $Le = 10$, $N = -3$ and $A = 4$.

Fig. 4. Comparaison des solutions analytique et numérique, effet de l'épaisseur relative de la couche anisotrope A_a sur (a) ψ_c et (b) Sh pour différents λ^r , $Le = 10$, $N = -3$ et $A = 4$.

The anisotropy is affecting the transitional N value (Fig. 3). For $\lambda^r \rightarrow +\infty$, the flow is driven solely by the solutal buoyancy forces and we reach an asymptotic state for $1/\lambda^r < 0.1$ (Fig. 3).

For imposed heat flux, the increase in horizontal conductivity induces a lower horizontal temperature gradients $\partial T/\partial x = -1/\lambda^r$ accompanied by a decrease in thermal buoyancy forces. This situation reach similar behaviour encountered in classical pure solutal Rayleigh–Bénard problem.

For low thermal anisotropy ($\lambda^r \gg 1$) an asymptotic branch is obtained and corresponds to equivalent Rayleigh–Bénard problem due to solely solutal destabilising forces [3]. The weak effect of the thermal anisotropy is due to the decrease of the horizontal temperature gradient.

Upon decreasing λ^r to 0.1 the strength of flow circulation and the mass transfer increase. The increase is essentially due to thermal buoyancy forces resulting from higher horizontal gradient. The thermal gradient increases especially on the left and right lower part of the cavity. The flow patterns discussed above circulate counter-clockwise ($\psi_c < 0$) in agreement with the buoyancy forces induced by the thermal boundary conditions reffered as natural flow.

In the absence of side heating ($R_T \partial T/\partial x \equiv 0$) the flow is induced solely by the vertical destabilising solutal gradient (Bénard's problem) and, above a given critical solutal Rayleigh number, it can rotate indifferently clockwise or counter-clockwise. For moderate stabilising vertical solute gradient, the flow is driven by both thermal and solutal buoyancy forces resulting in multiple possible solution natural (counter-clockwise) and antinatural (clockwise) flow. The presented results are only for the for natural flow, the strength of which depends on λ^r .

The comparison between analytical and numerical results shows a good agreement especially thus confirming the validity of the assumption of parallel flow.

As most porous domain have multilayer structures, the effect of the relative height of two horizontal layers will be analyzed. Fig. 4 represents the effect of the added anisotropic layer on the obtained transfer and flow focusing on fixed $N = -3$ where the solutal forces are stabilising.

The increase of the relative size of the anisotropic layer increases the flow and the transfer (Fig. 4). It is also shown that the increase in anisotropy ($1/\lambda^r$) causes intensification in flow and transfers as remarked previously. The other main conclusion is the transition from diffusive to convective solution for lower A_a with the decrease of the horizontal conductivity. The destabilising effect is due to the increase in the thermal buoyancy forces and also to a secondary destabilising thermal effect (heated from below) due to the obtained high temperature in the lower layer.

The more anisotropic is the layer the lower will be the critical A_a . The obtained results show that the partially anisotropic porous layer is equivalent physically to the totally anisotropic one especially for high thermal

anisotropy (λ'). For low anisotropy the coupling between the two superposed layers illustrates a more complex phenomenon especially the added Rayleigh–Bénard problem due to the higher temperature in the lower layer.

4. Conclusions

Thermal anisotropy effect on natural convection within a horizontal multilayer porous domain subject to cross fluxes of heat and mass has been investigated by both numerical and analytical approaches.

For destabilising solutal gradient, the solution is characterised by the existence of convective regime and for stabilising situation the flow is dominated by diffusive regime. The anisotropy intensifies or reduces the strength of convection and affects also the critical buoyancy ratio allowing the transition from the diffusive to the convective solution.

For high anisotropy the flow pattern decreases and reaches an asymptotic branch corresponding to pure Rayleigh–Bénard solutal problem.

The increase in the relative size of the anisotropic layer gives a more unstable system because of the lower anisotropic layer. An increase in the temperature value adds a thermal Rayleigh–Bénard contribution and modifies the stability of this problem.

The agreement between numerical and analytical solutions is excellent for all the analysed cases and allows the use of such analytical model for situations needing order of magnitude evaluation. Similarly the qualification of the numerical method allows its use on complex situations, such as 3D ones.

This work follows also on providing the effect of the thermal anisotropy on stability and bifurcations of fluid flow occurring in porous medium, allowing operating parameters for such situations encountered in industrial problems. The preliminary obtained marginal stability of monolayer isotropic domain has to be generalised for multilayer and anisotropic porous media.

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