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Numerical analysis of re-oscillation and non-centrosymmetric convection in a porous enclosure due to opposing heat and mass fluxes on the vertical walls ☆

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ABSTRACT

Two peculiar convection patterns–re-oscillation and stable non-centrosymmetric convection–are observed when two-dimensional double-diffusive convection in a porous enclosure (aspect ratio = 1.5) is analysed numerically. The top and bottom walls of the enclosure are insulated; constant and opposing heat and mass fluxes are prescribed on the vertical walls. Re-oscillation occurs when the convection pattern changes from centrosymmetric to non-centrosymmetric. When the buoyancy ratio, which generates re-oscillation convection, is marginally lower, the convection pattern changes to stable non-centrosymmetric. These two convection patterns can be observed only for limited values of the Rayleigh number, Lewis number, and buoyancy ratio.

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1. Introduction

Various researchers have theoretically and numerically studied double-diffusive convection in a fluid-saturated porous enclosure due to the opposing heat and mass fluxes on the vertical walls [1–9]. In these studies, the numerical calculations yielded oscillatory solutions [7–9]. It was observed that the competition between the heat and mass transfers with different diffusivities played an important role in generating oscillations even at low Rayleigh numbers. The convection pattern in a double-diffusive porous medium is determined by four non-dimensional parameters: the aspect ratio (A), Lewis number (Le), Rayleigh–Darcy number (R), and buoyancy ratio (N). Among the four parameters, N is expected to have the most significant effect on the characterization of the convection pattern and the oscillation, since N is the ratio of heat intensity to mass convection.

We have been investigating the double-diffusive convection in a fluid-saturated porous medium for more than 15 years. In 1994 [7], we observed oscillating convection in a double-diffusive porous medium, which, to the best of our knowledge, had not been observed before. We observed that oscillating convection occurs when $R = 100$; Le = 10, 20, 30, 40; and $A = 3$, 5, and 10. Further, we observed a monotonous oscillation pattern over one cycle. However, the characteristics of the oscillating region are not clear because the oscillating region of N was calculated at intervals of $\Delta N = 0.05$. In 2002 [8], we investigated the convection pattern only for $A = 5$; the oscillating region in graphs of N vs. Le for varying R was determined at intervals of $\Delta N = 0.01$. In 2007 [9], we found three peculiar types of oscillations. We discovered the re-oscillation phenomenon, which is one of the most peculiar types of oscillation. This phenomenon occurs when the convection pattern changes from centrosymmetric to non-centrosymmetric. Since this transition takes a very long time, the re-oscillation typically has a very long period. The re-oscillation phenomenon can be observed when $A = 2$ and 2.5. As A increases, complex oscillation can be observed more often.

In the present research, we analyse the convection patterns only when $A = 1.5$. If N becomes smaller than the value at which re-oscillation is observed, the Nusselt number (Nu) changes abruptly with time, and the convection pattern changes from centrosymmetric to stable (without oscillation) non-centrosymmetric, which is another peculiar convection pattern that we have observed when $A = 1.5$ for the first time.

In addition, we numerically study the double-diffusive convection (re-oscillation and stable non-centrosymmetric convection) in a fluid-saturated porous enclosure due to opposing heat and mass fluxes on the vertical walls. The values of R, Le, and the transition time are also investigated. One of the main objectives of the present research is to prepare an R–N map of the re-oscillation region and the stable (no oscillation) non-centrosymmetric region.

2. Problem statements

The geometry used in the mathematical model is shown in Fig. 1. We consider a two-dimensional vertical enclosure with an aspect ratio A. This enclosure is filled with a homogeneous, fluid-saturated porous medium. The top and bottom walls of the enclosure are

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Nomenclature

A	aspect ratio [−]
D	solute diffusivity [$m^2\ s^{-1}$]
f	non-dimensional frequency [−]
g	acceleration due to gravity [$m\ s^{-2}$]
2h	width of the enclosure [m]
2H	enclosure height [m]
k	permeability [m^2]
Le	Lewis number [−]
N	buoyancy ratio [−]
Nu	Nusselt number [−]
P	pressure [−]
R	Rayleigh number [−]
t	non-dimensional time [−]
$\mathbf{u}$	non-dimensional velocity vector = (u,v) [−]
x	non-dimensional horizontal coordinate [−]
y	non-dimensional vertical coordinate [−]

Greek symbols

α	coefficient of thermal expansion [K^{-1}]
β	coefficient of concentration expansion [$m^3\ mol^{-1}$]
ε	porosity [−]
ϕ	non-dimensional temperature [−]
κ	thermal diffusivity [$m^2\ s^{-1}$]
Λ_c	horizontal concentration gradient prescribed on the side wall [$mol\ m^{-4}$]
Λ_T	horizontal temperature gradient prescribed on the side wall [$K\ m^{-1}$]
ν	kinematic viscosity [$m^2\ s^{-1}$]
θ	non-dimensional concentration [−]
σ	heat capacity ratio [−]

insulated. Constant heat flux (Λ_T) and mass flux (Λ_c) are prescribed through the vertical walls. The following equations give the momentum conservation in the Darcy regime with the Boussinesq approximation:

$$\mathbf{u} = -\nabla P - R(\theta - N\varphi)\mathbf{e}_y \tag{1}$$

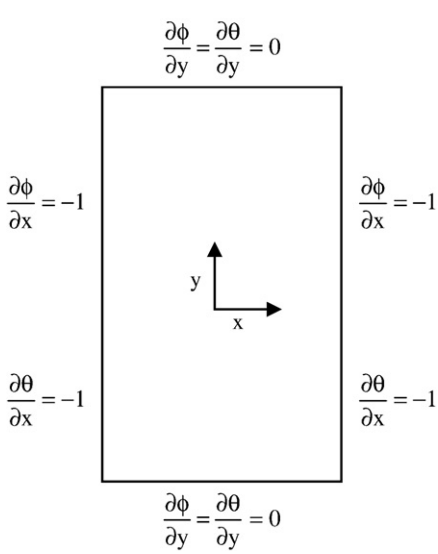

Fig. 1. Geometry of the porous enclosure.

The equation of continuity is

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

The equations for mass and thermal energy conservation are

$$\varepsilon \frac{\partial\theta}{\partial t} + \mathbf{u} \cdot \nabla\theta = \nabla^2\theta \tag{3}$$

and

$$\sigma \frac{\partial\varphi}{\partial t} + \mathbf{u} \cdot \nabla\varphi = Le\nabla^2\varphi \tag{4}$$

respectively, where

$$\sigma = \frac{\varepsilon(\rho C_p)_{\text{liquid}} + (1-\varepsilon)(\rho C_p)_{\text{solid}}}{(\rho C_p)_{\text{liquid}}} \tag{5}$$

The boundary conditions are

$$\frac{\partial\theta}{\partial x} = -1, \frac{\partial\phi}{\partial x} = -1,\ u = 0,\ \text{and}\ \frac{\partial v}{\partial x} = 0\ \text{at}\ |x| = 1 \tag{6}$$

and

$$\frac{\partial\theta}{\partial y} = 0, \frac{\partial\phi}{\partial y} = 0,\ v = 0,\ \text{and}\ \frac{\partial u}{\partial y} = 0\ \text{at}\ |y| = A \tag{7}$$

The initial conditions are

$$\theta = 0, \phi = 0,\ \text{and}\ \mathbf{u} = 0\ \text{at}\ t = 0 \tag{8}$$

The dimensionless parameters are defined as follows:

$$A = \frac{H}{h},\ Le = \frac{\kappa}{D},\ R = \frac{kg\beta\Lambda_c h^2}{\nu D},\ \text{and}\ N = \frac{\alpha\Lambda_T}{\beta\Lambda_c} \tag{9}$$

Governing equations (Eqs. (1)–(4)) are solved numerically by the finite difference method using the boundary values (Eqs. (6) and (7)) and initial conditions (Eq. (8)). The governing equations and the boundary conditions are discretised over a network of 202 × 302 grids with uniform spacing. No grid point is set on the physical boundaries ($|x| = 1$ and $|y| = A$). The first and last grid points are placed at a distance of half a grid from the boundaries. The boundary conditions at the walls are applied to these points. The numerical scheme used here is second-order accurate in space and first-order accurate in time. The matrices obtained from the governing equations are solved under the given boundary conditions by the conjugate gradient method. For further details regarding this method, please refer to Ref. [7].

In the present study, we performed calculations for the following cases: the aspect ratio $A = 1.5$; the Lewis number Le = 10, 20, and 30; and the non-dimensional time is less than 400. We studied the types of time-dependent Nu in this case because it is difficult to observe a drastic change the time-dependent Nu after $t = 400$.

3. Results and discussion

Fig. 2 shows a graph of Nu as a function of time and the flow pattern when $R = 500$, Le = 20, and $N = 0.445$. Such a pattern was referred to as the 're-oscillation case' in a previous study. The re-oscillation case is also observed when $A = 1.5$. Re-oscillation occurs because the convection pattern changes from non-centrosymmetric to centrosymmetric. Since this change requires a very long time, the re-oscillation typically has a very long period. For further details regarding the re-oscillation case, refer to Ref. [9]. In the case of these stream functions, positive values correspond to the clockwise flow

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