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Convective heat and solute transfer in partially porous cavities

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Abstract

This paper deals with natural convection driven by combined thermal and solutal buoyancy forces in a binary fluid. The configuration under study is a confined enclosure partially filled with a vertical porous layer. The mathematical description of the problem is based on a one-domain formulation of the conservation equations. The set of numerical results presented here quantitatively shows the influence of the porous layer on the flow structure and on heat and species transfer in the enclosure.

The paper is focused on the analysis of the influence of the characteristic parameters governing double diffusive convection, namely the ratios of solutal and thermal parameters: the diffusivities and the buoyancy forces. Heat and mass transfer is analyzed as a function of the permeability of the porous layer. It is shown that the coupling of the flow penetration in the porous layer with the combined buoyancy forces induces a specific behavior of the flow structure and average heat transfer in the enclosure.

Keywords: Double diffusion; Thermosolutal convection; Porous medium; Fluid–porous interface

1. Introduction

Heat and solute transport by convection in fluid or porous domains is relevant to a wide range of industrial processes or environmental situations. Among these the analysis of heat or mass transfer due to natural convection has been the subject of a very intense research activity over the past decades, and documented reviews are available to the interested reader [1,2].

The present paper deals with a particular subclass of such problems where natural convection takes place in a confined enclosure partially filled with a porous medium. Heat transfer and fluid flow through fibrous insulation [3], natural convection heat and mass transfer in solidification [4], or solute exchange in sediments in coastal environments [5] are some examples of the fields where transport phenomena take place at an interface between a fluid phase and a porous medium. The context of the present study aims at a better understanding of convective heat and solute transfer in the mushy zone of a solidifying multi-component system, where natural convection is known to be driven by combined thermal and solutal buoyancy forces in a binary fluid. This particular class of convection is termed thermosolutal or double diffusive convection. In the following paper we refer to a very simple model in the absence of phase change where the dendritic region is represented as an homogeneous porous medium.

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Nomenclature

A	aspect ratio, H/L
C	solute mass fraction, wt%
$\mathscr{D}$	mass diffusivity of the solute, m^2/s
Da	Darcy number, K/H^2
g	acceleration of gravity, m/s^2
H	height of the enclosure, m
$\vec{k}$	unit vector (vertical direction)
k	thermal conductivity, W/(m·K)
K	permeability (m^2)
L	width of the enclosure, m
Le	Lewis number: α/D
N	buoyancy ratio: $\beta_C \Delta C/\beta_T \Delta T$
Nu	average Nusselt number: $\int_0^1 -(\partial\theta/\partial x)\mathrm{d}z$
P	dimensionless pressure
Pr	Prandtl number, ν/α
Ra_S	solutal Rayleigh number, $N\,Le\,Ra_T$
Ra_T	thermal Rayleigh number, $g\beta_T \Delta T\, H^3/\alpha\nu$
Sh	average Sherwood number: $\int_0^1 -(\partial\phi/\partial x)\mathrm{d}z$
T	dimensional temperature, K
$\vec{V}$	dimensionless fluid velocity ($\vec{v}^* H/\alpha$)
w (u)	vertical (horizontal) component of $\vec{V}$
x_P^*	dimensional width of the porous layer, m
x_P	dimensionless width of the porous layer, (x_P^*/L)
$x(z)$	dimensionless coordinates, $x^*/H(z^*/H)$

Greek symbols

α	thermal diffusivity, m^2/s
β_T	thermal expansion coefficient: $-1/\rho_0(\partial\rho/\partial T)$
β_C	solutal expansion coefficient: $-1/\rho_0(\partial\rho/\partial C)$
ΔC	concentration difference
ΔT	temperature difference
ε	porosity of the porous layer
μ	dynamic viscosity of the fluid, kg·m/s
ν	kinematic viscosity, m^2/s
ϕ	dimensionless concentration, $\phi = (C - C_0)/\Delta C$
ψ	stream function: $u = -\partial\psi/\partial z$; $w = \partial\psi/\partial x$
ρ	fluid density
θ	dimensionless temperature, $\theta = (T - T_0)/\Delta T$

Subscripts

eff	effective property of the porous layer
F	refers to the fluid domain
P	refers to the porous medium
S or C	solutal parameter
T	thermal parameter

A complete overview of double diffusive convection in fluid or porous layers is not within the scope of the present introduction, and we will only briefly recall the main studies on convection in composite cavities where the fluid domain is partially occupied by a porous layer.

It should first be noticed that very few experimental papers are available on the topic [6–8], and that the main effort has been to address the numerical simulation of such flows. The mathematical description of the conservation laws at a fluid–porous interface has been the topic of many studies after the first approach presented by Beavers and Joseph [6], and the problem of using one- or two-domain formulations for the conservation equations has been extensively discussed in the literature (see [9]).

The problem of *thermal* convection for such a configuration in a vertical enclosure where the porous layer is parallel to the vertical walls has been previously studied in the context of wall insulation [10,11,3] or solidification [12,4,13]. An exact solution has been proposed by [14] and the stability problem has been tackled by [15]. Numerical results for a vertical enclosure with two porous layers have been presented by Merrikh and Mohamad [16]. In all these studies the one-domain formulation has been used.

Another class of studies considers superimposed horizontal layers, generally a fluid on top of a porous layer. Here the main interest is to compare the stability results with the well-known critical Rayleigh numbers for Rayleigh–Bénard convection in fluid or porous layers [17,7,18]. This analysis has been then extended to the double diffusive problem, using first a two-domain formulation [19,20] and more recently a one-domain approach [21].

The present paper focuses on the simulation of double diffusive convective flows in a binary fluid, confined in a vertical enclosure, divided into two vertical layers, one porous and the other fluid. The first analysis in this field has been proposed by Gobin et al. [22], where the influence of the Darcy number of the porous layer on heat and mass transfer has been analyzed, especially in the range of very small permeabilities for different Rayleigh numbers. The study was focused on the case of aqueous solutions ($Pr = 10$; $Le = 100$) as a binary fluid.

Following this first approach, several studies have concerned a similar situation with two porous layers, one along each vertical wall, a configuration supposed to refer to thermal insulation inside buildings [23,24]. In these studies, the fluid under consideration is a mixture of air with another gaseous component($Pr \sim 0.7$) and thus the Lewis number has the usual order of magnitude for gases: $Le \sim \mathcal{O}(1)$. Considering this range of parameters ($Le < 10$) considerably limits the relevance