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Heat transfer in enclosures having a fixed amount of solid material simulated with heterogeneous and homogeneous models

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Abstract

This work compares two different approaches for obtaining numerical solutions for laminar and turbulent natural convection within a cavity filled by a fixed amount of a solid conducting material. In the first model, a *porous-continuum*, *homogeneous* or *macroscopic* approach is considered based on the assumption that the solid and the fluid phases are observed as a single medium, over which volume-averaged transport equations apply. Secondly, a *continuum*, *heterogeneous* or *microscopic* model is considered to solve the momentum equations for the fluid phase resulting in a conjugate heat transfer problem in both the solid and the void space. In the *continuum* model, the solid phase is composed of square obstacles, equally spaced within the cavity. In both models, governing equations are numerically solved using the finite volume method. The average Nusselt number at the hot wall, obtained from the porous-continuum, *homogeneous* or *macroscopic* model, for several Darcy numbers, are compared with those obtained with the second approach, namely the *continuum* model, with different number of obstacles. When comparing the two methodologies, this study shows that the average Nusselt number calculated for each approach for the same Ra_m differs from each other and that this discrepancy increases as the Darcy number decreases, in the *porous-continuum* model, or the number of blocks increases, in the *continuum* model. Inclusion of turbulent transfer raises Nusselt for both the continuum and the porous-continuum models. A correlation is suggested to modify the macroscopic Rayleigh number in order to match the average Nusselt numbers calculated by the two models for $Ra_m = \text{const} = 10^4$ and Da ranging from 1.2060×10^{-4} to 1.

Keywords: Porous media; Heat transfer; Natural convection

1. Introduction

Studies on natural convection in porous enclosures have important applications in engineering and environmental research. Heat exchangers, underground spread of pollutants, environmental control, grain storage, food processing, material processing, geothermal systems, oil extraction, store of nuclear waste material, solar power collectors, optimal design of furnaces, crystal growth in liquids, packed-bed catalytic reactors and nuclear reactor safety are just some examples of applications of this subject of study.

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Nomenclature

c_F	Forchheimer coefficient
c_p	fluid specific heat, J/kg °C
Da_{eq}	equivalent Darcy number using K_{eq} given by Eq. (14); $Da_{eq} = \frac{K_{eq}}{H^2}$
Da	Darcy number using a porous medium permeability K; $Da = \frac{K}{H^2}$
D_p	square rod size, m
$\mathbf{g}$	gravity acceleration vector, m/s^2
h	heat transfer coefficient, W/m^2 °C
H	square height, m
K_{eq}	equivalent permeability for the continuum model, $K_{eq} = \frac{\phi^3 D_p^2}{120(1-\phi)^2}$; m^2
K	specified permeability used with the *porous-continuum* model; m^2
k_f	fluid thermal conductivity, W/m °C
k_s	solid thermal conductivity, W/m °C
N	number of obstacles
Nu	$Nu = hH/k_{eff}$, Nusselt number
Pr	$Pr = \nu/\alpha_{eff}$, Prandtl number
Ra	$Ra = \frac{g\beta H^3 \Delta T}{\nu_f \alpha}$, fluid Rayleigh number
Ra_ϕ	$Ra_\phi = \frac{g\beta_\phi H^3 \Delta T}{\nu_f \alpha_{eff}}$, volume-averaged Rayleigh number
Ra_m	$Ra \cdot Da_{eq} = Ra_\phi \cdot Da$, Darcy–Rayleigh number
T	temperature, °C
$\mathbf{u}$	microscopic velocity, m/s
$\mathbf{u}_D$	Darcy or superficial velocity (volume average of $\mathbf{u}$)

Greek symbols

α	fluid thermal diffusivity, m^2/s
β	fluid thermal expansion coefficient, 1/K
ΔV	representative elementary volume, m^2
ΔV_f	fluid volume inside ΔV
μ	fluid dynamic viscosity, N s/m^2
ν	fluid kinematic viscosity, m^2/s
ρ	fluid density, kg/m^3
ϕ	$\phi = \Delta V_f/\Delta V$, porosity

Special characters

φ	general variable
$\langle\varphi\rangle^i$	intrinsic average
$\langle\varphi\rangle^v$	volume average
$^i\varphi$	spatial deviation
$\lvert\varphi\rvert$	absolute value (Abs)
$\boldsymbol{\varphi}$	general vector variable
φ_{eff}	effective value, $\varphi_{eff} = \phi\varphi_f + (1-\phi)\varphi_s$
$\varphi_{s,f}$	solid/fluid
$\varphi_{H,C}$	hot/cold
φ_ϕ	macroscopic or porous continuum

The studies on natural convection has received extensive attention since the beginning of the 20th century [1,2]. Furthermore, natural convection in enclosures still attracts attention of researchers and a large number of experimental and theoretical works have been carried out mainly since the early 70s. The compilation and discussion of the main scientific contributions of researchers on understanding of natural convection during the conference on Numerical Methods in Thermal Problems, which took place in Swansea, yielded the classical benchmark of [3] for laminar clear fluid square cavities.

The works of [4–10] have exhibited some important results to the problem of free convection in a rectangular cavity filled with porous media and the monographs of [11] and [12] fully document natural convection in porous media. The recent work of [13], concerned a numerical study of the steady state free convection flow in rectangular and oblique cavities filled with homogeneous porous media using a nonlinear axis transformation. In the mentioned work, Darcy momentum and energy equations are solved numerically using the (ADI) method.

Macroscopic transport modeling of incompressible flows in porous media has been based on the volume-average methodology for either heat [14] or mass transfer [15–17]. In turbulent flows, when time fluctuations of the flow properties are also considered, in addition to spatial deviations, there are two possible methodologies to follow in order to obtain macroscopic equations: (a) application of time-average operator followed by volume-averaging [18–21], or (b) use of volume-averaging before time-averaging is applied [22–24]. However, both sets of macroscopic mass transport equations are equivalent when examined under the recently established *double decomposition* concept [25–28]. Such development, which was initially developed for only the flow variables, has been extended to heat transfer in porous media where both time fluctuations and spatial deviations were considered for temperature and velocity [29,30]. Further, a consistent program of systematic studies based on the *double-decomposition theory* for treating turbulent buoyant flows [31,32], mass transfer [32], non-equilibrium heat transfer [34] and double diffusion [35], in addition to a general classification of models [36], have been published. Recently, the problem of treating interfaces between a porous medium and a clear region, considering a diffusion-jump condition for the mean [37,38] and turbulence fields [39], have also been investigated under the concept first proposed by [25–28].