International Communications in Heat and Mass Transfer 49 (2013) 10–16

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Turbulent free convection in a porous square cavity using the thermal equilibirum model☆

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ARTICLE INFO

Available online 29 October 2013

Keywords:
Turbulence modeling
Porous media
Heat transfer
Natural convection

ABSTRACT

This work investigates the influence of porosity and thermal conductivity ratio on the Nusselt number of a cavity filed with a fluid saturated porous substrate. The flow regime considered intra-pore turbulence and a macroscopic k-ε model was applied. Heat transfer across the cavity assumed the hypothesis of thermal equilibrium between the solid and the fluid phases. Transport equations were discretized using the control-volume method and the system of algebraic equations was relaxed via the SIMPLE algorithm. Results showed that when using the one energy equation model under the turbulent regime, simulated with a High Reynolds turbulence model, the cavity Nusselt number is reduced for higher values of the ratio k_s/k_f as well as when the material porosity is increased. In both cases, conduction thorough the solid material becomes of a greater importance when compared with the overall transport that includes both convection and conduction mechanisms across the medium.

1. Introduction

Thermal convection in porous media and the parameters that affect heat transfer across a heterogeneous medium have been studied extensively in recent years. There are several applications in industry for this type of technology. Examples are studies on grain storage, optimization of solar collectors design, safety of nuclear reactors and design of porous burners for industrial furnaces, to mention a few. Traditionally, modeling of macroscopic transport for incompressible flows in porous media has been based on the volume-average methodology [1–4]. Additionally, if the flow fluctuates in time, the literature presents a number of time- and volume-averaging techniques that follow distinct sequences when applying both averaging operators [5–11]. Recently, a concept named *double decomposition* [12] showed that the sets of macroscopic mass transport equations are equivalent, regardless of the order of application of the averaging operators.

When buoyancy forces are of concern, natural convection occurs in enclosures as a result of gradients in densities which, in turn, are due to variations in temperature or mass concentration within the medium.

For clear cavities, the first turbulence model introduced for calculating buoyant flows was proposed by Markatos and Pericleous [13]. They performed steady 2-D simulations for Ra up to 10^{16} and presented a complete set of results. Ozoe et al. [14], in the light of the same model adopted by [13], applied it to 2D calculations up to $Ra = 10^{11}$. Henkes et al. [15] compared two different turbulence models for 2D calculations, namely the standard High Reynolds k-ε closure as well as the Low–Reynolds number form of the model. Further, Fusegi et al. [16] presented 3D calculations for laminar flow for Ra up to 10^{10} in a cube. The results revealed that the behaviors of the flow and comparisons were made with 2D simulations. The differences were reported considering heat transfer correlation between Nu and Ra for 2D and 3D cases. Later, Barakos et al. [17] also studied the problem of natural convection flow in a clean square cavity. The k-ε model has been used for modeling turbulence with and without wall functions.

For cavities fitted with a porous material, the problem of free convection in enclosures with distinct temperatures applied on each side of the cavity has been shown to represent a number of engineering systems of practical relevance. The monographs of Nield and Bejan [18] and Ingham and Pop [19] fully document natural convection in porous media. In addition, several articles published in the literature made important contributions to the understanding of this problem [20–26]. Baytas and Pop [27] considered a numerical study of steady free convection flow in rectangular and oblique cavities, filled with homogeneous porous media using a nonlinear axis transformation. The Darcy momentum and energy equations were numerically solved using the (ADI) method.

In the work of Braga and de Lemos (2004) [28], an approximate critical Rayleigh was proposed comparing the behavior of Laminar and High Reynolds turbulence model solutions. The geometry there investigated was a square cavity totally filled with a porous material, which was heated from the left and cooled from the opposing side. Also worth to mention is that the work in [28] was based on the local thermal equilibrium (LTE) hypothesis, which considers one unique temperature for both the fluid and the solid porous material. Other cases not involving gravity driven motion [29] have also been analyzed with the laminar version of the LTE model detailed in [12]. Further, in

☆ Communicated by Dr. W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2013.10.003

Nomenclature

Latin characters

c_F	Forchheimer coefficient
$c's$	Non-dimensional turbulence model constants
c_p	Specific heat
$\mathbf{D}$	Deformation rate tensor, $\mathbf{D} = [\nabla\mathbf{u} + (\nabla\mathbf{u})^T]/2$
Da	Darcy number, $Da = \frac{K}{H^2}$
D	Particle diameter, D
$\mathbf{g}$	Gravity acceleration vector
G^i	Generation rate of $\langle k \rangle^i$ due to the action of the porous matrix
G^i_β	Generation rate of $\langle k \rangle^i$ due to buoyant effects
h	Heat transfer coefficient
H	Cavity height
$\mathbf{I}$	Unit tensor
K	Permeability, $K = \frac{D^2\phi^3}{144(1-\phi)^2}$
k	Turbulent kinetic energy per unit mass, $k = \overline{\mathbf{u}' \cdot \mathbf{u}'}/2$
k_f	Fluid thermal conductivity
k_s	Solid thermal conductivity
$\mathbf{K}_{disp}$	Conductivity tensor due to thermal dispersion
$\mathbf{K}_{disp,t}$	Conductivity tensor due to turbulent thermal dispersion
$\mathbf{K}_t$	Conductivity tensor due to turbulent heat flux
$\mathbf{K}_{tor}$	Conductivity tensor due to tortuosity
L	Cavity width
Nu	Nusselt number, $Nu = {}^{hL}/_{k_{eff}}$
P^i	Production rate of $\langle k \rangle^i$ due to gradients of $\overline{\mathbf{u}}_D$
Pr	Prandtl number
Ra_f	Macroscopic Fluid Rayleigh number, $Ra_f = \frac{g\beta_\phi H^3 \Delta T}{\nu_f \alpha_{eff}}$
Ra_m	Darcy–Rayleigh number, $Ra_m = Ra_f \cdot Da = \frac{g\beta_\phi H \Delta T K}{\nu_f \alpha_{eff}}$
Ra_{cr}	Critical Rayleigh number
Re_D	Reynolds number based on the particle diameter, $\mathrm{Re}_D = \frac{\rho \lvert \overline{\mathbf{u}}_D \rvert D}{\mu_f}$
T	Temperature
$\mathbf{u}$	Microscopic velocity
$\mathbf{u}_D$	Darcy or superficial velocity (volume average of $\mathbf{u}$)

Greek characters

α	Thermal diffusivity
β	Thermal expansion coefficient
ΔV	Representative elementary volume
ΔV_f	Fluid volume inside ΔV
ε	$\varepsilon = \mu \overline{\nabla \mathbf{u}' : (\nabla \mathbf{u}')^T}/\rho$, Dissipation rate of k
μ	Dynamic viscosity
μ_t	Microscopic turbulent viscosity
μ_{t_ϕ}	Macroscopic turbulent viscosity
ν	Kinematic viscosity
ρ	Density
$\sigma's$	Non-dimensional constants
ϕ	$\phi = {}^{\Delta V_f}/_{\Delta V}$, Porosity

Special characters

φ	General variable
$\overline{\varphi}$	Time average
φ'	Time fluctuation
$\langle\varphi\rangle^i$	Intrinsic average
$\langle\varphi\rangle^v$	Volume average
${}^i\varphi$	Spatial deviation
$\lvert\boldsymbol{\varphi}\rvert$	Absolute value (Abs)
$\boldsymbol{\varphi}$	General vector variable
φ_{eff}	Effective value of φ, $\varphi_{eff} = \phi\varphi_f + (1-\phi)\varphi_s$
$\varphi_{s,f}$	solid/fluid
$\varphi_{H,C}$	Hot/cold
φ_ϕ	Macroscopic value
$()^T$	Transpose

[28] it was also shown that low Darcy numbers impact in higher average Nusselt numbers at the hot wall. However, in reference [28] simulations were limited to a single solid-to-fluid thermal conductivity ratio, $k_s/k_f = 1$, and a single porosity value, $\phi = 0.8$.

Motivated by the foregoing work, the contribution of this work is to extend the findings in [28] varying now the ratio k_s/k_f and the porosity ϕ. The turbulence model here adopted is the macroscopic k-ε with wall function in addition to the Low Reynolds number version of the model. The findings herein broaden the simulations presented earlier in [28] since a greater number of heterogonous systems are now investigated, leading to the analysis and optimization of a wider range of practical engineering systems.

2. The problem under consideration

The problem considered is showed schematically in Fig. 1a and refers to a square cavity with sides $L = H = 1$ m completely filled with a porous medium. The cavity is isothermally heated from the left, T_H, and cooled from the opposing side, T_C. The other two walls are thermally insulated. These boundary conditions are widely applied when solving buoyancy-driven cavity flows. The porous medium is considered to be rigid and saturated by an incompressible fluid. The modified Rayleigh number, Ra_m, is a dimensionless parameter used in porous media

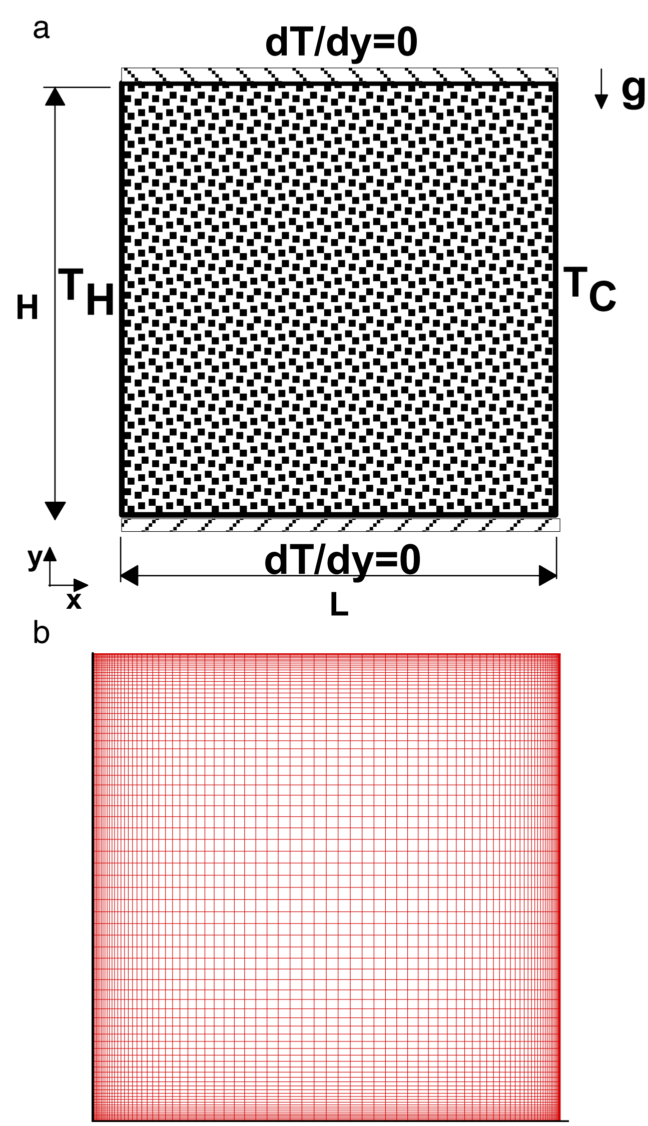

Fig. 1. a) Geometry under consideration; b) 80 × 80 stretched grid.