TURBULENT NATURAL CONVECTION IN A SQUARE CAVITY WITH A POROUS OBSTRUCTION

Edimilson Junqueira Braga
Marcelo J.S. De-Lemos *
Departamento de Energia - IEME
Instituto Tecnológico de Aeronáutica - ITA
12228-900 - São José dos Campos - SP – Brazil
* Corresponding author. E-mail: delemos@mec.ita.br

Abstract. *Turbulent natural convection in a horizontal two-dimensional square cavity, isothermally heated from below and cooled at the upper surface, is numerically analyzed using the finite volume method in a generalized coordinate system. The enclosure has a thin horizontal porous obstruction located at the cavity half height. Governing equations are written in terms of primitive variables and are recast into a general form. In general way, the porous obstruction decreases the heat transfer across the heated walls, showing an overall lower Nusselt numbers when compared with those without porous obstruction. However, the presence of a porous obstruction in a square cavity seems to force an earlier transition of the laminar regime to the turbulent regime due to the higher generation of turbulent kinetic energy in the porous matrix.*

Keywords*. Natural Convection, Turbulent Model, Porous Media, Heat Transfer.*

1. Introduction

Traditionally, modeling of macroscopic transport for incompressible flows in porous media has been based on the volume-average methodology for either heat Hsu & Cheng (1990) or mass transfer Bear (1972),Whitaker (1966),Whitaker (1967). If 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 Masuoka & Takatsu (1996), Kuwahara & Nakayama (1998) and Nakayama & Kuwahara (1999), or *b*) use of volume-averaging before time-averaging is applied Lee & Howell (1987), Antohe & Lage (1997)-Getachewa et al (2000). However, both sets of macroscopic mass transport equations are equivalent when examined under the recently established *double decomposition* concept Pedras & de Lemos (2000), Pedras & de Lemos (2001a), Pedras & de Lemos (2001b) and Pedras & de Lemos (2001c). This methodology, initially developed for the flow variables, has been extended to heat transfer in porous media where both time fluctuations and spatial deviations were considered for velocity and temperature Rocamora & de Lemos (2000) and de Lemos & Rocamora (2002). A general classification of all proposed models for turbulent flow and heat transfer in porous media has been recently published de Lemos & Pedras (2001).

Further, the analysis of buoyancy-driven flows in an enclosed cavity provides useful comparisons for evaluating the robustness and performance of numerical methods dealing with viscous flow calculations. The importance of the enclosure natural-convection phenomena can best be appreciated by noting several of their application areas. The optimal design of furnaces and solar collectors - contributing to energy losses minimization - nuclear reactor safety and insulation, ventilation rooms and crystal growth in liquids are some examples of applications of heat removal or addition by free convection mechanism.

Natural convection occurs in enclosures as a result of gradients in density which, in turn, is due to variations in temperature or mass concentration. Natural convection in an infinite horizontal layer of fluid, heated from below, has received extensive attention since the beginning of the 20th century when Bérnard (1901) observed hexagonal roll cells upon the onset of convection in molten spermaceti with a free upper surface. The work of Rayleigh (1926) was the first to compute a critical value, Ra_c, for the onset of convection. The accepted theoretical value of this dimensionless group is 1708 for infinite rigid upper and lower surfaces. The study of natural convection in enclosures still attracts the attention of researchers and a significant number of experimental and theoretical works have been carried out mainly from the 80's.

During the conference on Numerical Methods in Thermal Problems, which took place in Swansea, Jones (1979) proposed that buoyancy-driven flow in a square cavity would be a suitable vehicle for testing and validating computer codes. Following discussions at Swansea, contributions for the solution of the problem were invited. A total of 37 contributions from 30 groups in nine different countries were received. The compilation and discussion of the main contributions yielded the classical benchmark of de Vahl Davis (1983).

The first to introduce a turbulence model in their calculations were Markatos & Pericleous (1984). They performed steady 2-D simulations for Ra up to 10^{16} and presented a complete set of results. Ozoe et al (1985) used the same turbulence model adopted by them for 2-D calculations up to $Ra = 10^{11}$.

Henkes et al. (1991)), performed 2-D calculations using various versions of the k-ε turbulence model. These versions included the standard as well as the Low-Reynolds number k-ε models. A comparison with experimental results for Nu showed the superiority of the Low-Reynolds number k-ε closures.

Fusegi et al (1991), presented 3-D calculations for laminar flow for Ra up to 10^{10}. Their graphs revealed the 3-D character of the flow. Comparisons were made with 2-D simulations and differences were reported for the heat transfer correlation between Nu and Ra.

A recent paper by Barakos et al. (1994), reworked the problem for laminar and turbulent flows for a wide range of Ra. Turbulence was modeled with the standard k-ε closure and the effect of the assumed wall functions on heat transfer were investigated.

Thermal convection in porous media has been studied extensively in recent years. Underground spread of pollutants, grain storage, food processing are just some applications of this theme. The monographs of Nield & Bejan (1992) and Ingham & Pop (1998) fully document natural convection in porous media.

The case of free convection in a rectangular cavity heated on a side and cooled at the opposing side is an important problem in thermal convection in porous media. Walker & Homsy (1978), Bejan (1979), Prasad & Kulacki (1984), Beckermann et al. (1986), Gross et al (1986), Manole & Lage (1992) have contributed with some important results to this problem.

The recent work of Baytas & Pop (1999), concerned a numerical study of the 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 are solved numerically using the (ADI) method.

Following this path, the work of Braga & de-Lemos (2002a), presented results for laminar natural convection in a square cavity heated on the sides. Later, Braga & de-Lemos (2002b) extended their results for considering laminar natural convection in a horizontal annular cavity. Turbulent regime in horizontal cylindrical annuli, both for concentric and eccentric cases, was also calculated (Braga & de-Lemos (2002c). Further, the study of natural convection in cavities completely filled with porous material was reported in the work of Braga & de-Lemos (2002d). In that work the two geometries mentioned above, namely square and annular cavities were considered. The turbulent natural convection in enclosures with clear fluid and completely filled with porous material was investigated in Braga & de-Lemos (2002e). Finally, the modeling of turbulent natural convection in saturated rigid porous media was presented in de Lemos & Braga (2003).

Motivated by the foregoing work, this paper presents results for both laminar and turbulent flows in a square cavity heated from the bottom and cooled from the ceiling. The enclosure has a thin horizontal porous obstruction located at the cavity half height. The turbulence model here adopted is the standard k-ε with wall function.

2. The Problem Considered

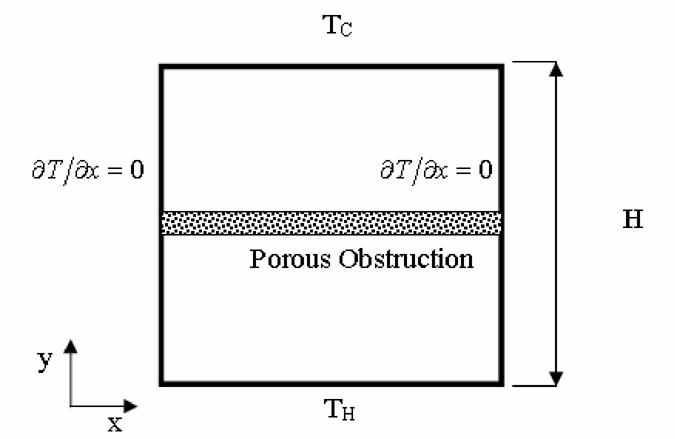


Figure 1 – Geometry under consideration.

The problem considered is shown schematically in Fig. (1), and refers to the two-dimensional flow of a Boussinesq fluid of Prandtl number 1 in a square cavity of side L=1m. The cavity is assumed to be of infinite depth along the z-axis and is isothermally heated from the bottom and cooled from the ceiling. The horizontal square cavity has a porous obstruction of thickness d=0.04 m positioned at cavity mid height

The no-slip condition is applied for velocity and the resulting flow is treated as steady. The controlling parameter is the Rayleigh number, $Ra = \frac{g\beta H^3 \Delta T}{\nu\alpha}$. Further, a relationship between the porosity, permeability and the particle diameter is given by $D_p = \sqrt{\frac{144K(1-\phi)^2}{\phi^3}}$.

3. Governing Equations

The equations used herein are derived in details in the work of Pedras & de Lemos (2001a), de Lemos & Rocamora (2002).and de Lemos & Braga (2003).

Basically, for porous media analysis, a macroscopic form of the governing equations is obtained by taking the volumetric average of the entire equation set. In that development, the porous medium is considered to be rigid and satured by an incompressible fluid.

The macroscopic continuity equation is given by,

$$\nabla \cdot \overline{\mathbf{u}}_D = 0 \tag{1}$$

The Dupuit-Forchheimer relationship, $\overline{\mathbf{u}}_D = \phi \langle \overline{\mathbf{u}} \rangle^i$, has been used and $\langle \overline{\mathbf{u}} \rangle^i$ identifies the intrinsic (liquid) average of the local velocity vector $\overline{\mathbf{u}}$. The macroscopic time-mean Navier-Stokes (NS) equation for an incompressible fluid with constant properties is given as,

$$\begin{aligned}\rho\left[\frac{\partial \overline{\mathbf{u}}_D}{\partial t} + \nabla \cdot \left(\frac{\overline{\mathbf{u}}_D \overline{\mathbf{u}}_D}{\phi}\right)\right] &= -\nabla\left(\phi \langle \overline{p} \rangle^i\right) + \mu \nabla^2 \overline{\mathbf{u}}_D + \nabla \cdot \left(-\rho\phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i\right) \\ &\quad - \rho\beta_\phi \mathbf{g}\phi\left(\langle \overline{T} \rangle^i - T_{ref}\right) - \left[\frac{\mu\phi}{K}\overline{\mathbf{u}}_D + \frac{c_F \phi \rho |\overline{\mathbf{u}}_D| \overline{\mathbf{u}}_D}{\sqrt{K}}\right]\end{aligned} \tag{2}$$

When treating turbulence with statistical tools, the correlation $-\rho\overline{\mathbf{u}'\mathbf{u}'}$ appears after application of the time-average operator to the local instantaneous NS equation. Applying further the volume-average procedure to this correlation results in the term $-\rho\phi\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i$. This term is here recalled the **Macroscopic Reynolds Stress Tensor** (MRST). Further, a model for the (MRST) in analogy with the Boussinesq concept for clear fluid can be written as:

$$-\rho\phi\langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i = \mu_{t_\phi} 2\langle \overline{\mathbf{D}} \rangle^v - \frac{2}{3}\phi\rho\langle k \rangle^i \mathbf{I} \tag{3}$$

where

$$\langle \overline{\mathbf{D}} \rangle^v = \frac{1}{2}\left[\nabla\left(\phi\langle \overline{\mathbf{u}} \rangle^i\right) + \left[\nabla\left(\phi\langle \overline{\mathbf{u}} \rangle^i\right)\right]^T\right] \tag{4}$$

is the macroscopic deformation rate tensor, $\langle k \rangle^i$ is the intrinsic average for k and μ_{t_ϕ} is the macroscopic turbulent viscosity. The macroscopic turbulent viscosity, μ_{t_ϕ}, is modeled similarly to the case of clear fluid flow and a proposal for it was presented in Pedras & de Lemos (2001a) as,

$$\mu_{t_\phi} = \rho C_\mu \frac{\langle k \rangle^{i\,2}}{\langle \varepsilon \rangle^i} \tag{5}$$

In a similar way, applying both time and volumetric average to the microscopic energy equation, for either the fluid or the porous matrix, two equations arise. Assuming further the **Local Thermal Equilibrium Hypothesis,** which considers $\langle \overline{T_f} \rangle^i = \langle \overline{T_s} \rangle^i = \langle \overline{T} \rangle^i$, and adding up these two equations, one has,

$$\begin{aligned}\left\{(\rho c_p)_f \phi + (\rho c_p)_s (1-\phi)\right\}\frac{\partial \langle \overline{T} \rangle^i}{\partial t} + (\rho c_p)_f \nabla \cdot \left(\overline{\mathbf{u}}_D \langle \overline{T} \rangle^i\right) &= \nabla \cdot \left\{\left[k_f \phi + k_s (1-\phi)\right]\nabla \langle \overline{T} \rangle^i\right\} + \nabla \cdot \left[\frac{1}{\Delta V}\int_{A_i} \mathbf{n}\left(k_f \overline{T_f} - k_s \overline{T_s}\right) dS\right] \\ &\quad - (\rho c_p)_f \nabla \cdot \left[\phi\left(\langle {}^i\overline{\mathbf{u}}\,{}^i\overline{T_f} \rangle^i + \overline{\langle \mathbf{u}' \rangle^i \langle T_f' \rangle^i} + \langle \overline{{}^i\mathbf{u}'\,{}^iT_f'} \rangle^i\right)\right]\end{aligned} \tag{6}$$

where to each underscored term on the right hand side of Eq. (6), the following significance can be attributed: I-**Tortuosity -** based on the stagnant heat path inside the porous medium, II-**Turbulent Heat Flux -** due to the macroscopic time fluctuations of the velocity and the temperature, III-**Thermal Dispersion** - associated to the spatial deviations of the time averaged microscopic velocity and temperature. Note that this term is also present in laminar flows in porous media. IV-**Turbulent Thermal Dispersion** - due to both time fluctuations and spatial deviations of the microscopic velocity and temperature.

A modeled form of equation (6) has been given in detail in the work of de Lemos & Rocamora (2002), and Rocamora & de-Lemos (2002), as,

$$\left\{(\rho c_p)_f \phi + (\rho c_p)_s (1-\phi)\right\}\frac{\partial \langle \overline{T}\rangle^i}{\partial t} + (\rho c_p)_f \nabla \cdot \left(\mathbf{u}_D \langle \overline{T}\rangle^i\right) = \nabla \cdot \left\{\mathbf{K}_{eff} \cdot \nabla \langle \overline{T}\rangle^i\right\} \tag{7}$$

where, $\mathbf{K}_{eff}$, given by:

$$\mathbf{K}_{eff} = \left[\phi k_f + (1-\phi) k_s\right]\mathbf{I} + \mathbf{K}_{tor} + \mathbf{K}_t + \mathbf{K}_{disp} + \mathbf{K}_{disp,t} \tag{8}$$

is the effective conductivity tensor. In order to be able to apply Eq. 7, it is necessary to determine the conductivity tensors in Eq. 8, *i.e.*, $\mathbf{K}_{tor}$, $\mathbf{K}_t$, $\mathbf{K}_{disp}$ and $\mathbf{K}_{disp,t}$. Following Kuwahara & Nakayama (1998), this can be accomplished for the tortuosity and thermal dispersion conductivity tensors, $\mathbf{K}_{tor}$ and $\mathbf{K}_{disp}$, by making use of a unit cell subjected to periodic boundary conditions for the flow and a linear temperature gradient imposed over the domain. The conductivity tensors are then obtained directly from the microscopic results for the unit cell (see Kuwahara & Nakayama (1998) for details on the expressions here used).

The turbulent heat flux and turbulent thermal dispersion terms, $\mathbf{K}_t$ and $\mathbf{K}_{disp,t}$, which cannot be determined from such a microscopic calculation, are modeled here through the Eddy diffusivity concept, similarly to Nakayama & Kuwahara (1999). It should be noticed that these terms arise only if the flow is turbulent, whereas the tortuosity and the thermal dispersion terms exist for both laminar and turbulent flow regimes.

Starting out from the time averaged energy equation coupled with the microscopic modeling for the 'turbulent thermal stress tensor' through the Eddy diffusivity concept, one can write, after volume averaging,

$$-(\rho c_p)_f \langle \overline{\mathbf{u}' T_f'}\rangle^i = (\rho c_p)_f \frac{\nu_{t_\phi}}{\sigma_T} \nabla \langle \overline{T}_f \rangle^i \tag{9}$$

where the symbol ν_{t_ϕ} expresses the macroscopic Eddy viscosity, $\mu_{t_\phi} = \rho_f \nu_{t_\phi}$, given by (5) and σ_T is a constant. According to equation 9, the macroscopic heat flux due to turbulence is taken as the sum of the turbulent heat flux and the turbulent thermal dispersion found by de Lemos & Rocamora (2002). In view of the arguments given above, the turbulent heat flux and turbulent thermal dispersion components of the conductivity tensor, $\mathbf{K}_t$ and $\mathbf{K}_{disp,t}$, respectively, are expressed as:

$$\mathbf{K}_t + \mathbf{K}_{disp,t} = \phi (\rho c_p)_f \frac{\nu_{t_\phi}}{\sigma_T}\mathbf{I} \tag{10}$$

In the equation set shown above, when the variable $\phi=1$, the domain is considered as a clear medium. For any other value of ϕ, the domain is treated as a porous medium.

4. Numerical Method and Solution Procedure

The numerical method employed for discretizing the governing equations is the control-volume approach with a collocated grid. A hybrid scheme, Upwind Differencing Scheme (UDS) and Central Differencing Scheme (CDS), is used for interpolating the convection fluxes. The well-established SIMPLE algorithm (Patankar & Spalding, (1972)) is followed for handling the pressure-velocity coupling. Individual algebraic equation sets were solved by the SIP procedure of Stone, (1968).

5. Turbulence Model

Transport equations for $\langle k\rangle^i = \langle \overline{\mathbf{u}' \cdot \mathbf{u}'}\rangle^i / 2$ and $\langle \varepsilon \rangle^i = \mu \langle \overline{\nabla \mathbf{u}' : (\nabla \mathbf{u}')^T}\rangle^i / \rho$ in their so-called High Reynolds number form are proposed in Pedras & de Lemos (2001a) and extended in de Lemos & Braga (2003) to incorporate the buoyant effects as:

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle k\rangle^i\right)+\nabla\cdot\left(\overline{\mathbf{u}}_D\langle k\rangle^i\right)\right]=\nabla\cdot\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_k}\right)\nabla\left(\phi\langle k\rangle^i\right)\right]+P^i+G^i+G^i_\beta-\rho\phi\langle\varepsilon\rangle^i \tag{11}$$

$$\rho\left[\frac{\partial}{\partial t}\left(\phi\langle\varepsilon\rangle^i\right)+\nabla\cdot\left(\overline{\mathbf{u}}_D\langle\varepsilon\rangle^i\right)\right]=\nabla\cdot\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_\varepsilon}\right)\nabla\left(\phi\langle\varepsilon\rangle^i\right)\right]+c_1P^i\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}+c_2\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}G^i+c_1c_3G^i_\beta\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}-c_2\rho\phi\frac{\langle\varepsilon\rangle^{i\,2}}{\langle k\rangle^i} \tag{12}$$

where c_1, c_2, c_3 and c_k are constants, $P^i=\left(-\rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i:\nabla\overline{\mathbf{u}}_D\right)$ is the production rate of $\langle k\rangle^i$ due to gradients of $\overline{\mathbf{u}}_D$, $G^i=C_k\rho\frac{\phi\langle k\rangle^i|\overline{\mathbf{u}}_D|}{\sqrt{K}}$ is the generation rate of the intrinsic average of k due to the action of the porous matrix and $G^i_\beta=\phi\frac{\mu_{t_\phi}}{\sigma_t}\mathbf{g}\beta_\phi\nabla\langle\overline{T}\rangle^i$ is the generation rate of $\langle k\rangle^i$ due to the buoyant effects.

6. Results and Discussion

Calculations for turbulent flow were performed for all cases using a 50x50 uniform grid. A turbulent case with 80x120 grid with several points near to the heated walls were performed for Ra=10^6. The percentual difference for the Nusselt number on the heated wall between these two meshes is less than 3%. The Rayleigh number is calculated as in the clear fluid case. It is important to emphasize that the present results were started with the solution for Ra=4x10^4 with a plume impinging at the center of the cavity. It is known that the solutions for horizontal cavities are not unique, but, the bifurcation of the solution is out of the concern of this work.

Figures (2), (3) and (4) show the isotherms, streamlines and isolines of turbulent kinetic energy for turbulent flow in a horizontal square cavity with a porous obstruction at its midheight for Ra ranging from 4x10^4 to 10^7. For lower values of Ra, not shown here, the isotherms are stratified and the main mechanism of heat transfer is conduction and the generation of turbulent kinetic energy is null due to the low velocity gradients.

For Ra=4x10^4, a plume arise from the bottom of the heated wall impinging through the porous obstruction, Fig (2a). The flow is divided in two vortices of each side of the porous obstruction, Fig (**3**a). The generation of turbulent kinetic energy remains small and it is almost null everywhere, Fig (4a).

Increasing Ra to 10^6, the plume becomes stronger, impinging through the porous obstruction more intensively, Fig (**2**b). The vortices move a little faster than before, Fig (3b) and the generation of turbulent kinetic energy is now remarkable, mainly inside and around the vicinity of the porous obstruction (**4**b). As proposed by Pedras (2000), the porous matrix contributes with the generation of turbulent kinetic energy such that a new term in the $\langle k\rangle^i$ transport equation was introduced. For a fixed value of the Darcy velocity through a porous bed, the amount of mechanical energy converted into turbulence should depend on the medium properties. For the limiting case of high porosity and permeability media ($\phi\to1\Rightarrow K\to\infty$) no fraction of this available mechanical energy is expected to generate turbulence. The flow, in this situation, behaves like clear fluid flow. As the flow resistance increases, by increasing $\phi/\sqrt{K}$, gradients of local **u** within the pore will contribute to increasing $\langle k\rangle^i$. This porous obstruction, as will be shown later, forces an earlier transition of regimes, namely, laminar and turbulent.

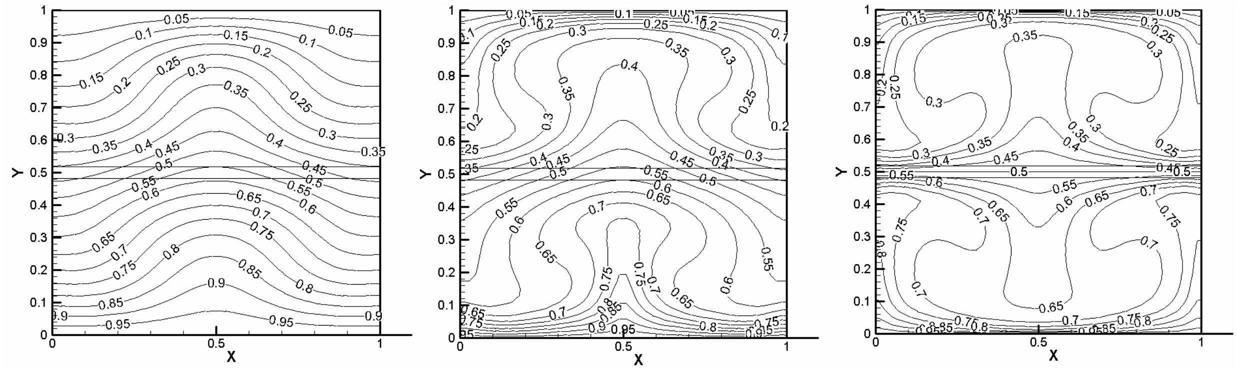
For Ra=10^7, two plumes arise from the porous obstruction of each side of the square cavity. Both plumes point to opposing directions and move toward to the heated walls, Fig (2c). This feature makes the streamlines, Fig (3c), change its directions, probably to minimize the shear stresses between the vortices. Therefore, the isolines of turbulent kinetic energy are very pronounced in the porous matrix and present symmetry with respect to the center of the cavity, Fig (4c).

Table (1) shows the Nusselt numbers for a horizontal square cavity with two possibilities: a) Horizontal square cavity with a porous obstruction. b) Horizontal square cavity without a porous obstruction.

Table (1) clearly shows that the overall values of the Nusselt number for a horizontal square cavity without a porous obstruction are higher than those with porous obstruction. The porous obstruction damps the heat transfer across the heated walls, showing an overall lower Nusselt numbers when compared with those without porous obstruction.
However, the presence of a porous obstruction in the square cavity seems to force an earlier transition of the laminar regime to the turbulent regime due to the higher generation of turbulent kinetic energy in the porous matrix.

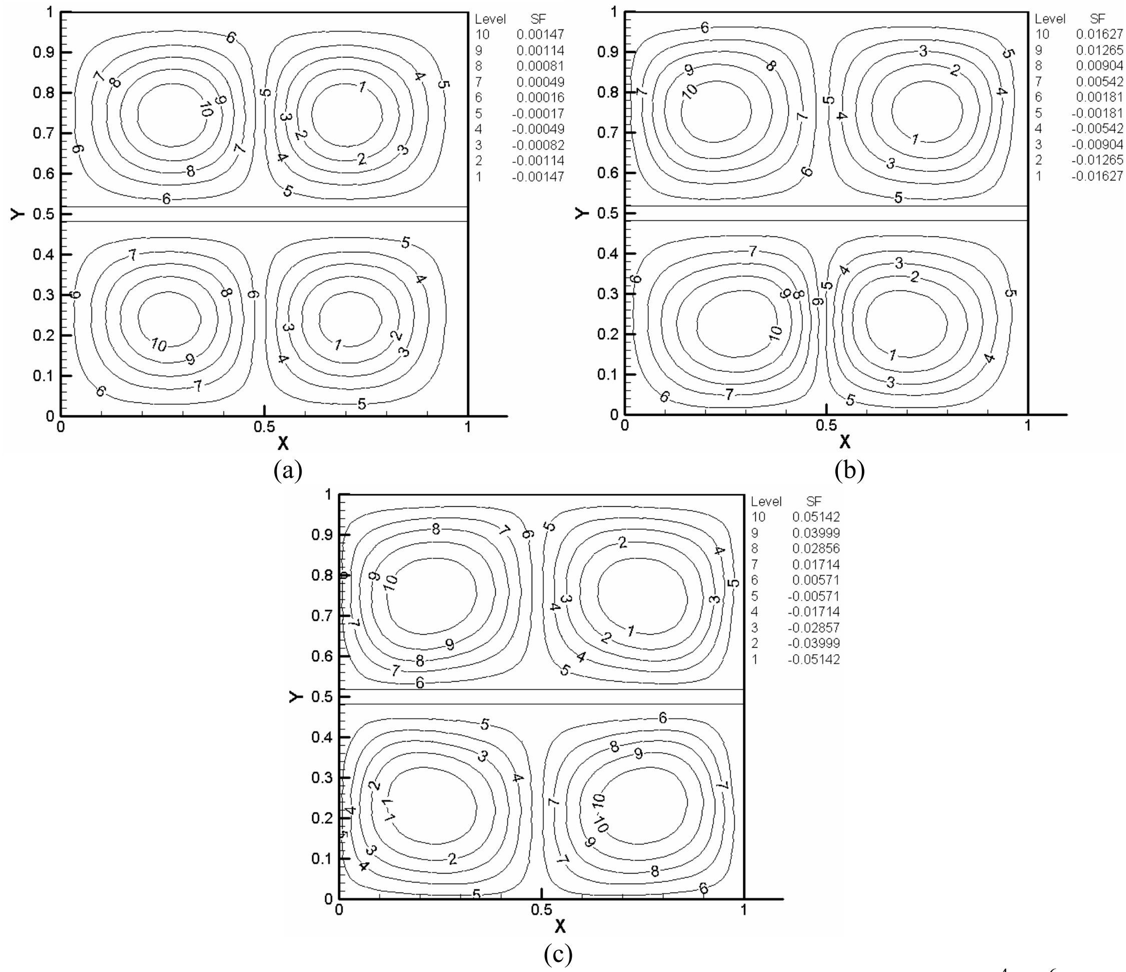
Table 1 - Average Nusselt numbers for a horizontal square cavity, a) with porous obstruction, b) Without porous obstruction, for Ra ranging from 10^2 to 10^7 with ϕ=0.95 and D_p=1 mm.

Model Applied \ *Ra*		10^2	4x10^4	10^6	10^7
Laminar solution	a	1.001	1.3655	4.1915	7.423
	b	0.997	2.9329	7.1330	16.446
Turbulent solution	a	1.010	1.3299	5.7922	11.087
	b	0.998	2.9327	7.8679	16.431



(a) (b) (c)

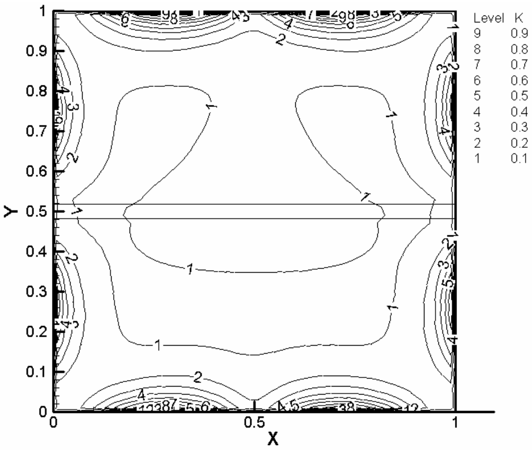
Figure 2 - Turbulent isotherms of a horizontal square cavity with a porous obstruction for a) Ra=4x10^4, b) 10^6 and c) 10^7 with ϕ=0.95 and D_p=1 mm.



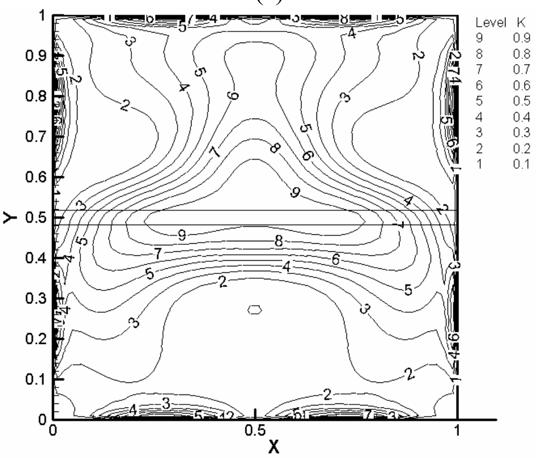
(a) (b)

(c)

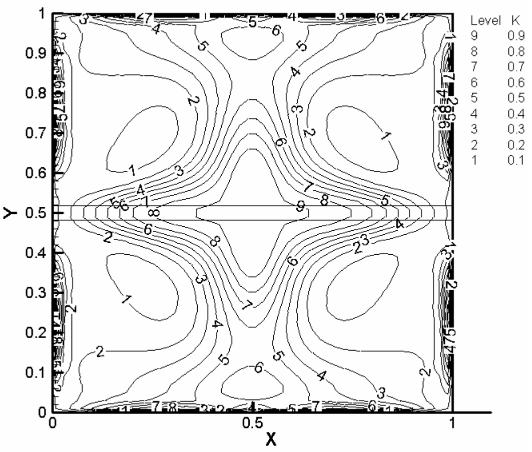
Figure 3 - Turbulent streamlines of a horizontal square cavity with a porous obstruction for Ra=4x10^4, 10^6 and 10^7 with ϕ=0.95 and D_p=1 mm.



(a)



(b)



(c)

Figure 4- Turbulent isolines of k of a horizontal square cavity with a porous obstruction for Ra=4x10^4, 10^6 and 10^7 with ϕ=0.95 and D_p=1 mm.

7. Concluding Remarks

This paper presented computations for laminar and turbulent flows with the standard k-ε model with a wall function for natural convection in a square cavity with a porous obstruction in the middle. Nusselt numbers for a horizontal square cavity without a porous obstruction are higher than those with porous obstruction. The porous obstruction damps the heat transfer across the heated walls, showing an overall lower Nusselt numbers when compared with those with porous obstruction. However, the presence of a porous obstruction in the square cavity seems to force an earlier transition of the laminar regime to the turbulent regime due to the higher generation of turbulent kinetic energy in the porous matrix.

8. Acknowledgement

The authors are thankful to CNPq, Brazil, for their financial support during the course of this research.

9. References

Antohe, B. V., Lage, J. L., 1997, A general two-equation macroscopic turbulence model for incompressible flow in porous media, *Int. J. Heat Mass Transfer*, vol. 40, pp. 3013-3024

Barakos, G., Mitsoulis, E., Assimacopoulos, D., 1994, NATURAL CONVECTION FLOW IN A SQUARE CAVITY REVITED: LAMINAR AND TURBULENT MODELS WITH WALL FUNCTION, *Int. J. Numerical Methods in Fluids,* Vol. 18, pp. 695-719.

Baytas, A. C., Pop, I., 1999, FREE CONVECTION IN OBLIQUE ENCLOSURES FILLED WITH A POROUS MEDIUM, Int. J. Heat Mass Transfer, Vol 42, pp. 1047-1057.

Bear, J., *Dynamics of Fluids in Porous Media*, American Elsevier Pub. Co., New York, 1972.

Beckermann, C., Viskanta, R., Ramadhyani, 1986, S., A NUMERICAL STUDY OF NON-DARCIAN NATURAL CONVECTION IN A VERTICAL ENCLOSURE FILLED WITH A POROUS MEDIUM, Num. Heat Transfer, Vol. 10, pp. 557-570.

Bejan, A., 1979, ON THE BOUNDARY LAYER REGIME IN A VERTICAL ENCLOSURE FILLED WITH A POROUS MEDIUM, Lett. Heat Mass transfer, Vol. 6, pp. 93-102.

Bérnard, H., 1901, Les Tourbillons Cellulaires dans une Nappe Liquide Transportant de la Chaleur par Convection em Régime Permanent, Ann. Chim. Phys., vol 23, pp. 62-144.

Braga, E.J., de-Lemos, M.J.S., 2002a, FREE CONVECTION IN SQUARE AND RECTANGULAR CAVITIES HEATED FROM BELOW OR ON THE LEFT, *Proceedings of CONEM2002, 3rd Congresso Nacional de Engenharia Mecânica*, João Pessoa, PB, Brazil, August 12-16.

Braga, E.J., de-Lemos, M.J.S., 2002b, LAMINAR NATURAL CONVECTION IN CONCENTRIC AND ECCENTRIC ANNULI, *Proceedings of ENCIT2002, 9th Brazilian Congress of Thermal Engineering and Sciences* (accepted for presentation), Caxambu, MG, Brazil, October 13-17.

Braga, E.J., de-Lemos, M.J.S., 2002c, NATURAL CONVECTION IN TURBULENT REGIME IN CONCENTRIC AND ECCENTRIC HORIZONTAL ANNULAR REGIONS, **Paper AIAA-2002-3316**, *Proc. of 8th AIAA/ASME, Joint Thermophysics and Heat Transfer Conference*, St Louis, Missouri, U.S.A, June 23-27.

Braga, E.J., de-Lemos, M.J.S., 2002d, NATURAL CONVECTION IN CAVITIES COMPLETELY FILLED WITH POROUS MATERIAL, *Proceedings of APM2002, 1st International Conference on Applications of Porous Media*, **Paper APM-164**, vol. 1, pp. 551-560, Jerba, Tunísia, June 2-8.

Braga, E.J., de-Lemos, M.J.S., 2002e, Turbulent Natural Convection in Enclosures With Clear Fluid and Completely Filled With Porous Material, **Paper IMECE2002-34403**, *2002 ASME International Mechanical Engineering Congress*, New Orleans, LA, USA, November 17-22.

Brinkman, H. C., 1947, A calculation of the viscous force exerted by a flowing fluid on a dense swarm of particles, *Appl. Sci. Research*, A 1, pp. 27-34.

de Lemos, M.J.S., 2000, Flow and heat transfer in rectangular enclosures using a new block-implicit numerical method, *Numerical Heat Transfer*, Part B, pp. 1-20.

de Lemos, M.J.S., Braga, E.J., 2003, Modeling of Turbulent Natural Convection in Saturated Rigid Porous Media, *Int. Comm. Heat and Mass Transfer*, (in press).

de Lemos, M.J.S., Pedras, M.H.J., 2001, *Journal of Fluids Engineering*, **123(**4), 935.

de Lemos, M.J.S., Rocamora Jr, F.D., 2002, Turbulent Transport Modeling for Heated Flow in Rigid Porous Media, *12th. Intern. Heat Transfer Conference*, Grenoble, France, August 18-23.

de Vahl Davis, G., 1983, Natural convection in a square cavity: A benchmark numerical solution, Int. J. Num. Methods in Fluids, Vol 3, pp. 249-264.

de Vahl Davis, G., Jones, I. P., 1983, Natural convection in a square cavity – A comparison exercise, Int. J. Num. Methods in Fluids, Vol 3, pp. 227-248.

Farouk, B., Guceri, S. I., 1981, LAMINAR AND TURBULENT NATURAL CONVECTION IN THE ANNULUS BETWEEN CONCENTRIC CYLINDERS, *in Symposium Volume on Natural Convection, 20th National Heat Transfer Conference, Milwaukee, Wis.,* pp. 143-150.

Fusegi, T., Hyun, J.M., Kuwahara, K., 1991, THREE-DIMENSIONAL SIMULATIONS OF NATURAL CONVECTION IN A SIDEWALL-HEATED CUBE, *Int. J. Numer. Methods. In Fluids,* Vol. 3, pp. 857-867.

Getachewa, D., Minkowycz, W.J., Lage, J.L., 2000, *Int J. Heat and mass Transfer,* **43**, 2909.

Gross, R. J., Bear, M. R., Hickox, C. E., 1986, THE APPLICATION OF FLUX-CORRECTED TRANSPORT (FCT) TO HIGH RAYLEIGH NUMBER NATURAL CONVECTION IN A POROUS M EDIUM, in: Proc, 8th Int. Heat transfer Conf., San Francisco, CA.

Henkes, R. A. W. M., Van Der Vlugt, F. F., Hoogendoorn, C. J.,1991, NATURAL-CONVECTION FLOW IN A SQUARE CAVITY CALCULATED WITH LOW-REYNOLDS-NUMBER TURBULENCE MODELS, *Int. J. Heat Mass transfer,* Vol. 34, No. 2, pp. 377-388.

Hsu, C. T., Cheng, P., 1990, Thermal dispersion in a porous medium, *Int. J. Heat Mass Transfer*, vol. 33, pp. 1587-1597.

Ingham, D. B., Pop, I., 1998, TRANSPORT PHENOMENA IN POROUS MEDIA, Elsevier, Amsterdam.

Jones, I. P., 1979, A comparison problem for numerical methods in fluid dynamics: the double-glazing problem, Numerical Methods in Thermal Problems, R. W. Lewis and K. Morgan (cds.), Pineridge Press, Swansea, U.K., pp. 338-348.

Kader, B. A., Yaglom, A. M., 1972, Heat and Mass Transfer Laws for Fully Turbulent Wall Flows, *Int. J. Heat Mass Transfer*, vol. 15, pp. 2329-2351.

Kuwahara, F., Kameyama, Y., Yamashita, S. e Nakayama, 1998, A., Numerical Modeling of Turbulent Flow in Porous Media using a Spatially Periodic Array, *Journal of Porous Media*, Vol. 1(1), pp. 47-55.

Kuwahara, F., Nakayama, 1998, A., Numerical modeling of non-Darcy convective flow in a porous medium, *Proc. 11th International Heat Transfer Conf.*, Kyongju, Korea, vol. 4, pp. 411-416.

Lee, K., Howell, J. R., 1987, Forced convective and radiative transfer within a highly porous layer exposed to a turbulent external flow field, *Proceedings of the 1987 ASME-JSME Thermal Engineering Joint Conf.*, vol. 2, pp377-386.

Manole, D. M., Lage, J. L., 1992, NUMERICAL BENCHMARK RESULTS FOR NATURAL CONVECTION IN A POROUS MEDIUM CAVITY, HTD-Vol 216, Heat and mass Transfer in Porous Media, ASME Conference, pp. 55-60.

Markatos, N. C., Pericleous, K. A., 1984, Laminar and turbulent natural convection in an enclosed cavity, Int. J. Heat Mass Transfer, Vol 27, pp. 755-772

Masuoka, T., Takatsu, Y., 1996, Turbulence model for flow through porous media, *Int. J. Heat Mass Transfer*, vol. 39, pp. 2803-2809.

Merrikh, A.A., Mohamad, A.A., 2002, Non Darcy Effects in Buoyancy Driven Flows in an Enclosure Filled with Vertically Layered Porous Media, *Intern. J. Heat and Mass Transfer,* Vol 45, pp. 4305-4313.

Moya, S.L, Ramos, E., Sen, M., 1987, NUMERICAL STUDY OF NATURAL CONVECTION IN A TILTED RECTANGULAR POROUS MATERIAL, Int. J. Heat Mass transfer, vol. 30, pp. 741-756.

Nakayama, A., Kuwahara, F., 1999, A macroscopic turbulence model for flow in a porous medium, ASME *Journal of Fluids Engineering,* vol. 121, pp. 427-433.

Nield, D. A., Bejan, A., 1992, CONVECTION IN POROUS MEDIA, Springer, New York.

Ozoe, H., Mouri, A., Ohmuro, M., Churchill, S. W., Lior, N., 1985, NUMERICAL CALCULATIONS OF LAMINAR AND TURBULENT NATURAL CONVECTION IN WATER IN RECTANGULAR CHANNELS HEATED AND COOLED ISOTHERMALLY ON THE OPPOSING VERTICAL WALLS, *Int. J. Heat Mass Transfer,* Vol. 28, pp. 125-138.

Patankar, S. V., Spalding, D. B., 1972, A CALCULATION PROCEDURE FOR HEAT, MASS AND MOMENTUMTRANSFER IN THREE DIMENSIONAL PARABOLIC FLOWS, *Int. J. Heat Mass Transfer*, Vol 15, pp. 1787.

Patankar, S. V., 1980, *Numerical Heat Transfer and Fluid Flow*, Hemisphere, New York.

Pedras, M. H. J., 2000, Análise do Escoamento Turbulento em Meio Poroso Descontínuo, Tese de Doutorado, ITA, S. J. Campos.

Pedras, M.H.J., de Lemos, M.J.S., 2001, Macroscopic Turbulence Modeling for Incompressible Flow through Undeformable Porous Media, *Intern. J. Heat and Mass Transfer*, vol. **44**(6), pp. 1081-1093.

Pedras, M.H.J., de Lemos, M.J.S., 1999b, Modelo de turbulência macroscópica em meios porosos saturados e indeformáveis, *Proc. of COBEM 99 15th Braz. Cong. of Mech. Eng.*, November 22-26, Águas de Lindóia.

Pedras, M.H.J., de Lemos, M.J.S., 2000, On the definition of turbulent kinetic energy for flow in porous media, *Int. Comm. In Heat & Mass Transfer*, **27** (2), pp. 211-220.

Pedras, M.H.J., de Lemos, M.J.S., 1999a, On volume and time averaging of transport equations for turbulent flow in porous media, *ASME-FED-vol. 248*, Paper FEDSM99-7273, ISBN 0-7918-1961-2.

Pedras, M.H.J., de Lemos, M.J.S., 2001a, Simulation of Turbulent Flow in Porous Media Using a Spatially Periodic Array and a Low Re Two-Equation Closure, *Numerical Heat Transfer - Part A Applications*, vol. **39**(1), pp. 35-59.

Pedras, M.H.J., de lemos, M.J.S, 2001b, *Journal of Fluids Engineering,* **123**(4), 941.

Prasad, V., Kulacki, F. A., 1984, CONVECTIVE HEAT TRANSFER IN A RECTANGULAR POROUS CAVITY-EFFECT OF ASPECT RATIO ON FLOW STRUCTURE AND HEAT TRANSFER, J. Heat Transfer, Vol 106, pp. 158-165.

Stone, H. L., 1968, ITERATIVE SOLUTION OF IMPLICIT APPROXIMATIONS OF MULTI-DIMENSIONAL PARTIAL DIFFERENTIAL EQUATIONS, *SIAM J. Num. Anal.*, Vol 5, pp. 530-558.

Rayleigh, Lord (J. W. Strutt), 1926, On convection currents in a horizontal layer of fluid when the higher temperature is on the underside, Phil. Mag., ser. 6, Vol 32, pp.833-844.

Rocamora Jr, F.D., de-Lemos, M.J.S., 2002, NUMERICAL DETERMINATION OF THE THERMAL DISPERSION TENSOR IN AN INFINITE POROUS MEDIUM, *Numerical Heat Transfer* (submitted).

Rocamora, F. D. Jr., de Lemos, M. J. S., 2000, Analysis of Convective Heat Transfer for Turbulent Flow in Saturated Porous Media, *Int. Comm. In Heat & Mass Transfer*, vol. **27** (6), pp. 825-834.

Walker, K. L., Homsy, G. M., 1978, CONVECTION IN POROUS CAVITY, J. Fluid Mech. Vol. 87, pp. 49-474.

Whitaker, S., 1966, *Chem.Eng. Sci.,* **21**, 291.

Whitaker, S., 1967, *J. Amer. Inst. Chem. Eng.,* **3**(13), 420.

Whitaker, S., 1969, Advances in theory of fluid motion in porous media, *Indust. Engng. Chem.*, vol. 61, pp. 14-28.