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ANALYSIS OF NATURAL CONVECTION IN A POROUS SQUARE CAVITY FORMED BY PERIODICALLY-DISPLACED SQUARE RODS

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Abstract. *Detailed numerical computations for steady state laminar natural convection within a square cavity filled by periodic square obstacles are numerically analyzed using the finite volume method in a generalized coordinate system. The square cavity composed by several obstacles was taken as the calculation domain to simulate a porous square cavity of regular arrangement. Governing equations are written in terms of primitive variables and are recast into a general form. The average Nusselt number at the hot wall obtained from the microscopic numerical results for several Darcy numbers are than compared with those obtained from the macroscopic model. Thus, a correlation is proposed to correct the average Nusselt number given by the macroscopic model with respect to the clear square cavity with several obstacles. Analyses of important environmental and engineering flows can benefit from the derivations herein and, ultimately, it is expected that additional research on this new subject be stimulated by the work here presented*

Keywords. *Porous Media, Natural Convection, Numerical Methods*

1. Introduction

The thermal convection in porous media has been studied extensively in recent years and has several applications in many fields of science, technology and environment. Heat exchangers , underground spread of pollutants, grain storage, food processing, geothermal systems, oil extraction, store of nuclear waste material, solar power collectors, optimal design of furnaces and solar collectors, crystal growth in liquids, packed-bed catalytic reactors, nuclear reactor safety, food processing and underground spread of pollutants are just some applications of this theme. The monographs of Nield & Bejan (1992) and Ingham & Pop (1998) fully document natural convection in porous media.

Basically, 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), 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), 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)). Extension of the double-decomposition theory for treating turbulent natural convection, (De Lemos & Braga (2003)), and mass transfer, (De Lemos & Mesquita (2003)), in saturated rigid porous media has also been recently documented.

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) and 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.

In order to verify the reability of the macroscopic model to predict results for porous square cavities, this paper presents values for average Nusselt number at the hot wall obtained from the microscopic numerical results for several Darcy numbers and than compares with those obtained from the macroscopic model. Thus, a correlation is proposed to correct the macroscopic model in relation to the microscopic one.

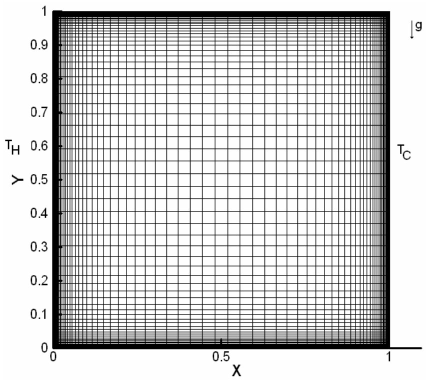

Figure 1 – Geometry and grid under consideration

2. Geometry And Boundary Conditions

The problem considered is showed schematically in Fig. 1 and refers to an porous square cavity with width L=1 m completely filled with 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 insulated. The porous medium is considered to be rigid and satured by an incompressible fluid. The Ra_m is the dimensionless parameter used for porous media and it is defined as, $Ra_m = Ra_f \cdot Da = \dfrac{g b_f H \Delta T K}{n_f a_{eff}}$, with $a_{eff} = k_{eff} \big/ (r c_p)_f$ and the particle diameter is given by $D_p = \sqrt{\dfrac{144K(1-f)^2}{f^3}}$. Here, $Ra_f = \dfrac{gbH^3 \Delta T}{v_f a_f}$ and $Da = K/H^2$, where g is the gravity accelerator, $b = b_f$ is the thermal expansion coefficient and the subscript f refers to a macroscopic quantity. H is the cavity height, $\Delta T = T - T_C$ is the temperature difference, K is the permeability, n_f is the fluid kinematic viscosity, f is the porosity defined by $f = \Delta V_f / \Delta V$, where ΔV_f is the Fluid volume inside ΔV (Representative elementary Volume). a_f is the fluid thermal diffusivity and a_{eff} the effective thermal difusivity. $k_{eff} = f k_f + (1-f) k_s$ is the effective thermal conductivity and k_f and k_s are the fluid and solid conductivities, respectively. r is the density and c_p is the specific heat.

3. Governing Equations

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

Thus, for steady-state laminar natural convection, the macroscopic equations for continuity, momentum and temperature take the form:

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

$$r\left[\nabla\left(\frac{\mathbf{u}_D \mathbf{u}_D}{f}\right)\right] = -\nabla\left(f \langle p \rangle^i\right) + m \nabla^2 \mathbf{u}_D - \left[\frac{m f}{K}\mathbf{u}_D + \frac{c_F f r |\mathbf{u}_D| \mathbf{u}_D}{\sqrt{K}}\right] - r b_f \mathbf{g} f\left(\langle T \rangle^i - T_{ref}\right) \tag{2}$$

$$\left(r c_p\right)_f \nabla\left(\mathbf{u}_D \langle T \rangle^i\right) = \nabla\left\{\left[k_f f + k_s (1-f)\right] \nabla \langle T \rangle^i\right\} \tag{3}$$

where $\mathbf{u}_D$ is the Darcy velocity defined as $\mathbf{u}_D = f \langle \mathbf{u} \rangle^i$, where $\langle \mathbf{u} \rangle^i$ is the intrinsic velocity vector, p is the total pressure and m is the dynamic viscosity. The β_ϕ is the macroscopic thermal expansion coefficient. $\langle T \rangle^i$ and T_{ref} are the intrinsic and the reference temperatures respectively. Finally, c_F is the Forchheimer coefficient. Its important to emphasize that when $K \to \infty$ and $f = 1$ the medium is interpreted as a clear medium.

4. Numerical Method And Computational Details

The numerical method employed for discretizing the governing equations is the control-volume approach with a generalized grid. A hybrid scheme, Upwind Differencing Scheme (UDS) and Central Differencing Scheme (CDS), is used for interpolating the convective 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).

The present results were performed with ϕ=0.84. The Prandtl number and the conductivity ratio between the solid and fluid phases are assumed to be equal to one. Runs for macroscopic laminar flow were performed with an 80x80 control volumes in a stretched grid like shown in Fig. 1. Although not shown here, several runs were performed with others meshes in order to guarantee grid independence. These runs showed that the 80x80 CV´s stretched mesh is refined enough to capture the thin boundary layers that appear along the vertical surfaces giving a percent error in relation with other with 110x110 CV´s stretched mesh less than 1%. The convergence process is terminated when the residual error is less than 10^{-5}.

5. Results and discussion

The main idea of this work is to submit the porous square cavity using the macroscopic model and the clear cavity with several obstacles using the clear medium formulation to the same conditions. It is expected that the two models could give the same average Nusselt number at the hot wall. But, this point will be shown later, the macroscopic model gives overall lower average Nusselt number values when compared with those obtained from the clear cavity with several obstacle. Thus a correlation is proposed in order to correct the macroscopic approach in relation to the clear one.

Further, When other parameters, e.g., (Porosity, Prandtl number, conductivity ratio between the fluid and solid matrix) are fixed the available literature shows that for the non-Darcy region, (Merrikh & Mohamad (2002), Braga & de Lemos (2004)), fluid flow and heat transfer depend on the fluid Rayleigh number, Ra_f, and the Darcy number, *Da*

In the work of Braga & de Lemos (2004) it was observed that for a fixed Ra_m the lower the permeability, the higher the average Nusselt number at the hot wall. It is evident that different combinations of Ra_f and *Da* yields different heat transfer results. The increasing of the fluid Rayleigh number increases the natural convection inside the enclosure. Since the Ra_m is fixed, a higher fluid Rayleigh number is associated with a less permeable media (i.e. lower Darcy number).

The range of Darcy numbers analyzed varies from $1{,}206.10^{-4} \le Da \le 0{,}3087.10^{-1}$. The parameter b is the controller parameter while the other parameters are kept fixed. Here, all calculations were made for Ra_m=10^4 and its evident that for different Darcy number there are different b parameters to keep the Ra_m fixed at 10^4. Table (1) shows all values used in the calculations.

Table 1 – Parameters used in the calculations

Pr=1, $f = 0.84$, Ra_m=10^4, k_s/k_f =1, g=10 [m/s^2], n_f =10^{-3} [m^2/s], a =10^{-3} [m^2/s], r =1 [kg/m^3], c_p=1 [$kJ/kg.^\circ C$], T_H=1 [°C], T_C=0 [°C]			
Da	$b_f = b$ [1/K]	$\boldsymbol{D_p}$ [m]	**N=number of obstacles**
0,3087.10^{-1}	0,0324	0,400	1
0,7717.10^{-2}	0,1295	0,200	4
1,9290.10^{-3}	0,5000	0,100	16
0,4823.10^{-3}	2,0734	0,050	64
1,2060.10^{-4}	8,2918	0,025	256

Figure (3) shows the streamlines for a clear square cavity with several obstacles for *Da* ranging from 0,3087.10^{-1} to 1,2060.10^{-4}. Its clearly seen from the Fig. (3) that, the lower the permeability, the higher the intensity of the recirculation motion, as discussed in Merrikh & Mohamad (2002), Braga & de Lemos (2004) for the macroscopic model. Figure (3) also shows that, in comparison with those patterns from the macroscopic model, Figs. (4b, d, f, h), the higher the number of obstacles inside the clear cavity, the higher the agreement of the basic features of the flow between the two approaches, namely, the clear cavity filled with obstacles and the macroscopic model. In other words, the macroscopic model is more representative when the number of obstacles inside the clear cavity is higher, *i.e.,* for lower permeability media. However, the overall values of the streamlines for the macroscopic model are lower when compared with those from the clear square cavity with several rods configuration. This point will be discussed later.

Figure (2) shows the isotherms for a clear square cavity with several obstacles for *Da* ranging from 0.3087x10^{-1} to 1.2060x10^{-4}. Figure (2) shows that, the higher the number of obstacles the higher the stratification of the thermal field. This characteristic is also observed for the patterns of the macroscopic model, Fig (4a, c, e, g). It is also an indication of the increasing of the capacity of the macroscopic model in fairly representing a porous square cavity.

Figure (4) shows the isotherms and streamlines for a porous square cavity using a macroscopic model for *Da* ranging from 0.7717x10^{-2} to 1.2060x10^{-4}. Figures (4a, c, e, g) shows that the isotherms tends to stratify with the decreasing of the *Da, i.e.,* the medium permeability. Figures (4a, c, e, g) shows, as discussed above, that the recirculation intensity also increases with the decrease of the medium permeability and this increasing is more pronounced near to the heated walls.

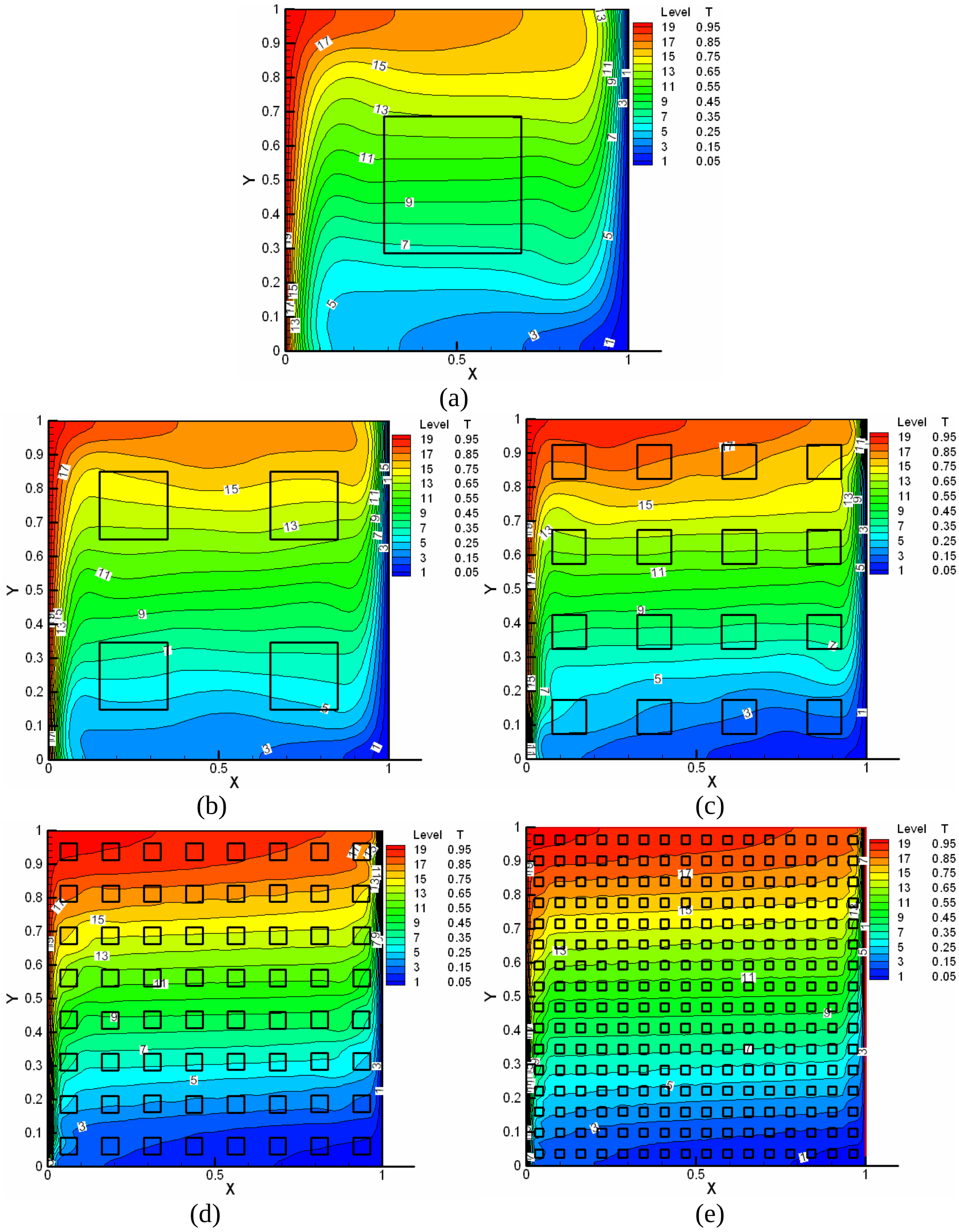

Figure 2 - Isotherms for laminar natural convection within a clear square cavity with several obstacles for Ra_m=10^4 and f =0.84; a) N=1, Da=0,3087.10^{-1}, b) N=4, Da=0,7717.10^{-2}, c) N=16, Da=1,9290.10^{-3}, d) N=64, Da=0,4823.10^{-3}, e) N=256, Da=1,2060.10^{-4}.

Figure (5) shows the behavior of the average Nusselt number at the hot wall for the two types of approaches here adopted, namely, the macroscopic model and the clear model with several obstacles. It is expected that if the two approaches were submitted to the same conditions, both approaches could be give the same average Nusselt number at the hot wall. However, its clearly seen from Fig. (5) that the overall values of average Nusselt number at the hot wall for the macroscopic model are lower than those obtained from the clear model with several obstacles. The macroscopic model fails in to predict correctly the average Nusselt number for this particular situation and a correlation is here proposed to correct the average Nusselt number from the macroscopic model with respect of those obtained from the clear model with several obstacles. The Nusselt number for the macroscopic model is calculated as, $Nu_{macro} = hL/k_{eff}$, where h is the heat transfer coefficient, L is the cavity side and $Nu_{micro} = hL/k_f$.

Thus, two curves are proposed to fit the points of the two approaches in Fig. (5);

$$\overline{Nu}_{micro} = 0{,}26511.\ln b + 2{,}82738 \tag{4}$$

$$\overline{Nu}_{macro} = 0{,}20142.\ln b_f + 2{,}43972 \tag{5}$$

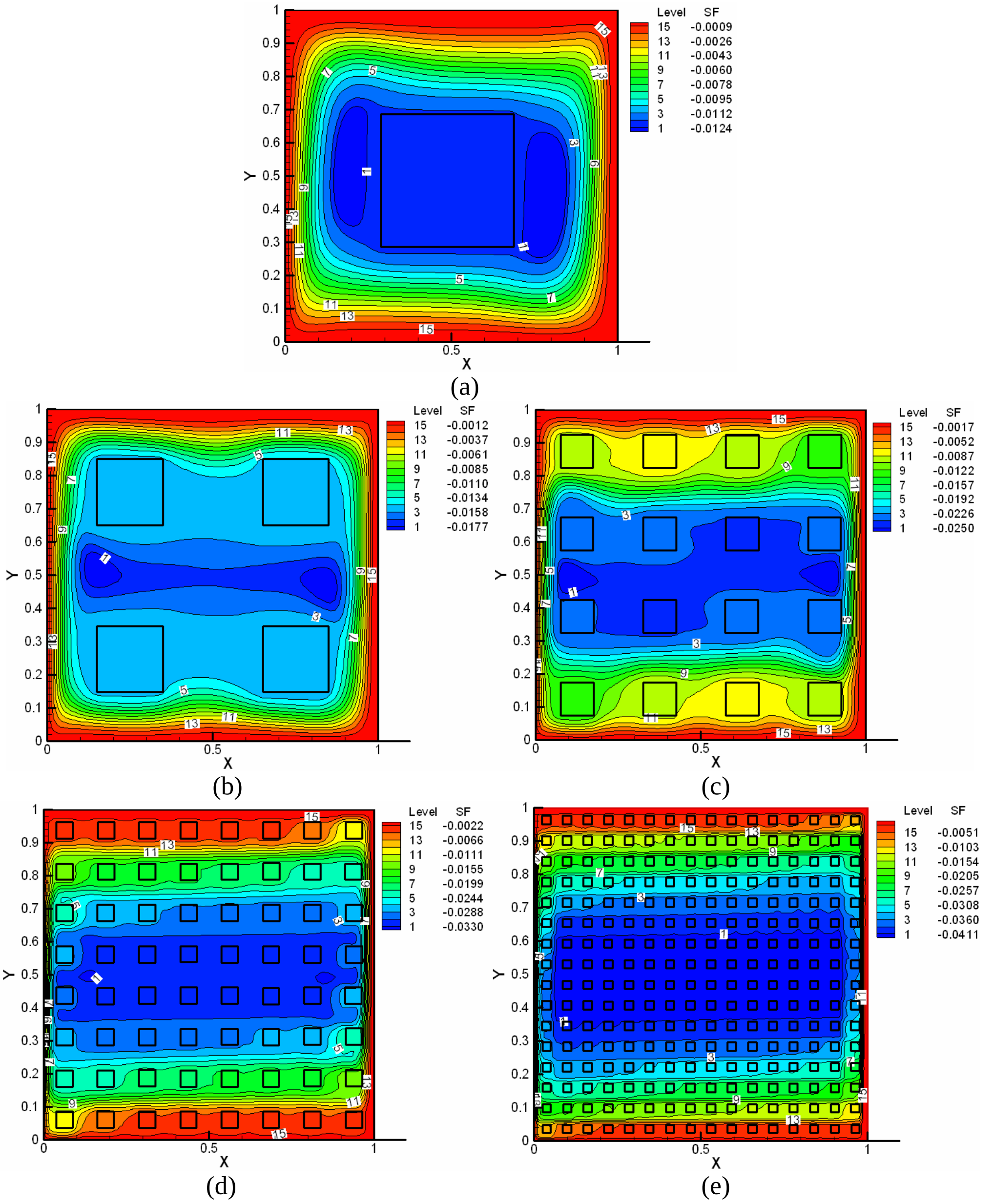

Figure 3 – Streamlines, [m^2/s], for laminar natural convection within a clear square cavity with several obstacles for Ra_m=10^4 and f =0.84; a) N=1, Da=0,3087.10^{-1}, b) N=4, Da=0,7717.10^{-2}, c) N=16, Da=1,9290.10^{-3}, d) N=64, Da=0,4823.10^{-3}, e) N=256, Da=1,2060.10^{-4}.

Equation (4) refers to the clear cavity with several obstacles and Eq. (5) refers to the macroscopic model. Combining Eq. (4) and Eq.(5) one yields a correlation between b_f and b , given by:

$$b_f = c_{1b} . b^{c_{2b}} \tag{6}$$

where, c_{1b}=6,8525 and c_{2b}=1,3162. It is important to emphasize that this work is a preliminary study and the correlation given by Eq. (6) must be better defined in future studies.

After that, new runs were performed for the macroscopic model with the corrected $b_{f,corr}$. Table (2) shows the values of the corrected macroscopic average Nusselt number, macroscopic model Nusselt number and the clear model with several obstacles Nusselt number.

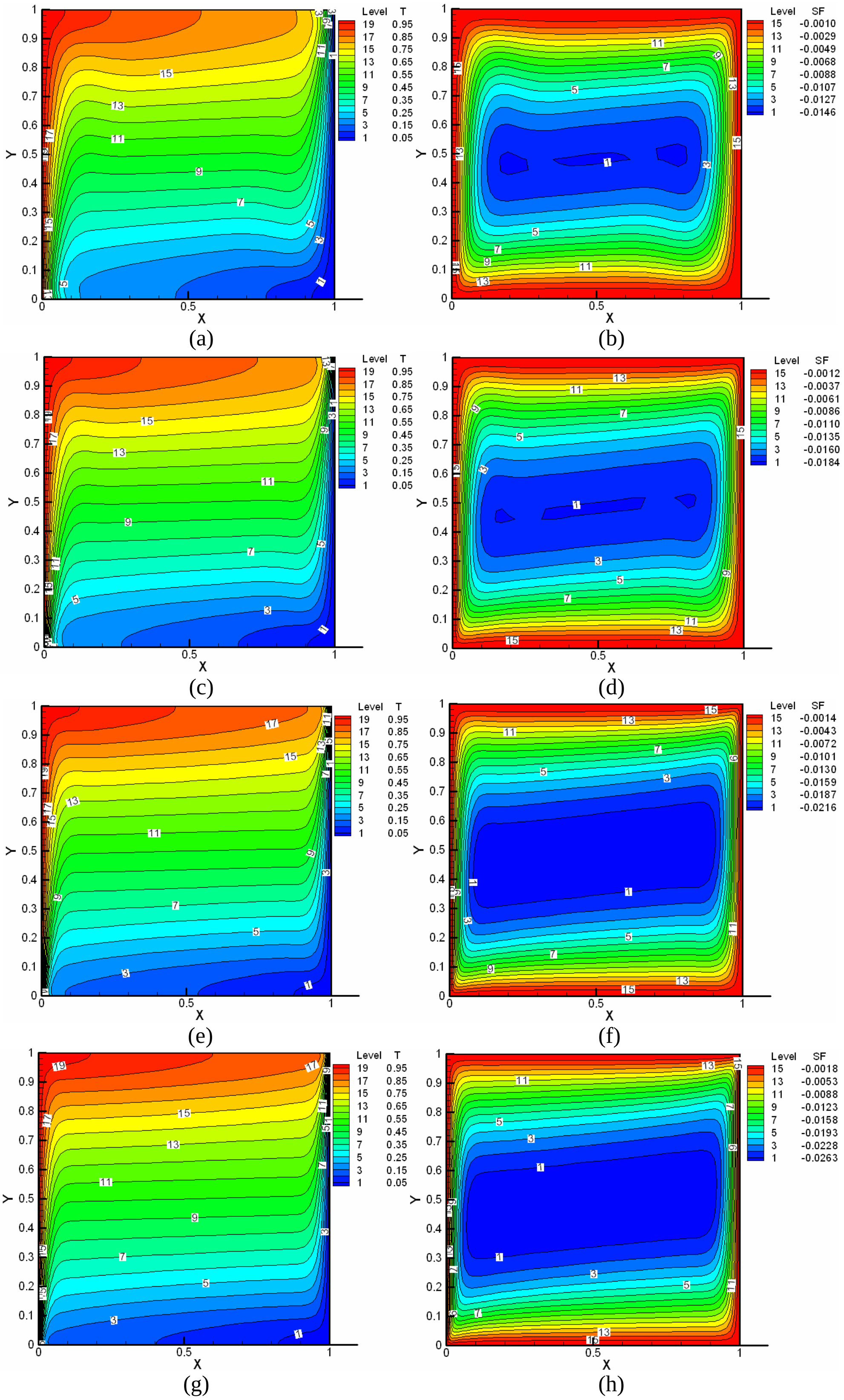

Figure 4 – Isotherms and streamlines, [m^2/s], for laminar natural convection within a square cavity using a macroscopic model for Ra_m=10^4 and f =0.84; a,b) Da=0,7717.10^{-2}, c,d) Da=1,9290.10^{-3}, e,f) Da=0,4823.10^{-3}, g,h) Da=1,2060.10^{-4}.

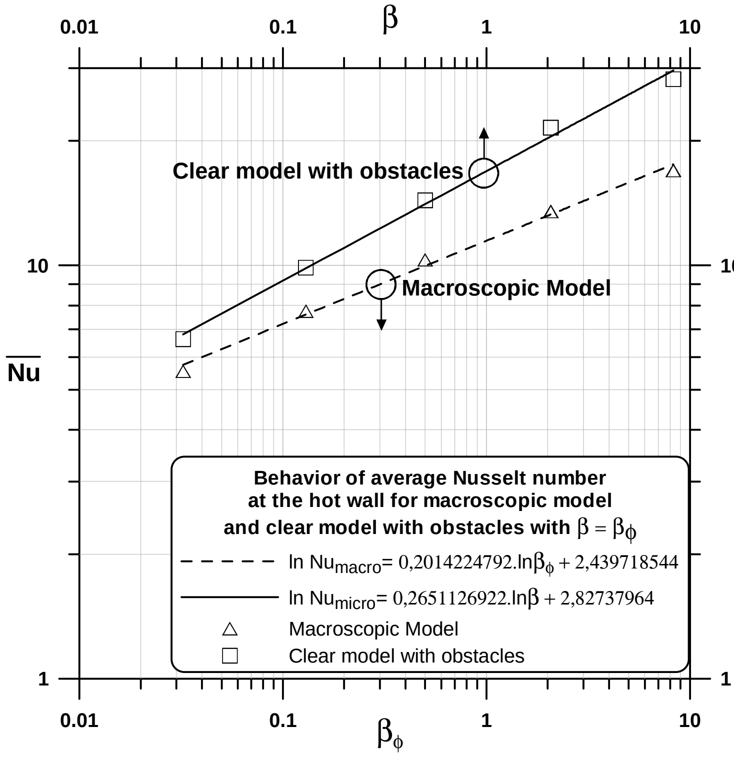

Figure 5 – Behavior of average Nusselt number at the hot wall for the two approaches under consideration.

Table 2 – Comparison between the corrected macroscopic model average Nusselt numbers and the macroscopic model and clear model with several obstacles average Nusselt numbers.

Da	$\overline{Nu}_{macro}$	$\overline{Nu}_{micro}$	$\overline{Nu}_{macro,corr}$
$0,3087.10^{-1}$	5,5468	6,6309	7,1151
$0,7717.10^{-2}$	7,7477	9,8734	11,2048
$1,9290.10^{-3}$	10,3087	14,3620	16,7587
$0,4823.10^{-3}$	13,5155	21,5369	24,8839
$1,2060.10^{-4}$	16,9754	28,2167	35,5048

According to Tab. (2), the overall values of the corrected average Nusselt number are higher than those obtained from the clear model with several obstacles. As mentioned above, this work is a preliminary study and the correlation proposed by Eq. (6) must be better defined in future studies. However, although the overall values of $\overline{Nu}_{macro,corr}$ are higher than the $\overline{Nu}_{micro}$, the percentual error between them is lower than the percentual error with respect to the macroscopic model without correction.

6. Conclusions

This work deals with numerical computations for steady state laminar natural convection within a clear square cavity filled by periodic square obstacles are numerically analyzed using the finite volume method in a generalized coordinate system. The square cavity composed by obstacles was taken as the calculation domain to simulate a porous square cavity of regular arrangement. The average Nusselt numbers at the hot wall obtained from the microscopic numerical results for several Darcy numbers were than compared with those values obtained from the macroscopic model. Thus, a correlation was proposed to correct the average Nusselt number given by the macroscopic model in relation to the clear square cavity with several obstacles. As pointed out in the previous section, this work is a preliminary study and the correlation proposed by Eq. (6) must be better defined in future studies. Although the overall values of $\overline{Nu}_{macro,corr}$ are higher than the $\overline{Nu}_{micro}$, the percentual error between them is lower than the percentual error with respect to the macroscopic model without correction. Analyses of important environmental and engineering flows can benefit from the derivations herein and, ultimately, it is expected that additional research on this new subject be stimulated by the work here presented

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