HEAT TRANSFER IN SQUARE CAVITIES FILLED WITH CIRCULAR RODS

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Abstract. *This work compares two different approaches for obtaining numerical solutions for laminar natural convection within a square cavity, which is filled by a fixed amount of a solid conducting material. The first model considered, namely, macroscopic model, is based on the assumption that the solid and the fluid phases are seen as the same medium, over which volume-averaged transport equations apply. Secondly, microscopic model is considered to solve the momentum equations for the fluid phase that would resemble a conjugate heat transfer problem in both the solid and the void space. In the microscopic model, the solid phase is composed of circular obstacles, equally spaced within the cavity. The average Nusselt number at the hot wall, obtained from the macroscopic model, for several Darcy numbers, are compared with those obtained with the second approach, namely the microscopic 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 between each other and that this discrepancy increases as the Darcy number decreases, in the macroscopic model, or the number of blocks increases and their size decreases, in the microscopic model.*

Keywords: *Porous Media, Heat Transfer Natural Convection*

1. Introduction

Traditionally, models found in the literature dealing with flows in porous media are based on averaging procedures. The well known *macroscopic* approach, based on the volume average principles, is usually used in the analysis of flows in several media such as soil and packed beds. However, this approach gives no details at the pore level. On the other hand, porous media problems can be tackled by means of the *microscopic* approach, which solves the Navier-Stokes equation at the particle level, but the computational cost involved is considerably higher. The understanding of the properties of such *microscopic* approach can, ultimately, aid the development of less expensive *macroscopic* models when dealing with natural convection in porous media.

The works of (Walker & Homsy, 1978, Bejan, 1979, Prasad & Kulacki, 1984, Beckermann *et al,* 1986, Gross et al, 1986, Manole & Lage, 1992, Moya et al, 1987) have exhibited some important results to the problem of free convection in a rectangular cavity filled with porous media and the monographs of Nield & Bejan, 1992 and Ingham & Pop, 1998 fully document natural convection in porous media. The recent work of Baytas & Pop, 1999, 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.

Studies considering the distribution of a fixed amount of solid material inside an enclosure for laminar buoyancy driven flows can be found in House *et al,* 1990 for the case of a single conducting square solid located at the center of a square cavity. The work of Merrikh & Mohamad, 2001 also considered heat transfer from within a fluid saturated enclosure with thermal energy being generated by discrete, disconnected solid bodies. Later, in Merrikh *et al,* 2002, a study in which the *continuum* and the *porous-continuum* models were compared for natural laminar convection in a non-homogeneous differentially heated enclosure, without heat generation, was documented. A work also considering the laminar macroscopic and microscopic approach for circular cylinders is presented in Massarotti *et al,* 2003. In the work of Merrikh *et al,* 2004 an extension of the work performed by Merrikh & Mohamad, 2001 was carried out. Finally, in (Merrikh & Lage, 2004, Merrikh & Lage, 2005) the effects of distributing a fixed amount of solid material inside a porous medium enclosure on the heat transfer process were recently studied.

Laminar and turbulent buoyant flows in porous media considering the macroscopic approach were documented in de Lemos & Braga, 2003, Braga & de Lemos, 2004, and comparisons between microscopic and macroscopic computations for natural convection were carried out in Braga & de Lemos, 2005. All of these papers are part of a systematic development of a turbulence model for flow in porous media based on the *double-decomposition* concept (Pedras & de Lemos, 2000, 2001, 2001a-b), which has been also applied to non-buoyant heat transfer (Rocamora & de Lemos, 2000, de Lemos & Rocamora, 2002), mass transfer, de Lemos & Mesquita, 2003, double-diffusion, de Lemos & Tofaneli, 2004, thermal non-equilibrium transport, Saito & de Lemos, 2005, and interface problems, Silva & de Lemos, 2003a, de Lemos, 2005. Reference to the above publications is here included because they document the systematic model development mentioned earlier and, as such, more information is made available to the interested reader.

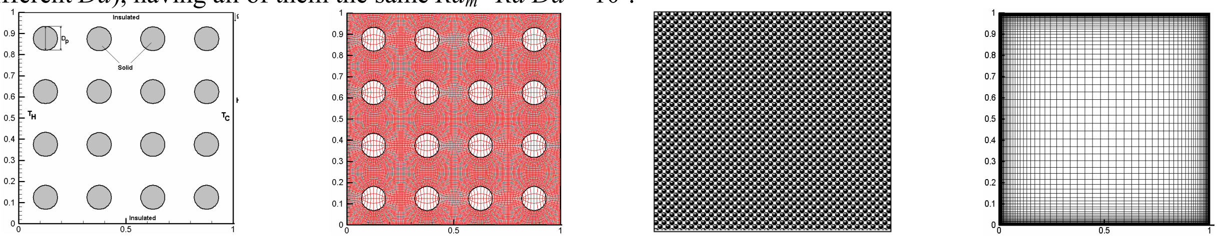
Motivated by the foregoing, this work presents numerical solutions for steady laminar natural convection within a square cavity filled by a fixed amount of solid conducting material. The solid phase is composed by circular obstacles, equally spaced within the cavity. Heat transfer across the cavity is simulated using two models. The first model consists in a conjugate heat transfer problem in which governing equations are separately solved for the fluid and solid phases. This approach is known as *continuum*, *heterogeneous* or *microscopic* model. The word “*continuum*” is employed with the idea of expressing the continuity of both media (solid and fluid), “heterogeneous” emphasizes the two phases considered and “microscopic” identifies the use of differential transport equations. For simplicity, this model shall be only referred as *microscopic* from now on. In the second approach, the cavity is supposed to be completely filled with a porous material instead, having the same quantity of solid material used in the first model. This second approach is recalled as *porous-continuum*, *homogeneous* or *macroscopic* approach. Likewise, the expression “*porous-continuum*” reflects the use of up-scaling techniques, “homogenous” indicates that only one phase is considered and “macroscopic” is associated with the application of the volume-averaging operator to the governing equations. Here, also for simplicity, only *macroscopic* is used to refer to such model. The objective herein is to compare the average Nusselt number calculated by the two models.

For designing engineering systems that would resemble the arrangement of the present analysis, considering an enclosure with distribution of a fixed amount of solid material, the use of a simpler *macroscopic* model, instead of using costly and memory demanding distributed flow calculations (*microscopic* approach), could benefit the overall design process if repetitive calculations are necessary in order to obtain initial engineering estimates. Thus, the contribution herein is based on evaluating the use of simpler porous media models when simulating more complex *microscopic* models for more complicated geometries.

2. Geometry and Grid under Consideration

As explained above, this work performs heat transfer calculations in cavities containing a fixed amount of solid material. While maintaining the same overall volume, the morphology, shape and distribution of the solid phase within the cavity may differ from case to case, once the numbers of blocks considered in each case are different. If one associate a permeability K to each system, its value will be different depending on how easy the fluid is able to flow through the solid matrix within the cavity.

Therefore values for Ra and Da are selected in order to maintain Ra_m constant. Each case represents distinct systems consisting of possibly different fluids and solid distribution, but all having the same modified Rayleigh number Ra_m. Considering such premise, the present work intends to study a family of cases with different Ra in distinct media (different Da), having all of them the same $Ra_m = Ra\ Da = 10^4$.



(a) (b) (c) (d)

Figure 1 - Continuum model: Cavities with distributed solid material (*a*) and corresponding grid (*b*), Porous continuum model: Porous cavity (*c*) and corresponding grid (d)

To analyze such an arrangement, the *microscopic* model is here employed, in which the flow equations are solved within the void (fluid) space. More specifically, the problem here investigated is schematically presented in Figure 1a. The corresponding computational grid is presented in Figure 1b and refers to a square cavity of side H=1m. In the *microscopic* model, the cavity is partially filled with a fixed amount of solid conducting material, in the form of circular obstacles of size D_p that is equally distributed within the cavity. Also, the cavity is isothermally heated from the left, with temperature T_H prevailing over that side, and cooled from the opposing surface, where a constant temperature T_C is maintained. The horizontal walls are kept insulated. On the other hand, the same physical system was also treated as a permeable structure (Figure 1c), having the same void- to void-plus-solid ratio, or porosity ϕ, and the same permeability K_{eq}, calculated with appropriated correlations. In this case, the *macroscopic* model was applied, in which the flow properties are integrated over a Representative Elementary Volume. The corresponding computational grid is presented in Figure 1d. In order to associate a value for an “equivalent” permeability of the arrangement in Figure 1a, to be used in the *macroscopic* model, the correlation of Nakayama & Kuwahara, 1999 was applied. That correlation is based on the work of Ergun, 1952 and reads,

$$K_{eq} = \frac{D_p^2\,\phi^3}{144(1-\phi)^2} \qquad (1)$$

where D_p, as seen, is the size of the circular obstacles. It is important to note that K_{eq} given by eqn. (1) was proposed for forced flows thorough permeable media and that use of such correlation in buoyancy driven flows might be questionable. Nevertheless, in the absence of better information, this work associates a permeability K_{eq} to the system in Figure 1a using eqn. (1). This equivalent permeability is used to form an equivalent Darcy number,

$$Da_{eq} = \frac{K_{eq}}{H^2} \tag{2}$$

As such, this work is based on the hypothesis that both systems in Figures 1a and 1c can be compared if the same Ra_m is applied, or say, $Ra_m = Ra\, Da_{eq}$ characterizing Figure 1a was equal to $Ra_m = Ra_\phi\, Da$ describing Figure 1c. This imposed condition is therefore,

$$\left. Ra_m = Ra \cdot Da_{eq} = \frac{g\beta\, H\Delta T\, K_{eq}}{\nu_f \alpha} \right\} \text{Continuum Model}\,; \left. Ra_m = Ra_\phi \cdot Da = \frac{g\beta_\phi H\Delta TK}{\nu_f \alpha_{eff}} \right\} \text{Porous - continuum Model} \tag{3}$$

3. Governing Equations and Numerics

3.1. Microscopic model solution

As mentioned before, the microscopic model solves the local momentum equation within the fluid phase and resolves a conjugated heat transfer problem in both the solid and the void space. Standard equations for this model are available in textbooks on Fluid Mechanics and Heat Transfer, and for that they need not to be repeated here. However, it is interesting to point out that the circular obstacles inside the cavity participate in the momentum transfer through their fluid-solid interfaces, over which, in turn, the no-slip condition was applied. The blocks are heat conducting and the energy balance equation valid inside them is given by:

$$k_s \nabla^2 T = 0 \tag{4}$$

3.2. Macroscopic Model Solution

In a series of papers, de Lemos and co-workers (de Lemos & Braga, 2003, Braga & de Lemos, 2004, Braga & de Lemos, 2005, Pedras & de Lemos, 2000, Pedras & de Lemos, 2001, Pedras & de Lemos, 2001a, Pedras & de Lemos, 2001b, Rocamora & de Lemos, 2000, de Lemos & Rocamora, 2002, de Lemos & Mesquita, 2003, de Lemos & Tofaneli, 2004, Saito & de Lemos, 2005, Silva & de Lemos, 2003, Silva & de Lemos, 2003a, de Lemos, 2005) have systematically developed a macroscopic turbulence model for highly porous, highly permeable media. For simplicity, a laminar version of the governing equation set is presented below. Basically, for porous media analysis, macroscopic form of the governing equations is obtained by taking the volumetric average of the entire equation set. In that development, the porous medium was considered to be rigid and saturated by an incompressible fluid.

The intrinsic average operator is defined by:

$$\langle \varphi \rangle^i = \frac{1}{\Delta V_f} \int_{\Delta V_f} \varphi\, dV \tag{5}$$

where ΔV_f is the volume of fluid phase of the Representative Elementary Volume, over which the integration takes place. For steady state laminar flow the equations take the form:

$$\nabla \mathbf{u}_D = 0 \tag{6}$$

$$\rho \left[\nabla \left(\frac{\mathbf{u}_D \mathbf{u}_D}{\phi} \right) \right] = -\nabla \left(\phi \langle p \rangle^i \right) + \mu \nabla^2 \mathbf{u}_D - \left[\frac{\mu\phi}{K} \mathbf{u}_D + \frac{c_F \phi \rho |\mathbf{u}_D| \mathbf{u}_D}{\sqrt{K}} \right] - \rho \beta_\phi \mathbf{g} \phi \left(\langle T \rangle^i - T_{ref} \right) \tag{7}$$

where all physical properties are assumed isotropic, uniform and constant, except the fluid density, ρ, in the buoyancy term which, in turn, is modeled using the Boussinesq-Oberbeck approximation. Also, $\mathbf{u}_D$ is the Darcy velocity defined as $\mathbf{u}_D = \phi \langle \mathbf{u} \rangle^i$,where $\langle \mathbf{u} \rangle^i$ is the intrinsic velocity vector, p is the total pressure and μ is the dynamic viscosity, $\langle T \rangle^i$ and T_{ref} are the intrinsic and the reference temperatures, respectively, and c_F is the Forchheimer coefficient.

The macroscopic energy equation reads,

$$\left(\rho c_p \right)_f \nabla \cdot \left(\mathbf{u}_D \langle T \rangle^i \right) = \nabla \cdot \left\{ \mathbf{K}_{eff} \cdot \nabla \langle T \rangle^i \right\} \tag{8}$$

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

$$\mathbf{K}_{eff} = \left[\phi k_f + (1-\phi) k_s \right] \mathbf{I} + \mathbf{K}_{tor} + \mathbf{K}_{disp} \tag{9}$$

is the effective conductivity tensor, $\mathbf{K}_{tor}$ and $\mathbf{K}_{disp}$ are the tortuosity and thermal dispersion conductivity tensors, respectively. Following Kuwahara & Nakayama, 1998, determination of $\mathbf{K}_{tor}$ and $\mathbf{K}_{disp}$ can be accomplished 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. Here, for simplicity, the contributions to heat transfer due to these two mechanisms are neglected.

5. Numerical Method and Solution Procedure

The numerical method employed for discretizing the governing equations is the control-volume approach with a generalized grid. The flux blended deferred correction, which combines linearly the Upwind Differencing Scheme (UDS) and Central Differencing Scheme (CDS), was 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 (see Stone, 1968 for details). Further, concentration of nodal points to walls reduces eventual errors due to numerical diffusion which, in turn, are further annihilated due to the hybrid scheme here adopted.

6. Results and Discussion

First, to validate the microscopic approach, runs were performed for a case with a single conducting square solid located at the center of the cavity showing good agreement with those summarized in Table 1.

Table 1 - Average Nusselt number for a square cavity with a single conducting solid at the center; $Ra_f = 10^5$, Pr=0.71 (unless otherwise noted).

Ra_f	D_p [m]	k_s/k_f	House *et al*, 1990	Merrikh & Lage, 2004	Present results *Pr=1*
10^5	0.5	0.2	4.624	4.605	4.667
10^5	0.5	5.0	4.324	4.280	4.375

As said, the main idea of this work is to compare heat transfer simulations in a porous square cavity using the macroscopic and microscopic models with several obstacles. Comparisons are based on similar conditions in order to verify if the two models yield equivalent values for the overall Nusselt numbers.

Runs were performed with a 120x120, 160x160 and 200x200 control volumes for N=4, N=16 and N=64, respectively, where N is the number of obstacles inside the cavity, in a grid schematically shown in Fig. 1b.

As such, when the number of blocks N in the cavity is increased while keeping the overall solid-to-void ratio (equivalent to a constant porosity cavity case), a reduced value of the square rod size D_p yield different K_{eq} values, according to (1), implying in distinct Da_{eq} numbers. However, looking back at the definition of Ra, for different Darcy numbers one has to modify Ra in order to keep Ram fixed at 10^4. One way to accomplish this is to modify the numerical value of coefficient β. One could also modify H, ρ, ΔT or another variable composing Ra. This work used several pairs of values for K and β so that the corresponding Ra and Da were such that their product would yield always $Ra_m = 10^4$. Therefore, coefficients β and K are the variables to be modified in order to maintain Ra_m constant and all cases here analyzed. Also, solid obstacles in the cavity yield an overall cavity porosity ϕ=0.84 (unless otherwise noted). The fluid Prandtl number and the conductivity ratio between the solid and fluid phases were assumed to be equal to one.

Figure 2 shows the streamlines for the two models analyzed, microscopic(left) and macroscopic(right), for a square cavity filled with circular obstacles with equivalent Da_{eq} ranging from 0.8188×10^{-2} to 5.1178×10^{-4}, $Ra_m = 10^4$, ϕ=0.84 and k_s/k_f=1. Figure 3 show corresponding results for the thermal field for the same parameters considered in Fig. 2.

Figures 2a,c,e shows that, in comparison with corresponding cases run with the macroscopic model, Figs. 2b,d,f, the higher the number of obstacles inside the clear cavity, the higher the similarity of the flow pattern between the two approaches, *i.e.*, the macroscopic and the microscopic solutions resemble each other for greater values of N (see Figs. 2e and 2f). In other words, the macroscopic model seems to be more representative of reality when the number of obstacles inside the cavity is higher, which, in turn, correspond to lower permeability cases. Further, Figures 3a,c,e shows that, the higher the number of obstacles, the higher the stratification of the thermal field. This characteristic is also observed for the isotherms of the macroscopic model, Figs 3b,d,f.

Figures 2b,d,f also indicates that the recirculation intensity increases as the medium permeability decreases and the flow patterns comprises primarily cells of relatively high velocity, which circulate around of the entire cavity. However, the secondary recirculation that appears in the center of the cavity, for the higher Darcy numbers analyzed, tends to disappear as the permeability decreases. In a similar way, the temperature gradients are stronger near the vertical walls, but decrease at the center. Figures 3b,d,f shows that the isotherms tend to stratification as Da is decreased, *i.e.*, as the medium permeability is decreased.

According to Merrikh & Lage, 2004, as the number of square rods increases, and their size becomes reduced, the flow tends to migrate away from the wall towards the center of the cavity. This phenomenon is seem in Merrikh & Lage, 2004, as a response of the system due to the increasing flow resistance closer to the solid wall, as the obstacles get closer to the solid surface.

Further, the available literature shows that for the non-Darcy region in a porous cavity, Braga & de Lemos, 2004, fluid flow and heat transfer depend on the fluid Rayleigh number, Ra_f, and on the Darcy number, Da, when other parameters, such as porosity, Prandtl number, and conductivity ratio between the fluid and solid matrix, are held constant. In Braga & de Lemos, 2004, it was shown that for a fixed Ra_m, the lower the permeability (lower Da), the higher the average Nusselt number at the hot wall. It then looks evident that different combinations of Ra_f and Da yields different heat transfer results, even when Ra_m is the same. The increasing of the fluid Rayleigh number increases the natural convection inside the enclosure. For a fixed Ra_m, a higher fluid Rayleigh number is associated with a less permeable media (*i.e.* lower Darcy number).

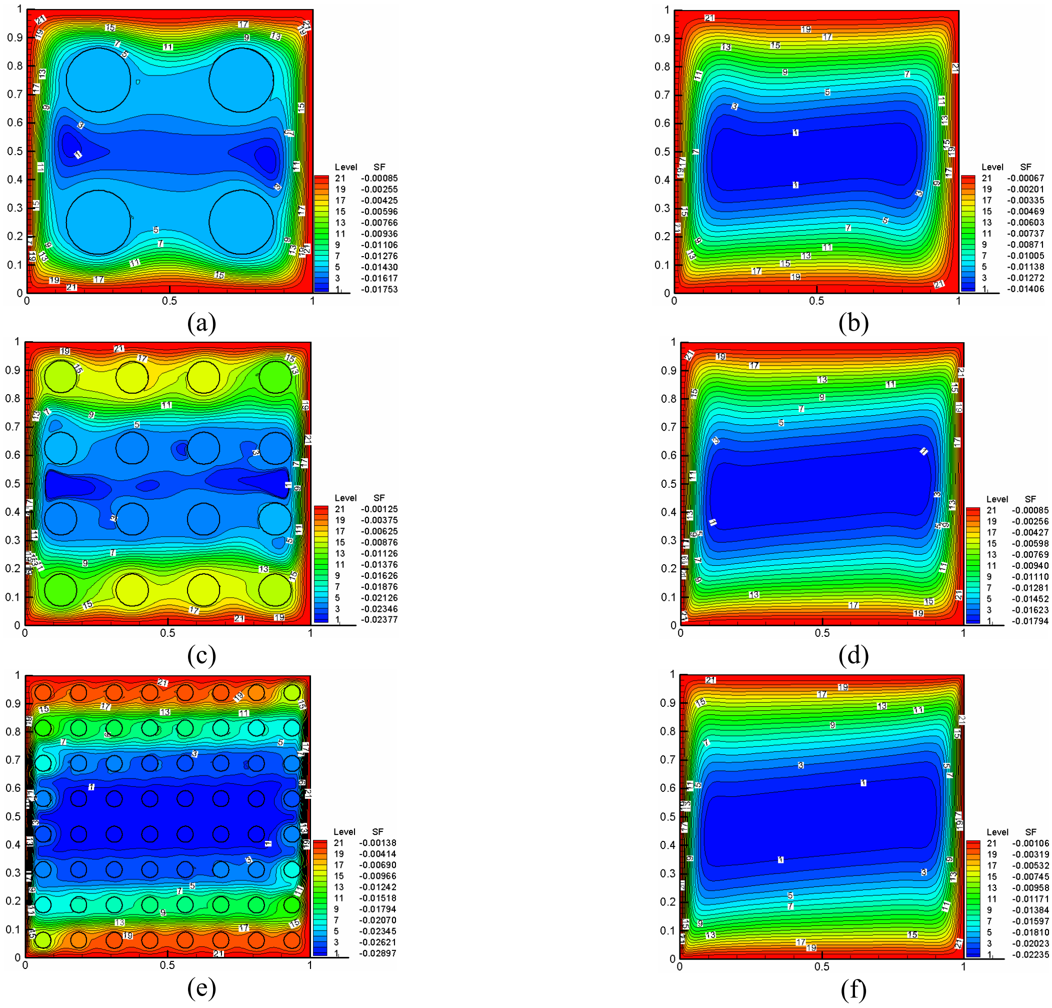


Figure 2 - Streamlines for a square cavity filled with circular obstacles simulated with microscopic(*left*) and macroscopic(*right*) models for, Ra_m=10^4, ϕ=0.84 and k_s/k_f=1; a) N=4, Da_{eq}=0.8188x10^{-2}, b) N=16, Da_{eq}=2.0471x10^{-3} and c) N=64, Da_{eq}=5.1178x10^{-4}.

7. Nusselt Number

Figure 4 compares the behavior of the average Nusselt number for the two models here investigated, namely the macroscopic and microscopic models. Both calculation methods were based on the same numerical values for both the Rayleigh and the Darcy numbers. It is clearly seen in Fig. 4 that, if $Ra = Ra_\phi$ and $Da_{eq} = Da$ for both models, the overall values of average Nusselt number for the macroscopic, Nu_ϕ model are lower than those obtained with the microscopic model, Nu. This difference increases, with increasing number of rods N. Therefore, the macroscopic model fails in predicting the average Nusselt number, when compared with those obtained from the continuum model with several obstacles. A possible explanation for such discrepancy is twofold: First, similar cases for the microscopic and macroscopic models were compared under the condition $Ra_\phi = Ra$ (or β_ϕ=β). However, it has already been pointed out in de Lemos & Braga, 2003, that these two thermal expansion coefficients do not, necessarily, have equal values. In fact, β_ϕ, derived in de Lemos & Braga, 2003, shows the relationship between these two parameters. The first one, β, is a fluid property and for an ideal gas it is given by $1/T$, where T is the absolute gas temperature. On the other hand β_ϕ, is a macroscopic quantity and by no means represents a local fluid property. Consequently, comparisons with the two models here investigated on the basis β_ϕ=β are strictly not quite correct. For having the same Nu, an inspection on Fig. 4 indicate that one should have $Ra_\phi > Ra$ when comparing the two models.

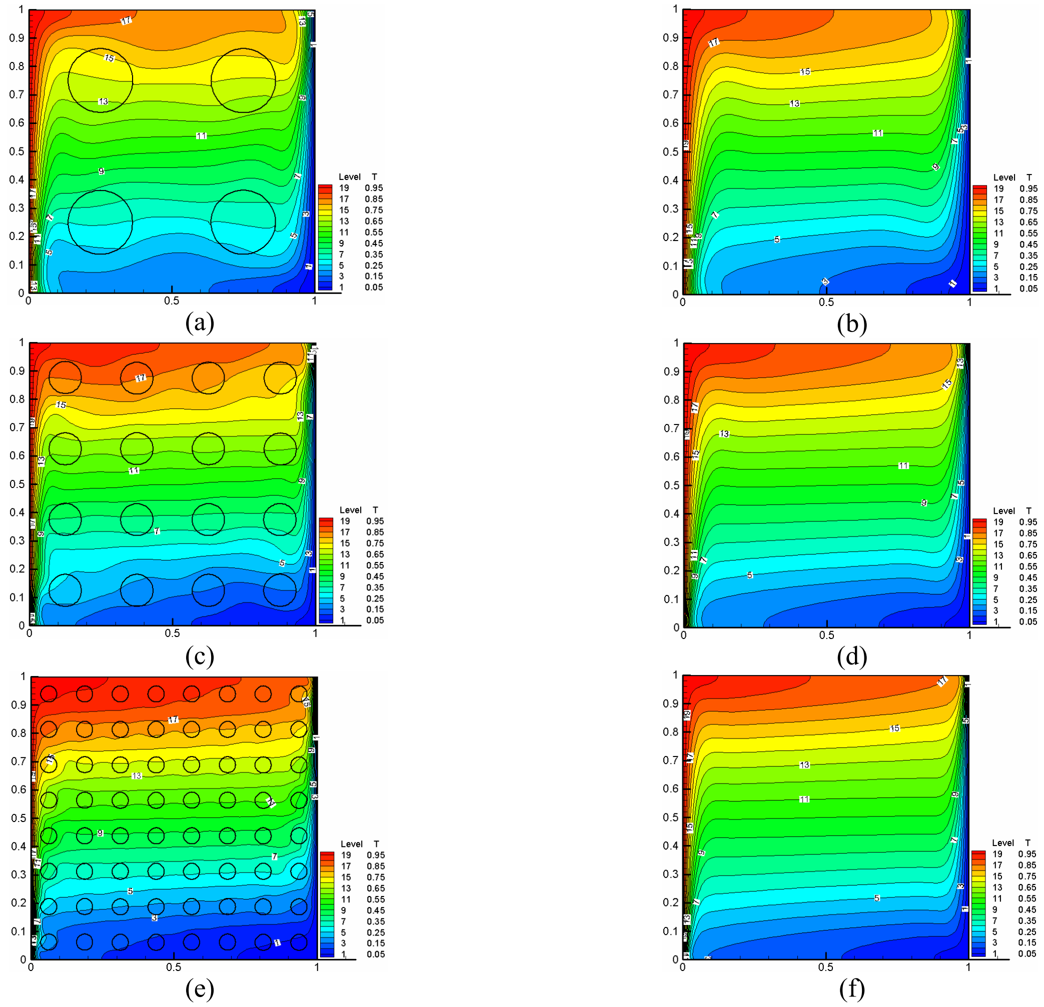


Figure 3 - Isotherms for a square cavity filled with circular obstacles simulated with microscopic(*left*) and macroscopic(*right*) models for, Ra_m=10^4, ϕ=0.84 and k_s/k_f=1; a) N=4, Da_{eq}=0.8188x10^{-2}, b) N=16, Da_{eq}=2.0471x10^{-3} and c) N=64, Da_{eq}=5.1178x10^{-4}.

Secondly, both models were compared in Fig. 4 using the same value for parameter Darcy, or $Da_{eq}=Da$. Note that Da_{eq} is an "equivalent" Darcy number, whose associated K_{eq} in the microscopic model was estimated by (1), being D_p the obstacles diameter. On the other hand, Da is the Darcy number for the porous cavity of Fig 1c formed with the porous medium permeability K. In the simulation herein, the same K_{eq} value was prescribed in the porous-continuum model for use in equation (7), or say, $K_{eq}=K$. However, Eq. (1) was derived for forced convection flow over a porous bed so that its application to the natural convection problem here under analysis is questionable. Also, real porous systems like the ones in Fig 1c may have lower permeability than those associated with their counterpart continuum models of Fig 1a. As the number of rods, N, increases, K_{eq} associated with Fig 1a might be reduced at a rate faster than that given by Eq. (1). So, when calculating a counterpart macroscopic model for the system in Fig 1a, a lower value for K should be used instead of K_{eq} given by eqn. (1), or say, $Da < Da_{eq}$.

In the work of Braga & de Lemos, 2005, a correlation to correct the value of the Nusselt number was proposed. Basically, the corrected Nusselt number is yielded by correcting the values of the Ra_ϕ and Da, but maintaining the value of Ra_m fixed in 10^4. Also, Braga & de Lemos, 2005, show that both microscopic and macroscopic models give higher values for the Nusselt number when turbulence is considered, being macroscopic solutions more sensitive to the inclusion of a turbulence model. This sensitivity increases with increasing the number of blocks and results herein indicate that inclusion of turbulence and dispersion constructs more realistic macroscopic models, making them a suitable engineering tool for analyzing complex physical systems.

8. Conclusion

This work presented numerical solutions for steady laminar natural convection within a square cavity filled by a fixed amount of conducting solid material using a *microscopic* model. The solid phase was composed by circular obstacles, equally spaced within the cavity. In addition, an isotropic and homogeneous *macroscopic* model was used for simulating the flow and heat transfer across the cavity, assuming the enclosure as totally filled with a porous material.

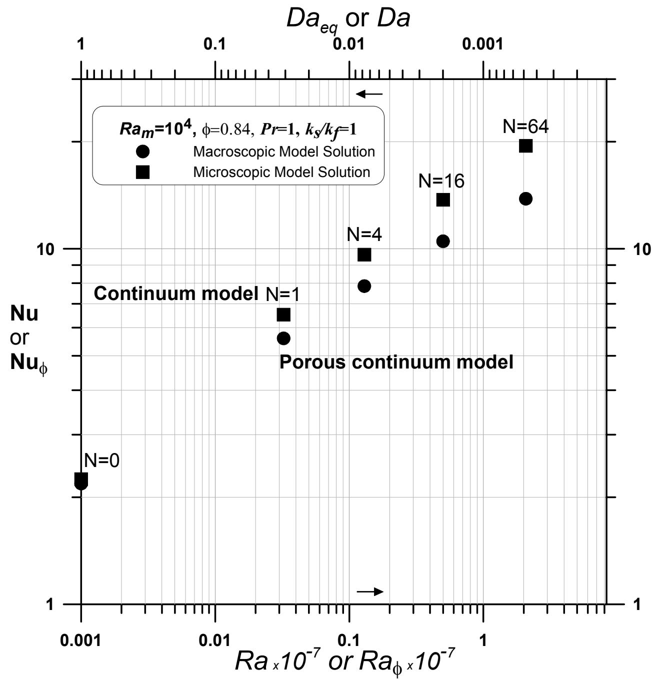


Figure 4 - Comparison between the microscopic and macroscopic models with respect to the average Nusselt number at the hot wall with *Ra*.

The *macroscopic* model failed to correctly predict the average Nusselt number when compared with those obtained from the *microscopic* model with several obstacles. This same conclusion has also been reached in the recent literature Massarotti *et al,* 2003. In future works the authors hope that the inclusion of turbulence and dispersion construct more realistic macroscopic models, making them a suitable engineering tool for analyzing complex physical systems. Ultimately, forthcoming works also intend to analyze cavities fulfilled with obstacles with different geometries and simulated with the dispersion mechanics in order to study the influence of the medium morphology and modeling details on the overall heat transfer process.

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