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NUMERICAL SIMULATIONS OF NATURAL CONVECTION AND SURFACE RADIATION IN AN OPEN CAVITY WITH DISCONNECTED SOLID BLOCKS

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Abstract. *Several studies have been conducted on natural convection in heterogeneous porous media. The majority of them have in common the hypothesis of negligible heat transfer by radiation. Recent investigations have shown that surface radiation plays an important role on the overall heat transfer in cavities subject to natural convection. In this study, numerical methods are used to solve natural convection and surface radiation in an open cavity containing several disconnected and conducting solid blocks. The cavity vertical wall is isothermally heated while in the other end, it is opened to a fluid reservoir. The horizontal walls are kept adiabatic. The blocks are squared, equally spaced, disconnected, and heat conducting, with fluid-to-solid thermal conductivity ratio set as unity. The fluid properties are assumed constant except for the buoyancy term in which is used the Oberbeck-Boussinesq approximation. The cavity and block surfaces are grey, opaque and diffuse, with surface emissivity set as unity. The effect of varying the Rayleigh number from* 10^3 *to* 10^8*, and the number of blocks from 9 to 144, at fixed porosity of 64%, are investigated. The average convective and radiative Nusselt numbers are evaluated and the convective and radiative drop phenomena are discussed.*

Keywords: *natural convection, surface radiation, open cavity flow, heterogeneous media*

1. INTRODUCTION

Understanding the heat transfer in heterogeneous cavities is of great importance due to the applicability of this geometry in industrial processes, such as drying processes, grain storage, thermal insulation, solar panels, among other applications (Nield and Bejan, 2006). The complexity of describing the structure of a real porous medium is extremely complex, making it difficult to accurately represent its geometry. Thus, in order to be able to analytically describe this medium, some geometric approximations need to be adopted. There are models that can be approached for the representation of a porous medium, of which the two best known are: the heterogeneous model and the homogeneous model. The heterogeneous model is a microscopic scale model that treats each of the phases, solid and fluid, separately. On this scale the interface between the solid and fluid domains is visible. The homogeneous model is a macroscopic scale model and considers the solid and fluid phases as a single medium. In this model the interfaces between phases are not visible and the conservation equations of mass, momentum and energy are applied throughout the domain, which is filled with fluid of approximate properties by a volumetric mean of a representative elemental volume(Nield and Bejan, 2006). In this paper, the heterogeneous model is adopted, as shown in Fig.1.

Many studies involving natural convection in cavities are found in the literature and a growing interest in porous cavities has been observed since the 1990s. The work that initiated the investigations in the area was published by House *et al.* (1990). The authors investigated natural convection in a closed cavity containing a single block. The work evidenced the effects of block size and its thermal conductivity on pure natural convection.

Since the pioneering work of House, several studies involving this subjects may be found in the literature (Massarotti *et al.*, 2003). Merrikh and Lage (2005a), Braga and De Lemos (2005a) and Daroz *et al.* (2012) carried out studies comparing the heterogeneous model and the homogeneous model. In general, the heterogeneous model is more accurate in the representation of the problem due to the interfaces question. Furthermore, this type of approach allows the exploration of a larger range of representations of a porous medium due to the geometric varieties that are likely to be implemented.

The effect of block format was later studied by Braga and De Lemos (2005b). It was found that square blocks provide higher rates of heat transfer by convection compared to a cylindrical arrangement of blocks due to perturbations generated

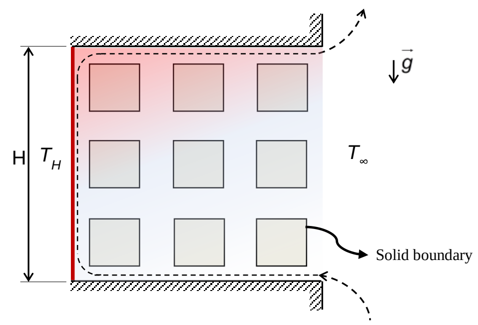


Figure 1. Open cavity filled with heterogeneous porous medium.

in the vicinity of the edges of the blocks. Merrikh and Lage (2005b) investigated natural convection in a closed cavity filled with heterogeneous porous medium which was represented by solid and conductive square blocks uniformly distributed inside the cavity. The variation of number of blocks and the ratio of solid-fluid thermal conductivity considering a constant porosity was investigated. The concept of boundary layer interference phenomena was introduced, which is described as a drastically decrease of the average Nusselt number due the increase of te number of blocks . This occurs once the thermal boundary layer is deconstructed due the block invasion, considerably reducing the withdrawal of heat of the heated wall by advection. De Lai *et al.* (2008) investigated the effect of porosity and the ratio of solid-fluid thermal conductivity, complementing Merrikh and Lage (2005b).

A study including thermal radiation in closed cavity with a centralized square block was presented by Mezrhab *et al.* (2006). The influence of emissivity and the thermal conductivity ratio were investigated. The results indicated that the radiation tends to uniform the temperature in the cavity and considerably increases the number of average Nusselt, especially when the ratio of solid-fluid thermal conductivity and Rayleigh number are high. In addition, the authors have found that in cavities, the heat transfer by natural convection and by thermal radiation are usually of the same order of magnitude. Subsequently, Mezrhab *et al.* (2008) investigated natural convection and thermal radiation in a closed cavity with a cylindrical block. The results showed that radiation tends to increase heat transfer regardless of cylinder size or location.

Franco *et al.* (2013) investigated the open cavity of Chan and Tien (1985) filled with heterogeneous medium. The cavity has adiabatic horizontal walls and a heated vertical wall while the opposite wall is opened to a quiescent medium and an extended computational domain is applied to avoid imposing a boundary condition directly on the cavity opening. The effects of the number of blocks inside the cavity and the number of Rayleigh, for a constant porosity, on the average Nusselt number in the hot wall and the dimensionless volumetric flow entering the cavity were analyzed. Results showed that the effect of number of blocks on average Nusselt number increases as the number of Ra increases. Results also show that the volumetric flow measured at the cavity entrance has little influence of the interference phenomena, but great influence of the number of blocks.

A study that took into account the presence of thermal radiation next to the natural convection in an open cavity with the presence of a centralized square block was presented by de Souza *et al.* (2014). It has been found that there is a strong effect of radiation on the total heat transfer. With increasing block size and emissivity, the contribution of natural convection in the heat transfer of the heated wall decreases, while the contribution of thermal radiation increases considerably, resulting in an increased total heat transfer. The work also points out that it is possible that the convection will suffer the effect of boundary layer interference. In addition, it was verified the effect of radiative drop, that occurs with the increase of block size which implies in a decrease of the heat transfer by radiation.

It is known that the thermal radiation may drastically affects the heat transfer in cavities subject to natural convection (Mezrhab *et al.*, 2006). However, despite of its importance, much of the published works available in literature have in common the hypothesis of neglecting the heat exchanges by thermal radiation. In what concerns porous media few publications that take into account radiative heat fluxes along with convective heat flows are found in the literature. Thus, the present work aims to investigate how the heat transfer and the flow pattern in an open cavity filled with heterogeneous porous medium in the presence of natural convection are altered when the thermal radiation is taken into account in the system. To aid in the interpretation of the results, the values of the average radiative and convective Nusselt numbers will be analyzed, as well as the dimensionless volumetric flow that is induced by natural convection into the cavity. Further, streamlines and isotherms are presented.

2. MATHEMATICAL AND NUMERICAL MODELLING

The adopted geometry is shown in Figure 1. The cavity is square with the left vertical wall kept at an uniform temperature θ_H and adiabatic top and bottom walls. The heterogeneous porous medium is formed by solid and conductive square blocks uniformly distributed within the cavity which is open to a quiescent medium kept at temperature $\theta_\infty < \theta_H$. An extended domain is applied to avoid imposing an unknown boundary condition at the cavity opening. No-slip and adiabatic boundary condition are applied at the up and down left wall of the extended domain.

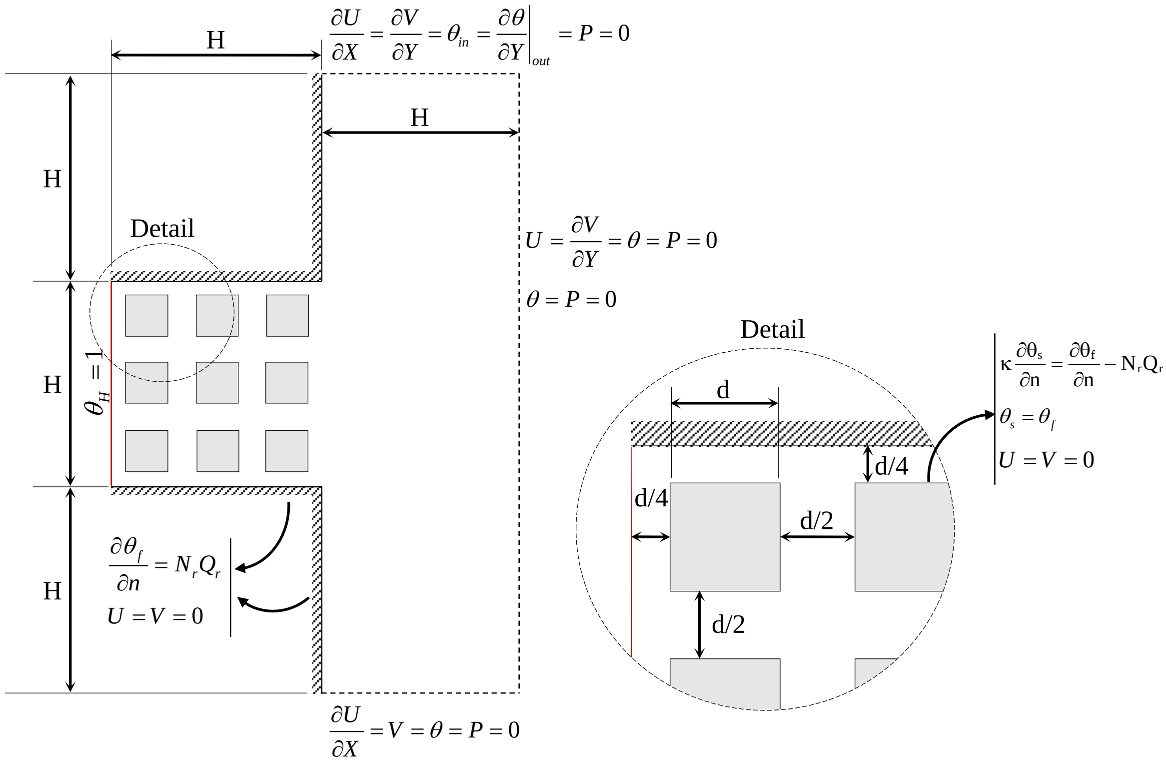


Figure 2. Geometry and boundary conditions.

The dimensionless equations of continuity, momentum in x and y directions and energy of the fluid and solid domains are respectively:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

$$U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + Pr\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

$$U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + Pr\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) + RaPr\theta \tag{3}$$

$$U\frac{\partial \theta_f}{\partial X} + V\frac{\partial \theta_f}{\partial Y} = \left(\frac{\partial^2 \theta_f}{\partial X^2} + \frac{\partial^2 \theta_f}{\partial Y^2}\right) \tag{4}$$

$$0 = \frac{\partial^2 \theta_s}{\partial X^2} + \frac{\partial^2 \theta_s}{\partial Y^2} \tag{5}$$

where the dimensionless variables defined as:

$$(X,Y) = \frac{(x,y)}{H};\; (U,V) = \frac{(u,v)\,H}{\alpha_f}\;;\; \tau = \frac{\alpha_f}{H^2}t\;;\; P = \frac{(p-p_\infty)\,H^2}{\rho_f \alpha_f^2}\;;\; \theta = \frac{T-T_\infty}{T_H - T_\infty} \tag{6}$$

The number of Prandtl (Pr) and Rayleigh (Ra), are respectively given by:

$$Pr = \frac{\nu}{\alpha}\;\;;\;\; Ra = \frac{g\beta\,(T_h - T_c)\,H^3}{\nu\alpha} \tag{7}$$

The heat flux by thermal radiation (Qr) depends on the surface Radiosity (R) and is given by:

$$R_i = \varepsilon\Theta^4 + (1-\varepsilon)\sum_{j=1}^{n} R_j F_{ij} \tag{8}$$

$$Q_{r,i} = R_i - \sum_{j=1}^{n} R_j F_{ij} \tag{9}$$

where F_{ij} is defined as the fraction of radiation leaving a surface i and intersecting surface j. The boundary conditions are represented in Figure 1.

For the solution of the conservation equations the finite volume method was applied with the SIMPLEC algorithm. The interpolation scheme of θ, U and V applied was the QUICK scheme.

The mesh sensitivity test was performed for the most critical configuration of Ra and N, ie: $Ra = 10^8$ and $N = 144$, considering $\varepsilon = 1$. The computational domain was divided into two parts, which comprises the extended computational domain in which an irregular mesh was applied and the inner part of the cavity comprising the physical domain of the problem in which a regular mesh was applied. First, a grid resolution test for the extended domain was performed. The number of control volumes within the cavity was set at 250×250 and the number of divisions (n) required at the edges of the domain was investigated to generate a grid-independent result. The percentage difference obtained for Nu_t between $n = 25$ and $n = 35$ divisions was less than 1% and therefore it was adopted that the number of divisions imposed on the edges of the extended domain would be $n = 25$. For the interior of the cavity, the test of mesh showed that the percentage difference obtained for Nu_t between $n = 350$ and $n = 300$ divisions was less than 1% and therefore the number of control volumes inside the cavity was 300×300.

3. RESULTS AND DISCUSSION

An investigation of the effects of thermal radiation in open cavity filled with porous medium was conducted. For this, two extreme cases were compared, the case of pure natural convection ($\varepsilon = 0$) and the case of maximum emissivity of the surfaces ($\varepsilon = 1$). The two cases were compared taking into account different configurations of permeability which is given by the number of blocks inside the cavity for a constant porosity (ϕ) of 0.64. The Rayleigh number (Ra) ranged from 10^5 to 10^8 and the Prandtl number (Pr) was set as 1. The parameters investigated vary according to Table 1.

Table 1. Range of investigated parameters

Rayleigh	Ra	10^5;10^6;10^7;10^8
Prandtl	Pr	1
Porosity	ϕ	64%
Solid-fluid conductivity	κ	1
Number of blocks	N	9;16;36;64;144

3.1 Global effect of thermal radiation

Figure 3 shows the differences in the distribution of isotherms and streamlines between the cases of pure natural convection ($\varepsilon = 0$) and the cases in which the radiative changes between the surfaces are taken into consideration ($\varepsilon = 1$) for 16 blocks Inside the cavity and intermediate Ra values ($Ra = 10^6$ and $Ra = 10^7$). Only the cavity and the region close to the cavity opening are represented. Results show that in general the consideration of thermal radiation increases the heat transfer exchange between the heated wall and the fluid as can be seen by a increase in the total average Nusselt number (Nu_t) shown in Fig. 3. Further, when $\varepsilon = 1$ the isotherms are better distributed and approach the cavity opening, which indicates that the cavity temperature is more uniformly distributed. Streamlines are little affected, however the flow of fluid induced inside the cavity increases when ε goes from 0 to 1, observed by the greater concentration of streamlines and the increase in volumetric flow rate ($\dot{M}$).

3.2 Volumetric flow rate ($\dot{M}$)

Besides making the temperature inside the cavity more uniform the consideration of thermal radiation causes the appearance of boundary layer regions next to the left wall of the blocks closest to the heated wall and also next to the lower adiabatic wall, as shown in Figure 3. The boundary layer next to the blocks causes compression of the isotherms in the wall of these blocks, which indicates an increase of the buoyancy in this region, intensifying the circulation of fluid. Consequently an increase of ($\dot{M}$) is observed when ε changes from 0 to 1.

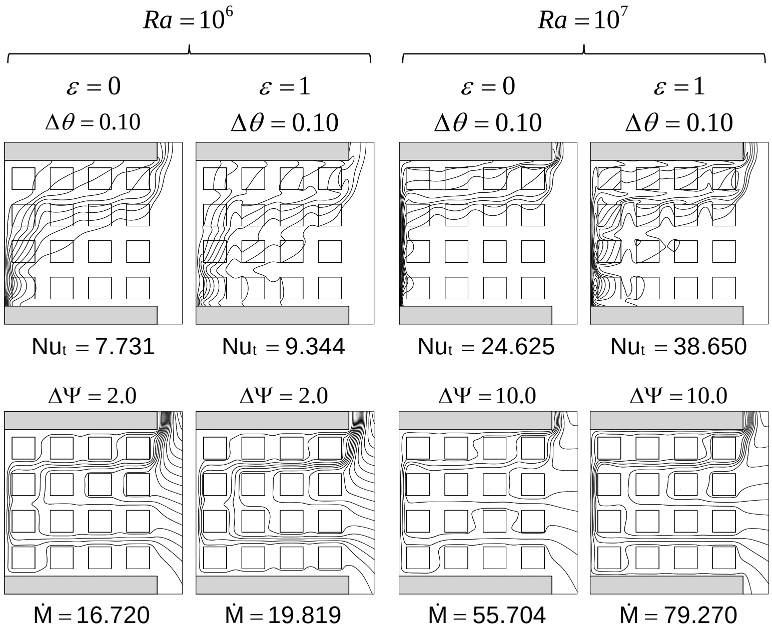


Figure 3. Differences in the distribution of isotherms (above) and streamlines (below) between $\varepsilon = 0$ and $\varepsilon = 1$ for $N = 16$.

Figure 4 shows the results of $\dot{M}$ obtained for all values of N and Ra investigated. For lower Ra (eg $Ra = 10^5$ and $Ra = 10^6$), the observed difference between the values obtained for $\varepsilon = 1$ and $\varepsilon = 0$ is not significant. This occurs once the heat transfer by conduction predominates over the heat transfer by convection. In this case, the buoyancy forces arising along the left wall of the blocks when $\varepsilon = 1$ are less intense and the induced flow into the cavity is not as great as the induced flow when the boundary layer next to the block is small or does not appear ($\varepsilon = 0$). For high numbers of Ra ($Ra = 10^7$ and $Ra = 10^8$), when $\varepsilon = 1$, the $\dot{M}$ is considerably higher and in some cases up to twice the observed value of $\dot{M}$ for $\varepsilon = 0$.

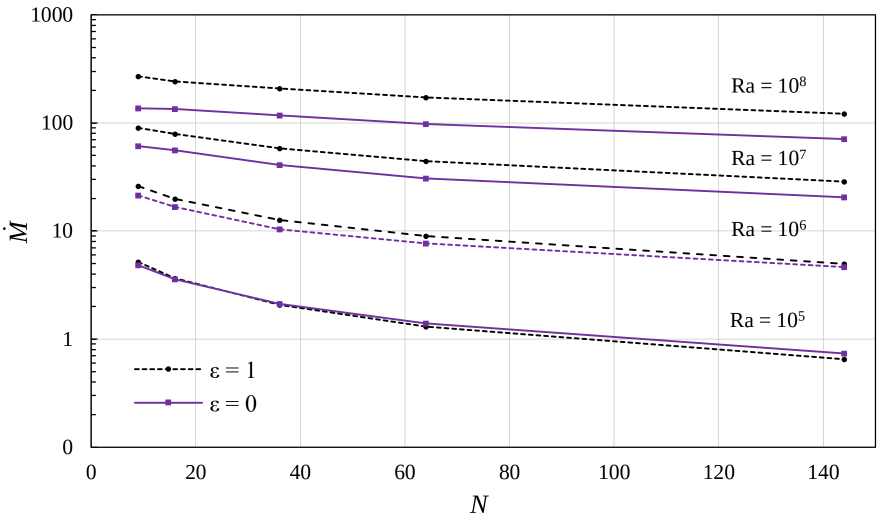
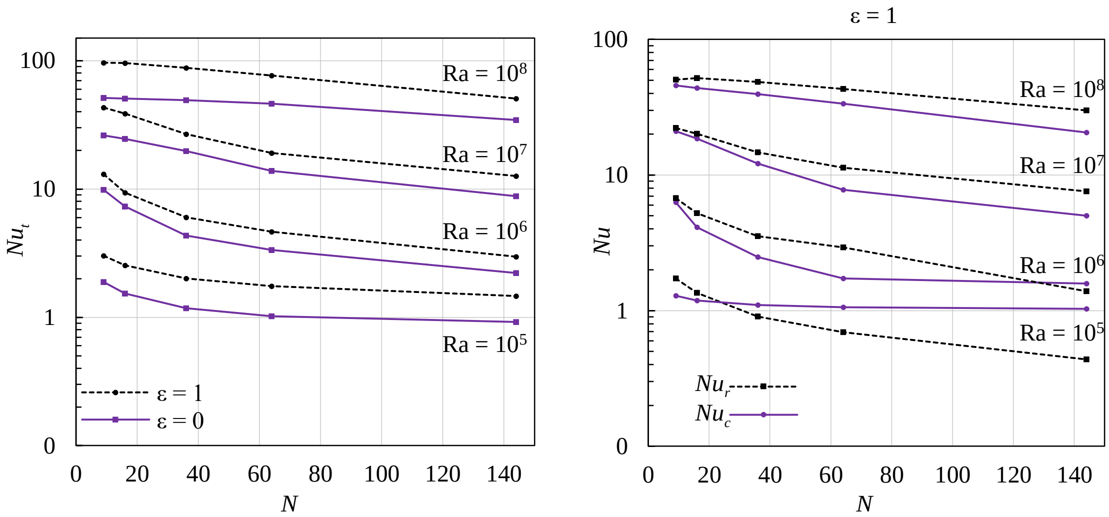


Figure 4. Effect of ε, N and Ra on the $\dot{M}$ for all cases considered

3.3 Average Nusselt number

The total average Nusselt number (Nu_t) is composed of a portion of radiative average Nusselt number (Nu_r) and of a portion of convective average Nusselt number (Nu_c). Figure 5.a shows the results obtained for Nu_t in cases of pure natural convection ($\varepsilon = 0$ and consequently $Nu_r = 0$) and in cases where the heat exchange through surface radiation was considered ($\varepsilon = 1$). It is observed that Nu_t suffers a substantial increase when the thermal radiation is taken into consideration, independently of the Ra or N configuration adopted. That is, heat transfer from the hot wall to the medium is greater when thermal radiation is considered.



(*a*) (*b*)

Figure 5. Average Nusselt Number. (a) Effect of ε, N and Ra on the Nu_t for all cases considered. (b) Effect of N and Ra on the convective and radiative portion of Nu_t, Nu_c and Nu_r respectively, for $\varepsilon = 1$.

The importance of considering the thermal radiation in problems of natural convection in cavities filled with heterogeneous porous medium can still be observed when analyzing the plots of average radiative Nusselt (Nu_r) and average convective Nusselt (Nu_c). Figure 5.*b* shows the results obtained for the convective and the radiative portion of Nu_t, Nu_c and Nu_r respectively, when $\varepsilon = 1$. As observed by Mezrhab *et al.* (2008) and de Souza *et al.* (2014), results show that these two portions that make up the total average Nusselt are of the same order of magnitude. In addition, for most cases the average radiative portion of the Nusselt is even greater than the convective portion. Nu_c exceeds Nu_r only when $Ra = 10^5$ and $N = 36$ and when $Ra = 10^6$ and $N = 144$. The constant drop of Nu_r with the increase of N is due to the shading effect (Mezrhab and Bouzidi, 2005). As N increases, the more the blocks approach the walls of the cavity and the heated wall "sees" less and less the thermal reservoir and consequently the heat flux by thermal radiation decreases.

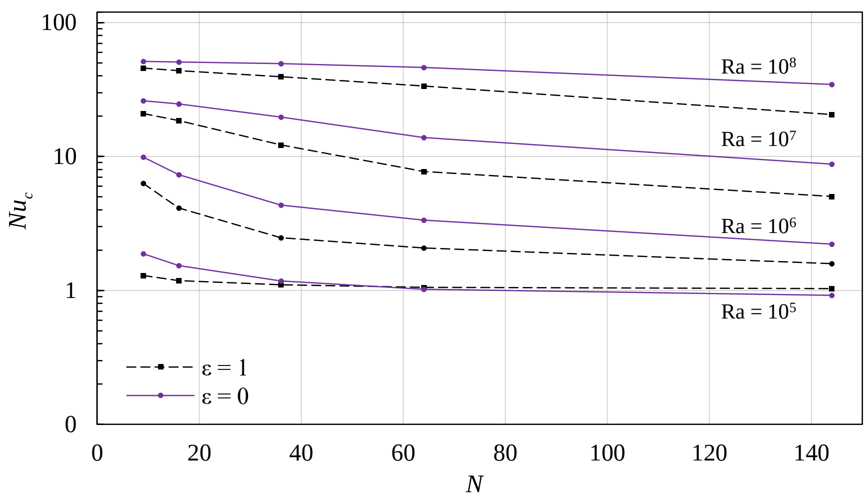


Figure 6. Effect of ε, N and Ra on the Nu_c.

Results also indicate that the radiative portion of the average Nusselt is not simply added to the results obtained only with pure natural convection. Figure 6 shows the values obtained for the average convective Nusselt for $\varepsilon = 1$ and $\varepsilon = 0$, for the entire range of Ra and N investigated. As discussed by Balaji and Venkateshan (1993), when considering the radiative changes in natural convection problems in cavities, the average convective Nusselt tends to decrease. This phenomenon is called convective drop which is the attenuation of natural convection heat transfer due to the consideration of heat exchanges by thermal radiation. The convective drop occurs due to a preheating of the fluid induced into the cavity. When $\varepsilon = 1$ the lower adiabatic wall receives heat through thermal radiation and consequently its temperature is elevated. A thermal boundary layer forms in that region and the cold fluid induced into the cavity has its temperature increased as it passes through this region of new thermal boundary layer, which reduces its ability to draw heat from the heated wall, as schematically shown in Figure 7.

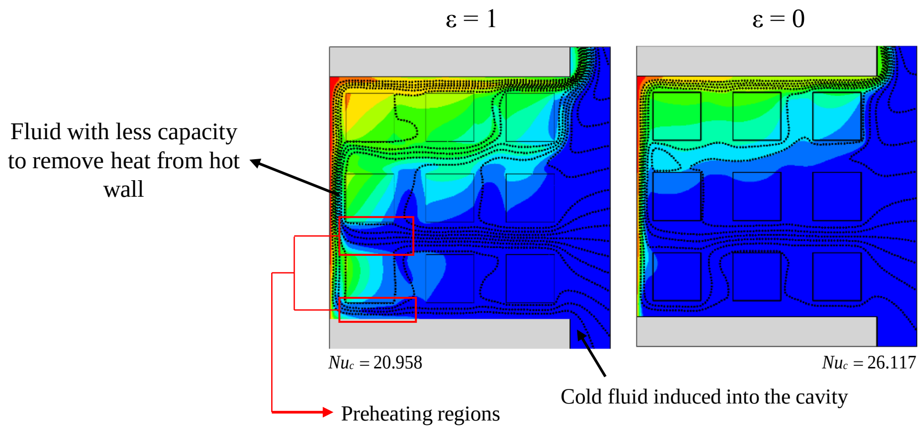


Figure 7. Schematic diagram for the convection drop.

4. CONCLUSIONS

Heat transfer in open cavity subjected to natural convection and filled by heterogeneous medium is intensified by surface thermal radiation. The average total Nusselt, comprised of a convective and a radiative portion, increases and in some cases it overcomes twice the values observed for pure natural convection, which means the results cannot be superposed. Further, it was observed that when considering thermal radiation, the radiative portion of the average Nusselt is not simply added in the results obtained for pure natural convection. The observed value of the convective portion pf the total Nusselt for $\varepsilon = 1$ is lower than the convective Nusselt value observed for $\varepsilon = 0$. This attenuation of the natural convection due to the consideration of the thermal radiation is called the convective drop and shows that natural convection and thermal radiation present a dual behavior, that is, one interferes in the other.

A radiative drop, that is a decrease in the radiative Nusselt, is observed when increasing the number of blocks which increases the shading effect. Thus, the heated wall "sees" fewer domain and has its capacity for heat exchange by radiation reduced.

With the consideration of the thermal radiation, even with the fall of the heat transfer by natural convection, observed by the fall of the convective Nusselt, an increase in the volumetric flow rate induced inside the cavity was observed regardless of the number of blocks. This increase occurs due to the thermal boundary layer appearing along the left wall of the blocks closest to the heated wall of the cavity, increasing the thrust regions and the circulation of fluid within the cavity.

5. REFERENCES

Balaji, C. and Venkateshan, S., 1993. “Interaction of surface radiation with free convection in a square cavity”. *International Journal of Heat and Fluid Flow*, Vol. 14, No. 3, pp. 260–267.

Braga, E.J. and De Lemos, M.J., 2005a. “Heat transfer in enclosures having a fixed amount of solid material simulated with heterogeneous and homogeneous models”. *International Journal of Heat and Mass Transfer*, Vol. 48, No. 23, pp. 4748–4765.

Braga, E.J. and De Lemos, M.J., 2005b. “Laminar natural convection in cavities filled with circular and square rods”. *International communications in heat and mass transfer*, Vol. 32, No. 10, pp. 1289–1297.

Chan, Y. and Tien, C., 1985. “A numerical study of two-dimensional natural convection in square open cavities”. *Numerical Heat Transfer*, Vol. 8, No. 1, pp. 65–80.

Daroz, V., Hanauer, G., Nardi, V., De Lai, F., Franco, A. and Junqueira, S., 2012. “Conveccao natural em uma cavidade parcialmente preenchida com um bloco poroso: Compraracao entre os modelos homogeneo e heterogeneo". In *Rio Oil and Gas Expo and Conference 2012*. 2012, Instituto Brasileiro de Petróleo, Gás e Biocombustíveis - IBP.

De Lai, F.C., Junqueira, S.L., Franco, A.T. and Lage, J.L., 2008. "Natural convection through enclosed disconnected solid blocks". In *Proceedings of the 12th Brazilian Congress of Thermal Engineering and Sciences, Belo Horizonte, Minas Gerais, Brasil*.

de Souza, A.L., Franco, A., Junqueira, S. and Lage, J., 2014. "Numerical simulations of natural convection with radiation in an open cavity containing a conducting and centered solid body". In *ASME 2014 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, pp. V08AT10A024–V08AT10A024.

Franco, A., Loyola, L., De Lai, F., Junqueira, S., Ganzarolli, M. and Lage, J., 2013. "Natural convection through an open cavity heated from the side and filled with fluid and discrete solid blocks". In *ASME 2013 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, pp. V08CT09A065–V08CT09A065.

House, J.M., Beckermann, C. and Smith, T.F., 1990. "Effect of a centered conducting body on natural convection heat transfer in an enclosure". *Numerical Heat Transfer*, Vol. 18, No. 2, pp. 213–225.

Massarotti, N., Nithiarasu, P. and Carotenuto, A., 2003. "Microscopic and macroscopic approach for natural convection in enclosures filled with fluid saturated porous medium". *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 13, No. 7, pp. 862–886.

Merrikh, A. and Lage, J., 2005a. *From continuum to porous-continuum: The visual resolution impact on modeling natural convection in heterogeneous media*, Elsevier Science, Vol. III, chapter 3.

Merrikh, A.A. and Lage, J.L., 2005b. "Natural convection in an enclosure with disconnected and conducting solid blocks". *International Journal of Heat and Mass Transfer*, Vol. 48, No. 7, pp. 1361–1372.

Mezrhab, A., Bouali, H., Amaoui, H. and Bouzidi, M., 2006. "Computation of combined natural-convection and radiation heat-transfer in a cavity having a square body at its center". *Applied energy*, Vol. 83, No. 9, pp. 1004–1023.

Mezrhab, A. and Bouzidi, M., 2005. "Computation of view factors for surfaces of complex shape including screening effects and using a boundary element approximation". *Engineering computations*, Vol. 22, No. 2, pp. 132–148.

Mezrhab, A., Moussaoui, M. and Naji, H., 2008. "Lattice boltzmann simulation of surface radiation and natural convection in a square cavity with an inner cylinder". *Journal of Physics D: Applied Physics*, Vol. 41, No. 11, p. 115502.

Nield, A.D. and Bejan, A., 2006. *Convection in porous media*. Springer, New Jersey, 3rd edition.

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