COUPLED HEAT TRANSFERS THROUGH BUILDING ROOFS FORMED BY HOLLOW CONCRETE BLOCKS

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The aim of this work is to study numerically the coupled heat transfers by conduction, natural convection and radiation through building roofs constructed by hollow concrete blocks. Heat transfer is assumed to be two-dimensional and the fluid flow in the different air cells of the system under investigation is laminar. Equations governing heat transfer are discretized using the control volumes approach and are solved by the SIMPLE algorithm. Streamlines, isotherms and overall heat fluxes are presented for building roofs heated from below and formed by different types of hollow concrete blocks. Analysis of results obtained for different numbers of air cells in the horizontal direction shows that the study of the entire system can be reduced, with a very good approximation, to the study of a single hollow concrete block. This permits a very important reduction of the computational time.

Keywords: building roof, hollow concrete blocks, conduction, convection, radiation, numerical simulation

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Introduction

Hollow concrete blocks are often used in the construction of building roofs. In general, each hollow block is formed by three cavities surrounded by solid concrete partitions. Thus, the heat transfer within such structures is done simultaneously by conduction in the solid partitions, natural convection inside the cavities and radiation between the internal faces of these cavities. Furthermore, the three heat transfer processes are intimately bound. Therefore, the fine study of the thermal behavior of the hollow blocks needs a simultaneous solving of the complex and sometimes non linear equations modeling the different thermal transfer mechanisms.

The coupling problem between the three modes of heat transfer was the subject of numerous investigations. The bibliographic studies presented in the works [1-6] show that the most of these investigations are generally limited to simple configurations constituted by rectangular cavities with one or several conducting walls and were especially has been interested to the study of the effects of conduction and/or radiation on natural convection in the cavities.

The coupled heat transfers in vertical alveolar building envelopes formed by hollow clay tiles have been studied by Abdelbaki and Zrikem [5]. Based on a detailed simulation model, the authors determined characteristic coefficients that permit fast and accurate estimation of heat exchanges through the alveolar walls without solving the complex coupled equations governing the different thermal mechanisms [6]. These characteristic coefficients are the overall heat exchange coefficients in the steady state regime and the transfer function coefficients in time varying regime.

Recently, the previous studies are extended to the case of hollow concrete blocks used in the construction of building roofs by Ait-Taleb et al. [7, 8]. In this case, the considered alveolar structures are horizontal but are subjected to a vertical gradient temperature. The two situations of heating have been considered: heating from below and from above.

In the practice, a building roof having, for example, 4 meters length contains about 8 units of hollow blocks. In construction, the hollow blocks are placed in such a way that each hollow blocks possesses 3 cavities (Nx = 3) in the horizontal direction separated by supporting girders. Therefore, the total number of alveolar in the considered building roof is about 24 cavities in the horizontal direction (Nx = 24). Consequently, the simulation of the global system requires an important computational time. Then, it is more interesting to reduce the size of the system under investigation. However, this reduction is only efficient if its influence on the global thermal behavior of the system is limited.

To examine this solution, this paper presents a numerical study of the vertical coupled heat transfers by conduction, convection and radiation through horizontal hollow structures that differ by the alveolar number (Nx) in the horizontal direction and by the aspect ratio of the internal cells.

Mathematical formulation

The studied alveolar system is sketched in Fig. 1 and is formed by a range of Nx rectangular cavities of width l and height h surrounded by vertical solid partitions of thickness ex_i ($1 \le i \le Nx + 1$) and horizontal partitions of thickness ey_j ($1 \le j \le 2$). The top and bottom sides of the hollow structure are considered isothermal and are maintained at constant temperatures T_0 and T_i respectively. The structure vertical sides are considered adiabatic or submitted to periodicity conditions.

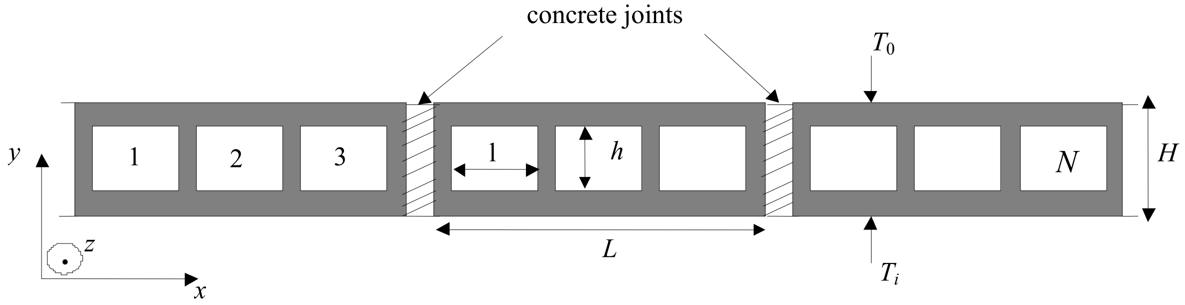

Fig. 1. *Schematic diagram of disposition of hollow blocks in building roofs*

In formulating governing equations, the fluid motion and the heat transfer are considered two-dimensional and the fluid flow is laminar. The solid and fluid properties are assumed to be constant except for the density in the buoyancy term where the Boussinesq approximation is utilized. Viscous heat dissipation in the fluid is neglected. The fluid is assumed to be non-participating to radiation and the inside surfaces of all cavities are considered diffuse-grey. The governing equations are written in dimensionless form as:

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

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

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

$$\frac{\partial\theta_f}{\partial\tau}+U\frac{\partial\theta_f}{\partial X}+V\frac{\partial\theta_f}{\partial Y}=\frac{\partial^2\theta_f}{\partial X^2}+\frac{\partial^2\theta_f}{\partial Y^2}, \quad (4)$$

where U and V are the dimensionless velocity components in X and Y directions respectively, P is the pressure, θ_f is the fluid temperature, Pr is the Prandtl number and Ra is the Rayleigh number given by: $Ra=\frac{g\beta H^3\Delta T}{\nu^2}Pr$, $Pr=\frac{\nu}{\alpha_f}$, where ν and α_f are respectively the fluid kinematic viscosity and the thermal diffusivity.

The dimensionless equation of heat conduction in the solid walls is:

$$\frac{\alpha_f}{\alpha_s}\frac{\partial\theta_s}{\partial\tau}=\frac{\partial^2\theta_s}{\partial X^2}+\frac{\partial^2\theta_s}{\partial Y^2}, \quad (5)$$

where α_s is the solid thermal diffusivity and θ_s is the dimensionless solid temperature. The boundary conditions of the problem are:

* $U = V = 0$ on the inner sides of each cavity.
* $\theta_s(X,0)=1$ and $\theta_s(X,1)=0$ $(0 \le X \le L/H)$

$$* \begin{cases} \theta_s(0,Y)=\theta_s(L/H,Y)\ (0\le Y\le 1) & \text{for the periodicity condition} \\ \left(\frac{\partial\theta_s}{\partial X}\right)_{X=0;L/H}=0\ (0\le Y\le 1) & \text{for the adiabaticity condition} \end{cases}$$

The continuity of the temperature and the heat flux at the fluid-wall interfaces gives:

$$\theta_s(X,Y)=\theta_f(X,Y), \quad (6)$$

$$-\frac{\partial\theta_s}{\partial\eta}=-N_k\frac{\partial\theta_f}{\partial\eta}+N_r Q_r, \quad (7)$$

where η represents the dimensionless coordinate normal to the wall, N_k is the thermal conductivity ratio K_f/K_s, Q_r is the dimensionless radiative heat flux and N_r is the dimensionless radiation to conduction parameter defined by:

$$N_r=\frac{\sigma T_0^4 H}{k_s\Delta T}.$$

The dimensionless radiative heat flux Q_r is related to the radiative heat flux q_r by:

$$Q_r=\frac{q_r}{\sigma T_0^4}.$$

The net radiative heat flux $q_{r,k}(r_k)$ exchanged by the finite area dS_k, located at a position r_k on the surface k, is given by:

$$q_{r,k}(r_k)=J_k(r_k)-E_k(r_k), \quad (8)$$

where $J_k(r_k)$ is the radiosity and $E_k(r_k)$ is the incident radiative heat flux on the surface dS_k given respectively by:

$$J_k(r_k)=\varepsilon_k\sigma(T_k(r_k))^4+(1-\varepsilon_k)E_k(r_k), \quad (9)$$

$$E_k(r_k)=\sum_{j=1}^{4}\int_{A_j}J_j(r_j)dF_{dS_k-dS_j(r_k,r_j)}, \quad (10)$$

where ε_k is the emissivity of the surface k and $dF_{dS_k-dS_j}$ is the view factor between the finite surfaces dS_k and dS_j located at r_k and r_j respectively. Taking into account equations (8) to (10), the dimensionless radiative heat flux can be expressed as:

$$Q_{r,k}(r'_k)=\varepsilon_k\left(\left|1-\frac{1}{G}\right|\theta_k(r'_k)+\frac{1}{G}\right)^4-$$
$$-\varepsilon_k\sum_{j=1}^{4}\int_{S_j}J'_j(r'_j)dF_{dS_k-dS_j}, \quad (11)$$

where G is the temperature ratio T_0/T_i, $J'_j(r_j)$ is the dimensionless radiosity at the position r_j on surface j. By dividing the walls into finite isothermal surfaces, equation (11) leads to a set of linear equation where the unknowns are the dimensionless radiosities $J'_j(r_j)$.

The dimensionless average heat flux across the structure is given by:

$$Q_a=-\frac{H}{L}\int_0^{L/H}\left.\frac{\partial\theta_S}{\partial Y}\right|_{Y=0}dX=-\frac{H}{L}\int_0^{L/H}\left.\frac{\partial\theta_S}{\partial Y}\right|_{Y=1}dX. \quad (12)$$

The previous equations are discretized using the finites differences method based on the control volumes approach with a power law scheme and are solved by the SIMPLE algorithm. The resulting system of algebraic equations is solved by the Tri-Diagonal-Matrix-Algorithm. To accelerate the convergence of solutions, the governing equations are solved in their instationary form. The numerical code has been validated by comparing its results with those reported in reliable works in literature [4]. To realize a compromise between accuracy and computation time, a study on the effects of both grid spacing and time step on the simulation results has been conducted. It was found that a no uniform grid size of 185×20 is sufficient to model accurately the heat transfer and fluid flow inside the hollow block. The dimensionless time used is 10^{-4}. The convergence criterion is 10^{-4}.

Results and discussion

Results presented in this study (Table 1) are obtained for the hollow blocks mostly used in Morocco which are made in light concrete and characterized by a thermal conductivity $K_s = 0.5$ W/m·K and emissivity $\varepsilon = 0.9$. The geometrical parameters for the different hollow blocks considered are given in table 1 where l is the length and h is the height of the internal cavities, A_c is the aspect ratio of these cavities ($A_c = h/l$), e_x and e_y are respectively the thickness of the vertical and horizontal solid partitions. The Prandtl number is $Pr = 0.71$. The temperature difference $\Delta T = (T_0 - T_i)$ values vary between 1 °C and 30 °C in accordance with the practical conditions.

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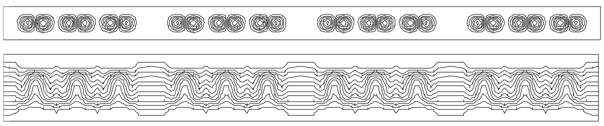
Table 1
Geometrical dimensions of the different studied hollow blocks

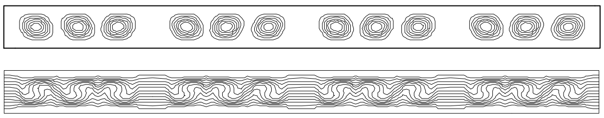
Aspect ratio	l (m)	h (m)	e_x (m)	e_y (m)	$A_c = h/l$
$A_c = A_{c1} \approx 1/4$	0.13	0.035	0.025	0.02	0.26
$A_c = A_{c2} \approx 1/2$	0.13	0.07	0.025	0.02	0.53
$A_c = A_{c3} \approx 1$	0.13	0.1	0.025	0.02	0.77

Streamlines and isotherms

Fig. 2 presents the streamlines contours and the isotherms obtained for $N_x = 12$, $\Delta T = 20$ °C, $G = 1.035$ and for the two considered types of hollow blocks characterized by $A_c \approx 1/2$ and $A_c \approx 1$. The other dimensionless parameters corresponding to these data are $Ra_H = 2.5 \cdot 10^6$ and $Nr = 5.850$ for $A_c \approx 1/2$, $Ra_H = 5.169 \cdot 10^6$ and $Nr = 4.596$ for $A_c \approx 1$. It should be mentioned that the effective Rayleigh numbers in the different internal cavities are $Ra_h = 5.13 \cdot 10^5$ for $A_c \approx 1/2$ and $Ra_h = 1.53 \cdot 10^6$ for $A_c \approx 1$ in such way the air flow remains laminar. Results of the Fig. 2 show that the flow structures and the temperature fields in the different cells of the same building roof are practically similar. Indeed, it is shown a nearly repetitivity of the flow structures and the temperature profiles in the different hollow blocks. It can be seen also that, the flow nature and temperature distribution are significantly affected by the aspect ratio of the alveolar. In fact, natural convection in the hollow block of aspect ratio $A_c \approx 1/2$ is characterized by the formation of two adjacent cells circulating in opposite directions and symmetrical with respect the central vertical axis of the cavity. However, for the same temperature difference, the flow structure in the hollow block of aspect ratio $A_c \approx 1$, is characterized by a single cell. The concentration of the isotherms near the superior horizontal surfaces of the alveolar indicates an important gradient of temperature in these regions. This is due essentially to the motion of the fluid going up following the alveolar vertical axis. Toward the central and low parts of the cavities, the heat transfer is less important but has a very marked two dimensional character.



a



b

Fig. 2. *Streamlines (at the top) and isotherms (at the bottom) obtained for ΔT = 20 °C and for the aspect ratios: (a) $A_c \approx 1/2$; (b) $A_c \approx 1$*

As expected, in the solid partitions separating the hollow blocks (concrete joints). the stratification of the isotherms indicates the linear character of the conductive heat transfer through these partitions.

Heat transfer

In order to show the effect of the alveolar number *Nx* on the global heat transfer through the system, Fig. 3 presents the variation of the dimensional heat flux Q (W/m^2) crossing the structure as a function of the temperature difference ΔT for $A_c \approx 1/2$ and different values of *Nx*. The heat fluxes obtained for *Nx* = 3, 6, 9 and 12 by applying adiabatic boundary condition imposed on the vertical limits of the system (building floor) are compared to those calculated for *Nx* = 3 using the periodicity condition at the system vertical limits. Fig. 3 shows that the results obtained in the five considered situations are in very good agreement. Indeed, the observed difference on heat fluxes calculated for different values of ΔT and *Nx* are lower than 0,5 %. This result confirms the observations made in the previous paragraph when the analysis of the structures flow and the temperature fields has indicated a repetitively physical phenomenon in the different hollow blocks of the same building roofs.

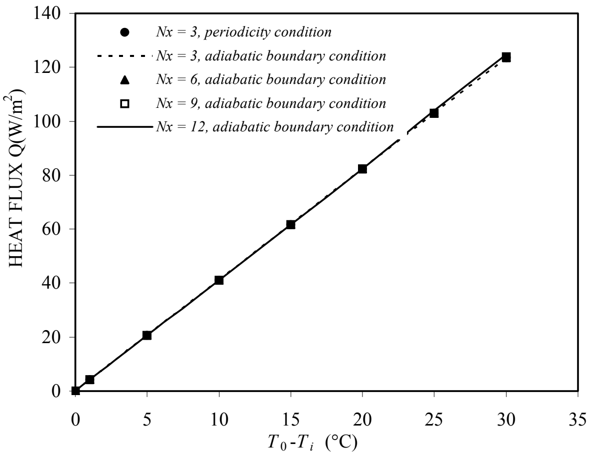


Fig. 3. *Effects of both alveolar number in the horizontal direction Nx and boundary conditions on the average heat transfer through the hollow block of aspect ratio $A_c \approx 1/2$*

The results established above are observed also for other alveolar aspect ratios. In fact, Fig. 4 presents the variations of the mean vertical heat flux Q (W/m^2) as a function of the temperature difference ΔT (°C) between the horizontal surfaces for $A_c \approx 1/4$, $A_c \approx 1/2$ and $A_c \approx 1$. This figure gives the results obtained for different values of *Nx*. It can be noted that, for each type of hollow block, the heat fluxes simulated in the different considered cases (*Nx* = 3, 6, 9 and 12) are in very good agreement. The maximal relative difference between the results obtained for the different values of *Nx* is lower than 0,7 %. Therefore the study of the entire system formed by *Nx* alveolar can be reduced with a very good approximation to that of hollow block with three alveolar

(Nx = 3). This approximation permits significant reduction in computational time especially in transient conditions where the latter becomes extremely high.

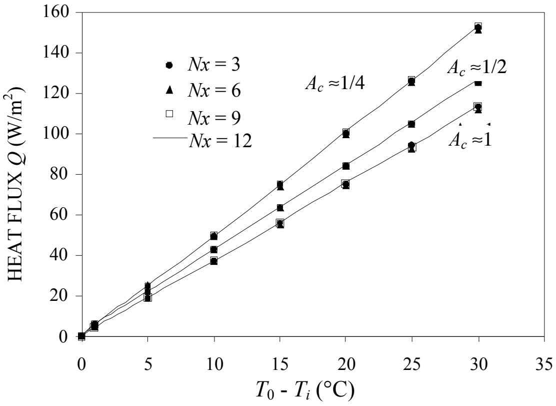


Fig. 4. *Variations of the global heat flux as function of the temperature differences ΔT for the three types of hollow blocks of aspect ratios $A_c \approx 1/4$; $A_c \approx 1/2$; $A_c \approx 1/4$ and different values of Nx*

Conclusion

The simulation results showed that the flow structures and the thermal behaviors in the different hollow blocks of a alveolar building roof are similar. For the different types of hollow block considered, the average heat flux crossing roofs that differ by the alveolar number Nx in the horizontal direction are practically the same. Therefore, the numerical simulation of the thermal behavior of the building roof can be reduced with a very good approximation to that of hollow block with three cells in the horizontal direction. This permits a considerable reduction of the computation time, especially in transient conditions where the latter becomes extremely important.

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