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Simulation of coupled heat transfers in a hollow tile with two vertical and three horizontal uniform rectangular cavities heated from below or above

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ABSTRACT

This paper presents a numerical study of the coupled heat transfers in hollow tile with two air cells deep in the vertical direction and three identical cavities in the horizontal one, uniformly heated from below or from above. The end vertical side walls of the structure are assumed to be adiabatic. The Boussinesq approximation is invoked and the flows are considered laminar and two-dimensional for the whole range of parameters considered. Conduction heat transfer in the solid partitions and radiation exchange between gray and diffuse surfaces are accounted for. The governing equations are solved by finite difference technique based on the control volume approach and the SIMPLE algorithm. Based on steady state simulation, the appropriate overall thermal conductances U' are derived for the two considered situations (heating from below and from above). The results show that the hollow block with two air cells deep in vertical direction permits a considerable reduction of heat transfer between the inside and the outside of the building roofs.

1. Introduction

An all-particular attention is carried to the hollow blocks owing to the thermal insulation and to the reduction of the expenses of heating and air-conditioning that they can procure. In general, in these structures when are submitted to the temperature difference, the heat transfers are coupled and done simultaneously by natural convection, conduction and radiation. Therefore, a better evaluation of heat exchanges through these structures necessitates a detailed study of the three processes of heat transfers. The majority of works carried out in this sense have been devoted to study the effects of conduction and/or radiation on natural convection in differentially heated cavities [1–4].

On the other hand, many theoretical, experimental and numerical studies have been focused on hollow blocks properties, which are in related to the thermal behavior of these systems, we can quote here some works [5,6]. Among these properties of hollow blocks, the overall thermal conductance (U-value, W/m^2 K) is the most important one since it allows simple (classical) buildings heat loss computations for engineers. Nevertheless, accurate prediction of this property for different hollow blocks is not a trivial task, as its value cannot be simply acquired by one-dimensional thermal transfer models. Consequently, there are strict rules in order to determine the overall thermal conductance (i.e. the U-value) or the thermal resistance (i.e. R-value, m^2 K/W) of hollow blocks walls [7–9]. In addition, most general building thermal analysis programs simplify the thermal problem by neglecting convection and radiation hat transfers and assuming one-dimensional heat flow through walls (TRNSYS [10] or CODYBA 6.0 [11]). As a result, it is not obvious to obtain precise assessments of heat loss through walls made of hollow blocks by means of classical building simulations codes.

Therefore, a detailed numerical study which taken account, at the same time, the two-dimensional conductive, convective and radiative heat transfers in concrete hollow blocks has been presented by Abdelbaki and Zrikem [12]. Among the effects which were examined in this study, there was the effect of cellular numbers in the two directions of heat transfer. Thus, by comparing the heat fluxes predicted for structures that differ by their number of cavities, the authors are concluded that the estimation of heat transfer through building walls consisting of hollow tiles can be reduced to a hollow tile with one air cells in the vertical direction. Also, based on the results of a detailed numerical simulation in transient state of coupled heat transfers through a differentially heated hollow clay tile with two air cells deep, Abdelbaki et al. [13]

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Nomenclature

A	aspect ratio of the hollow structure, H/L
A_c	aspect ratio of the inner cavity, h/l
dF	view factor between finite surfaces
dS	finite area (m^2)
E	incident radiative heat flux ($W\,m^{-2}$)
e_x	vertical partition thickness (m)
e_y	horizontal partition thickness (m)
G	temperature ratio, T_{out}/T_{in}
g	gravity ($m\,s^{-2}$)
H	structure height (m)
h	cavity height (m)
J	radiosity ($W\,m^{-2}$)
J'	dimensionless radiosity, $J/(\sigma T_{out}^4)$
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	structure depth (m)
l	cavity width (m)
N_k	thermal conductivity ratio, k_f/k_s
N_r	radiation to conduction number, $(\sigma T_{out}^4)H/k_s\Delta T$
Nu	Nusselt number
P	dimensionless pressure, $(p+\rho_0 gy)/\rho_0(\alpha_f/H)^2$
p	pressure (Pa)
Pr	Prandtl number, ν/α_f
Q_a	dimensionless average heat flux
Q	average heat flux, $(k_s\Delta T/H)Q_a$ ($W\,m^{-2}$)
$q_{r,k}$	net radiative heat flux at surface k ($W\,m^{-2}$)
$Q_{r,k}$	dimensionless net radiative heat flux at surface k, $q_{r,k}/(\sigma T_{out}^4)$
r	position on the cavity surface
r'	dimensionless position associated with r
Ra	Rayleigh number, $g\beta\Delta TH^3/\nu\alpha_f$
T	temperature (K)
ΔT	temperature difference, $(T_{out}-T_{in})$ if $T_{out}>T_{in}$; $(T_{in}-T_{out})$ if $T_{out}<T_{in}$ (K)
U,V	dimensionless velocity components in x and y directions, $(u,\ v)/(\alpha_f/H)$
U'	overall thermal conductance ($W\,m^{-2}\,K^{-1}$)
X,Y	dimensionless Cartesian coordinates in x and y directions, $(x, y)/H$
X_c	position on the internal horizontal face of a cavity
Y_c	position on the internal vertical face of a cavity
Y_0	position in y direction of the lower horizontal side of a cavity

Greek symbols

α	thermal diffusivity ($m^2\,s^{-1}$)
β	thermal expansion coefficient (K^{-1})
ε	cavity surface emissivity
η	dimensionless coordinate normal to a cavity surface
ν	kinematic viscosity ($m^2\,s^{-1}$)
ρ	fluid density ($kg\,m^{-3}$)
σ	Stephan–Boltzman constant ($W\,m^{-2}\,K^{-4}$)
θ	dimensionless temperature, $(T-T_{in})/\Delta T$
τ	dimensionless time, $t/(H^2/\alpha_f)$

Subscripts

a	above
b	below
conv	convection
f	fluid
in	inside
out	outside
rad	radiative
s	solid

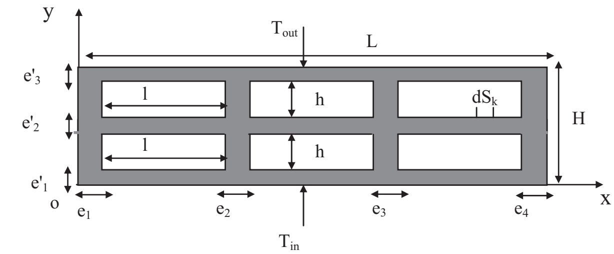

Fig. 1. Schematic diagram of a hollow tile with two air cells deep in the vertical direction.

have determined the overall thermal conductances from the empirical Transfer Function Coefficients (TFC) using an identification technique. The results have been presented for the hollow bricks which are widely used in the construction of the buildings vertical walls.

Lately, the previous study has been extended to the case of the hollow tiles with one air cell in the vertical direction, which mostly used in the construction of building roofs [14,15]. In these studies, it required the resolution of the problem of the coupling between the three heat transfer processes in alveolar structure vertically heated. Thus, the two situations have been considered: heating from below and heating from above. The considered hollow tiles had only one cell deep in the vertical direction.

In the practice, hollow block with two air cells deep in the vertical direction also exists. The numerical study of heat transfers coupled by conduction, natural convection and radiation in such new hollow block is the subject of the present work. Based on the simulation results, the overall thermal conductance has been determined and compared with the old values of the systems with a single cell in the vertical direction. These characteristic coefficients conductances are more interesting. Indeed, they permit fast and accurate estimation of heat exchanges through the building roofs without solving again the complex coupled equations governing the different heat transfer mechanisms.

2. Mathematical formulation

2.1. Studied configuration and governing equations

In the construction of buildings roofs, the used hollow tile has, in general, three cavities in the horizontal direction ($Nx = 3$) and in the maximum one or two cavities, in the vertical direction ($Ny = 1$ or 2). Fig. 1 is the sketch of the studied configuration. It is formed by two ranges of rectangular cavities of width l and height h surrounded by solid partitions. The top and bottom sides of the hollow tile are considered isothermal and are maintained at temperatures T_{out} and T_{in} respectively, while its vertical sides are considered adiabatic. In formulating governing equations, the problem is considered laminar and two-dimensional. 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 no participating to radiation and the cavities inside surfaces are considered diffuse-gray. The governing equations are written in dimensionless form as:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \quad (1)$$

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

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