International Journal of Heat and Mass Transfer 54 (2011) 533–548

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Nonlinear thermal analysis of multi-holed lightweight concrete blocks used in external and non-habitable floors by FEM

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ARTICLE INFO

Article history:
Available online 8 October 2010

Keywords:
External floors
Lightweight concrete
Finite element modelling
Nonlinear complex heat transfer
Energy savings
Thermal analysis
Multi-holed block

ABSTRACT

The aim of this current and innovative work is the numerical thermal analysis of multi-holed lightweight concrete blocks for external and non-habitable floors by the finite element method (FEM). Twelve different block designs with the same external dimensions 0.57 × 0.45 × 0.20 m were built varying the number of the horizontal intermediate bulkheads, from 3 to 12. Besides, five different compositions of the lightweight aggregate concrete (LWAC) and five different bulk temperatures have been taken into account, giving place to a total of 600 different floor configurations, 300 cases per each heat flow direction: upward and downward heat flows. A nonlinear thermal problem is solved for all cases analysed and then, it is possible to choose the best candidate block from the standard rule requirements. Mathematically, the nonlinearity due to the radiation boundary condition inside the inner recesses of the blocks is tackled by the matrix radiation method. Once the nonlinear thermal problem is solved, the temperature distribution is obtained and the thermal characteristic values of the floors, both for downward and upward heat flows, are calculated. From the numerical results, we can conclude that the main variables in the thermal performance are the total number of recesses and the material conductivities. Therefore, increasing the number of horizontal intermediate bulkheads and decreasing the material conductivities, the best thermal efficiency is obtained. The selection of the best candidate block of external floors and floors in contact with non-habitable spaces is carried out through the following parameters: the average mass overall thermal efficiency and the equivalent thermal conductivity. Finally, detailed instructions are provided in order to select the appropriate floor satisfying the standard rule requirements and conclusions of this work are exposed.

1. Introduction

In year 2050 new buildings will consume zero net energy from external power supplies and produce zero net carbon dioxide emissions while being economically viable to construct. Nowadays buildings consume about 40% of energy in developed countries. Consequently, an important effort for transforming the way in which buildings are designed, constructed and operated must be performed [1].

The new buildings require a combination of onsite power generation and ultra-efficient building materials and equipment. These 'green' buildings already are erected in various parts of the world but current cost structure prevents widespread adoption by builders. In this way, new standard rules for energy efficiency in buildings [2] and the use of new materials (such as lightweight aggregate concrete [3]) will be the starting point for the energy savings objective.

Lightweight aggregate concrete (LWAC) was used even before the Christian era. With time, because of the advantages of the LWAC, specifically its low density and thermal insulating properties, its demand has increased [3]. In recent years, it has become an important structural material in building construction [4]. This has led to the development of synthetic lightweight aggregates which are made from natural raw materials like clay, slate, shale, etc., and from industrial by-products like fly ash, slag ashes, etc. There are many types of lightweight aggregates of mineral origin, ranging from weights below 50 kg/m^3 up to heavy types of 1000 kg/m^3 or even more. They enable the production of concrete and mortars in very wide ranges with properties that will suit the requirements of different building industries [3,4].

Thermal behavior of the LWAC is related to its thermal conductivity and density which, in turn, is influenced by its pore structure: the air-void system, aggregates, and the matrix. Thus, the thermal conductivity will depend upon the pore structure of the

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doi:10.1016/j.ijheatmasstransfer.2010.09.016

Nomenclature

A	surface area of the body through which heat flows (m^2)
A_i, A_j	areas of surface i and surface j, respectively
CSI	climate severity index, dimensionless
t_r	thickness of the recesses in the vertical direction
$[F] = \begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix}$	conductivity matrix
t_f	thickness of the floor (m)
$e_{thermal\_p}$	mass overall thermal efficiency in percentage (m^2 K/W/kg)
G_{ji}	radiation view factors
h	heat transfer coefficient or film coefficient (W/(m^2 K))
h_r	radiation heat transfer coefficient (W/(m^2 K))
k_n	thermal conductivity of the material in normal direction at the surface (W/(m K))
k_x, k_y, k_z	thermal conductivities of the material in x, y and z-directions (W/(m K))
$[K^{ts}]$	effective conductivity matrix
M	mass (kg)
$\vec{n}$	unit outward normal vector
N	number of radiating surfaces
N_i, N_j	surface normal of dA_i and dA_j
$\vec{p}$	heat flux vector (W/m^2)
p^B	rate of heat generated per unit volume (W/m^3)
p^S	prescribed heat flux input on the surface (W/m^2)
p_x, p_y, p_z	heat flows conducted per unit area in x, y or z direction (W/m^2)
p^i	concentrated heat flow inputs (W/m^2)
p_i	energy loss of surface i
d	distance between differential surfaces i and j, m
R_{tot}	overall thermal resistance of the floors, taking into account the corrections due to moisture, holes, and film coefficients, (m^2 K/W)
R_{si}	internal surface resistance of the floor (m^2 K/W)
R_{se}	external surface resistance of the floor, (m^2 K/W)
S_θ	boundary on which the value of temperature is specified as $\theta_0(t)$ (Dirichlet condition)
S_p	boundary on which the heat flow p is specified (Neumann condition)
θ	temperature of the body or surface temperature (K)
θ_e	environmental or external radiative source temperature (K)
θ_i, θ_j	absolute temperatures at surface i and j, respectively (K)
θ^S	specified temperature at the surface S_θ of the model (K)
$\Delta\theta$	difference of temperature (K)
$\delta\theta$	an allowable virtual temperature ($\delta\theta(x, y, z, t)$)
U	overall heat transfer coefficient (W/m^2 K)
$U^{soil}_{ex\_floor}$	thermal transmittance of external soil floors (W/m^2 K)
$U^{roof}_{ex\_floor}$	thermal transmittance of external roof floors (W/m^2 K)
$U^{soil}_{nh\_floor}$	thermal transmittance of soil floors in contact with non-habitable spaces (W/m^2 K)
$U^{roof}_{nh\_floor}$	thermal transmittance of roof floors in contact with non-habitable spaces (W/m^2 K)
δ_{ji}	Kronecker delta
κ	radiation coefficient evaluated using absolute temperatures
σ	Stefan–Boltzmann constant (=5.67 × 10^{-8} W/m^2 K^4)
ε_i	emissivity of the surface (i), dimensionless and $\varepsilon \leqslant 1$
ρ	density of the material (kg/m^3)
λ	conductivity of the material (W/m K)
λ_{eq}	equivalent thermal conductivity (W/m K)
φ_i	angle between N_i and the radius line to surface dA_j
φ_j	angle between N_j and the radius line to surface dA_i

lightweight aggregates and the cement paste matrix. Air is one of the best insulating materials. It implies that the thermal conductivity of a dense LWAC (less the air voids) is more than that of the porous LWAC. Porosity and density are interrelated, the higher the porosity, the lower the density [3–5].

At present, there are some research works that provides a comprehensive treatise on the application of thermal analysis techniques (both experimental and numerical ones) for various types of construction elements applied to walls [4–9] and floors [10–14], but nowadays there are not many research papers about the numerical thermal behavior of multilayer floors and, specifically, there are not manuscripts about the thermal influence of the recesses in the multi-holed lightweight concrete blocks to be used in external and non-habitable floors.

The new CTE-Spanish Building Standard Code [2] establishes the requirements of thermal insulation of the building's walls, floors, envelopes and so on. Moreover, the CTE rule limits the energy demand of buildings depending on the climatic zones, both in winter and in summer seasons. There are five different climatic zones in winter (A, B, C, D and E) and four in summer (1, 2, 3 and 4), according to CTE Spanish standard rule [2].

In order to avoid decompensations between the thermal qualities of different rooms, each one of external floors and floors in contact with non-habitable spaces, the thermal envelope should have a transmittance lower than the values shown in Tables 1 and 2.

The actual possible locations of the external floors and floors in contact with non-habitable spaces are show in Fig. 1 for a typical building. This figure also indicates the possible directions of thermal flows between the building and the external ambient. In Spanish buildings, both for industrial and housing, the most common floor used is the multilayer one-way slab (see Fig. 2) and, consequently, this work is applied to the thermal study in detail of this type of external floors and floors in contact with non-habitable spaces.

Table 1
Maximum thermal transmittance of external floors.

Climatic zone	Thermal transmittance of soil floors $U^{soil}_{ex\_floor}$ [W/m^2 K]	Thermal transmittance of roof floors $U^{roof}_{ex\_floor}$ [W/m^2 K]
A3 and A4	0.53	0.50
B3 and B4	0.52	0.45
C1, C2, C3 and C4	0.50	0.41
D1, D2 and D3	0.49	0.38
E1	0.48	0.35

Table 2
Maximum thermal transmittance of floors in contact with non-habitable spaces.

Climatic zone	Thermal transmittance of soil floors $U^{soil}_{nh\_floor}$ [W/m^2 K]	Thermal transmittance of roof floors $U^{roof}_{nh\_floor}$ [W/m^2 K]
A1–A4	0.69	0.65
B1–B4	0.68	0.59
C1–C4	0.65	0.53
D1–D4	0.64	0.49
E1–E4	0.62	0.46