EXPERIMENTAL AND NUMERICAL ANALYSIS OF HEAT TRANSFER IN THE CAVITIES OF HOLLOW BLOCKS

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SUMMARY

Given the importance of the assessment of the insulation performance of the building envelope in the context of energy certification of buildings, a detailed analysis of the reliability of the methods of evaluation of heat transfer in the air cavities of hollow blocks has been carried out.

An experimental study was conducted in the laboratory. Heat transfer measurements on specimens with parallelepiped cavities were done, through a guarded hot plate device according to UNI EN 12664. A numerical analysis of the heat transfer in the specimens through the software ANSYS FLUENT was carried out.

The analysis of the numerical and experimental results when compared with the predictions obtained from simplified models of technical standards, have called attention to the order of magnitude of the calculation accuracy obtainable with such procedures. For some geometric configurations and boundary conditions, the application of the standards can lead to large errors of evaluation of the thermal resistance of the cavity.

1. INTRODUCTION

In building constructions, air cavities in a solid matrix are used to increase the thermal resistance with a simultaneous decrease of apparent density of the structure.

A large number of studies were conducted, either experimentally or through numerical simulations, on the heat transfer in air cavities of different shapes.

Boundary conditions as imposed flux or known temperature were considered. A comparison between the experimental results and a numerical simulation model has been reported in [1], for a configuration of the cavity surrounded by conductive solid walls.

The presence of the thermal conduction in the boundary walls influence the convective motion inside the cavity, lowering the velocity of the internal fluid. The direct radiation between the inner surfaces of the cavity helps to reduce the movement of air through a more uniform distribution of the surface temperatures.

A numerical study on natural convection in a square cavity surrounded by thin vertical porous walls is reported in [2]. The main effect of the porous layers is the reduction of vertical upward flow and a consequent reduction of the convective heat exchange.

A numerical study on the transmission of heat in two dimensions in structures with cavities used in building construction has been reported in [3]. The heat transfer in the building walls of hollow blocks with various number of air cavities in the heat flux direction has been studied.

The effects of conduction in the boundary walls and of the radiation between the inner surfaces in the condition of natural convection in two-dimensional cavities of rectangular shape are reported in [4]. The convection in the cavity is attenuated by thermal conduction in the boundary walls and by the radiative heat exchange among the inner surfaces.

Natural convection is very sensitive to the configuration of the cavity and to the boundary conditions [5]; therefore it is desirable that the numerical results are validated by experimental measurements.

A simplified analytical method for the assessment of the heat transfer in hollow blocks with vertical perforations has been proposed in [6]. The author claims to be in good agreement with previous experimental measurements.

Standard methods reported in various national and European technical standards are often used for technical calculations of sufficient accuracy.

UNI EN ISO 6946 [7] reports a procedure for the calculation of heat transfer in ventilated and non-ventilated air cavities.

UNI 10355 [8] reports a procedure for the numerical calculation of the thermal resistance of walls and roofs, and in particular for the estimation of the thermal resistance of air cavities. The heat transfer in the cavity, due to convection and radiation, is modeled as an equivalent thermal conduction that gives rise to the same heat flux transfer as in the real cavity.

The results of a numerical Finite Differences Model (2D) for solving the system of differential equations that describe the combined transport by conduction, convection and radiation in air cavities bounded by conductive walls are reported in [9].

The thermal behavior of the walls of hollow blocks has been studied in [10, 11] also from the point of view of the interaction between temperature and humidity in the presence of air cavities.

A study to optimize the thermal performance of hollow blocks with low-emissivity coatings on the inner surfaces of the cavity is reported in [12].

2. EXPERIMENTAL MEASUREMENTS

The hollow blocks can be installed in two ways: in either with vertical perforations or with horizontal perforations.

Depending upon the position of the blocks the air cavities have different height-to-thickness and width-to-thickness ratios. These ratios affect the convective heat transfer but also the radiation through the cavities.

At the Laboratory of Technical Physics of the University of Politecnico di Bari, measurements of thermal resistance of specimens with air cavities of parallelepiped shape have been carried out. The measurements were done on a guarded hot plate equipment according to UNI EN 12664 [13]. The device has an exchange section 50x50 cm^2 with a central metering area 25x25 cm^2. Measurements were done with central hot plate in vertical arrangement. A specimen was put on the right and one to the left and finally the cold plate containment tightened to close the package with the minimum pressure required by the technical standard.

Measurements were carried out in stationary thermal conditions with uniform distribution of surface temperatures. The heat flux, generated in the central zone, crosses the two specimens and is discharged in the heat sink made up by two end plates chilled by circulating cold water at constant temperature. The measurement of heat flux (*q*) is carried out through the measurement of voltage and current (direct current) supplied to the electrical resistance in the central area of measurement.

In order to deepen the thermal behavior of the air cavity bounded by solid material, it was considered necessary to use specimens constructed in the laboratory by sheets of PVC foam that allow partitions of reduced thickness and plain and parallel walls.

The sheets of PVC foam had a thickness of 2 mm and the specimens were manufactured by inserting between two square plates (50x50 cm^2) transverse partitions equally spaced so as to achieve cavities with rectangular transverse section (Fig. 1).

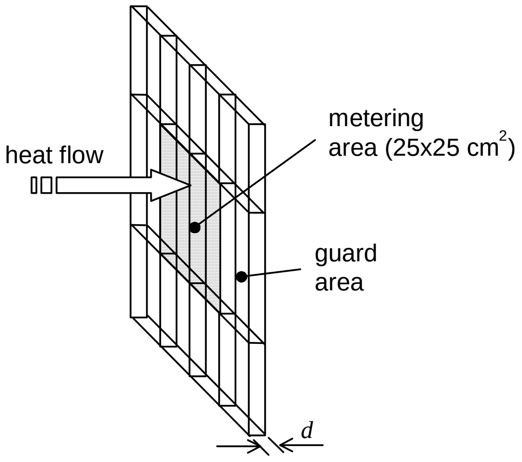

Fig. 1 – Schematic of the specimen of PVC foam (50x50 cm^2)

Pairs of specimens with a thickness of 1, 3 and 5 cm were built up. The other dimensions of the air cavity were 24.2 cm in height and 3.28 cm in width. The value of the height is limited by the size of the metering area of the apparatus, but in any case it is close to the one which is the normal size of cutting brick blocks. The width has assumed a value in order to have a whole number of cavities inside the metering zone of the apparatus.

The thermal conductivity of PVC was measured with the same apparatus and was found to be 0.077 W/(m·K), while the hemispherical emissivity was assumed equal to 0.9 according to [14].

From the measurement of heat flux transmitted (*q*) and temperature difference on the hot and cold sides of the specimen, the thermal resistance of the specimen was found:

$$R = \frac{\Delta T}{q} \tag{1}$$

From a series-parallel resistances model of the structure PVC-air cavities, the thermal resistance of the air cavities was estimated.

Measurements of the thermal resistance was carried out with thermal conditions corresponding to an average temperature of 288 K and a temperature difference between the two faces of the specimen (hot and cold sides) equal to 4, 6 and 10 K respectively.

Results are shown in Fig. 2.

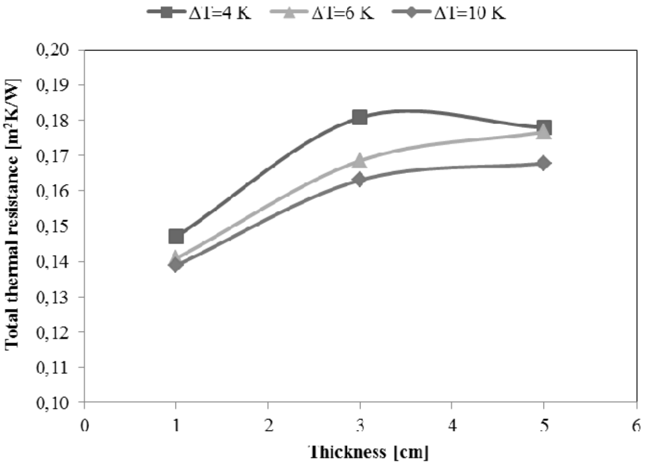

Fig. 2 – Experimental results. Thermal resistance of the air cavities.

3.CALCULATION MODELS

3.1 CFD

A numerical analysis of the heat transfer in the specimens through the software ANSYS FLUENT [15] has been carried out. The simulation was done in a 2D section of the specimen at the centerline of a cavity, with the boundary conditions reported in Fig. 3.

A heat transport by natural convection with fluid motion activated by the variation of density with temperature, under the action of gravity, has been modeled in the cavity. The air flow is laminar ($Ra \ll 10^8$). A stationary, double precision and pressure-based solver with a SIMPLE scheme was used in order to segregate the pressure-velocity coupling.

The heat transfer by radiation into a cavity of N gray-diffusive surfaces, with emissivity ε_k, area A_k, temperature T_k (k=1,..,N), is computable from the following system of equations [16, 17]:

$$\{Q\} = [B]^{-1}\{C\} \tag{2}$$

Where, $\{Q\}$ is the column-matrix of the radiation fluxes, $\{C\}$ is a column-matrix with $C_k = \sum_{j=1}^{N}\left(\delta_{kj} - F_{kj}\right)\sigma T_j^4$ and $[B]$ is the matrix of coefficients with $B_{kj} = \left(\frac{\delta_{kj}}{\varepsilon_j} - \frac{F_{kj}\left(1-\varepsilon_j\right)}{\varepsilon_j}\right)\frac{1}{A_j}$, where δ_{kj} is the Kronecker's delta.

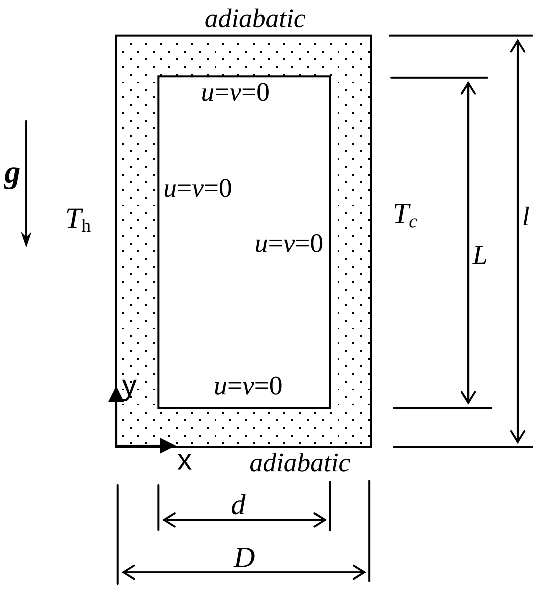

Fig. 3 – Coordinate system and boundary conditions.

Fig. 4 – Temperature (left) and velocity (right) for 5 cm thick cavity, ΔT=10 K, T_m=288 K.

Fig 4 shows the solution obtained for the cavity of 5 cm thickness with ΔT=10 K.

This approach requires the calculation of the black body view factors (F_{kj}, k = 1, ... N, j = 1, ... N) between all pairs of surfaces that face into the cavity. This method corresponds to what in FLUENT is called “S2S method” (surface-to-surface).

If the computational domain has more than one cavity, the method S2S is not usable. So the method DTRM (Discrete Transfer Radiation Model) was selected, which uses a ray-tracing technique to assess the exchange of radiation in the cavity [15].

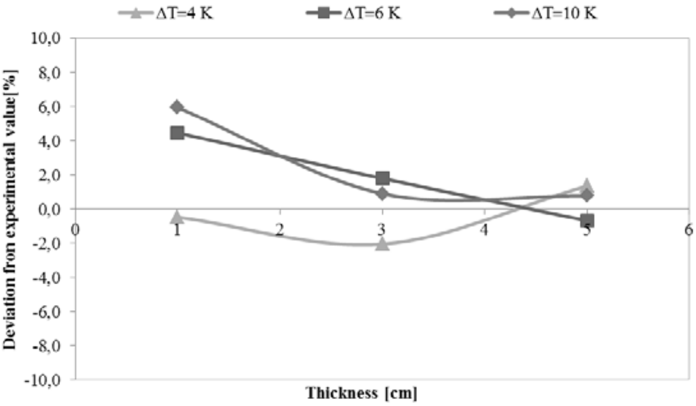

Fig. 5 – Deviation (%) of the thermal resistance of the cavity evaluated with FLUENT 2D versus the experimental value.

A radiative heat transfer coefficient on the hot surface of the cavity is calculated, as:

$$h_r = \frac{q_{mean,rad}}{\Delta T} = \frac{\frac{1}{L}\int_0^L q_{rad}\ dy}{\Delta T} \tag{3}$$

and a convection heat transfer coefficient as:

$$h_a = \frac{q_{mean,tot} - q_{mean,rad}}{\Delta T} = \frac{\frac{1}{L}\int_0^L q_{tot}\ dy - \frac{1}{L}\int_0^L q_{rad}\ dy}{\Delta T} \tag{4}$$

The total thermal resistance of the cavity was calculated as:

$$R = \frac{1}{h_a + h_r} \tag{5}$$

The percentage deviation of the thermal resistance value of the cavity evaluated with FLUENT 2D versus the measured value is reported in Fig. 5.

The result is within the range of the estimated error for the experimental measurement (7%).

3.2 UNI EN ISO 6946

For vertical air cavities (horizontal heat flux) the standard UNI EN ISO 6946 proposes two calculation methods depending on the type of cavity:

1) Air layer of width b (Fig 6) larger than 10 times the thickness d;
2) Air void with b<10 d.

In both cases, the thermal resistance of the air cavity is calculated through the relation (5).

For unventilated cavities the convection coefficient (h_a), in both cases, is given by:

$$h_a = \max\left(1.25; \frac{0.025}{d}\right) \quad \text{per } \Delta T \le 5K \tag{6}$$

$$h_a = \max\left(0.73\left(\Delta T\right)^{1/3}; \frac{0.025}{d}\right) \quad \text{per } \Delta T > 5K \tag{7}$$

Instead, the radiation coefficient is given by:

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \quad \text{se } b \ge 10\ d \tag{8}$$

$$h_r = \frac{h_{r0}}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 2 + \frac{2}{\left(1 + \sqrt{1 + \frac{d^2}{b^2}} - \frac{d}{b}\right)}} \quad \text{se } b < 10\, d \qquad (9)$$

with $h_{r0} = 4\sigma T_m^3$, ε_1 and ε_2 hemispherical emissivity of the hot and cold surfaces of the cavity, $\sigma = 5.67 \cdot 10^{-8}\ \frac{W}{m^2 K^4}$ Stefan-Boltzmann's coefficient, $T_m = (T_1 + T_2)/2$ mean temperature (K).

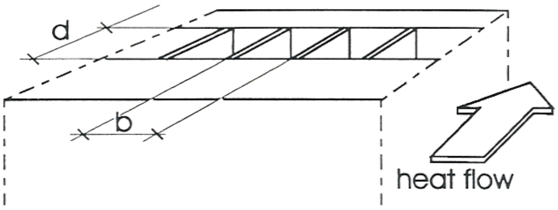

Fig. 6 – Dimensions of the air cavity (UNI EN ISO 6946).

3.3 UNI 10355

The Italian standard UNI 10355 [8] proposes a method for the calculation of the thermal resistance of the cavity under the combined effect of convection (h_a) and radiation (h_r) with air transparent to the radiation. The exchange by radiation is evaluated considering the cavity as a space between two flat plates, parallel and indefinite at a distance equal to the thickness of the cavity, i.e. the dimension in the direction of heat flux. If d is the thickness of the cavity in the direction parallel to the prevailing direction of the heat transfer, it follows that:

$$R = \frac{1}{h_a + h_r} \qquad (10)$$

where,

$h_r = \frac{h_{r0}}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$;

$h_a = \frac{Nu \cdot \lambda}{d}$;

λ = 0.025 W/(m K) is the thermal conductivity of the still air;

$Nu = 1 + 0.014\ Ra^{0.39} \left(\frac{L}{d}\right)^{0.18}$ is the Nusselt number for vertical cavity (horizontal heat flux);

L is the cavity height;

$Ra = \frac{d^3 \rho\ \beta\ g\ \Delta T\ c_p}{\mu\ \lambda}$ is the Rayleigh number;

ΔT is the temperature difference between the two surfaces, the hot and the cold one, facing into the cavity.

4. RESULTS FOR PVC SPECIMENS

The percentage deviations of the thermal resistance values calculated by the two standards compared to the value measured experimentally are reported in Fig. 7 for $\Delta T = 4\ K$.

The first model (UNI 10355) makes a conservative estimate (-10%) of the resistance to the smaller thickness (1 cm) at a temperature difference of 4 K. The second model (UNI EN ISO 6946) shows the maximum error (+8%) for the intermediate value of the thickness (3 cm) and temperature differences of 6 and 10 K.

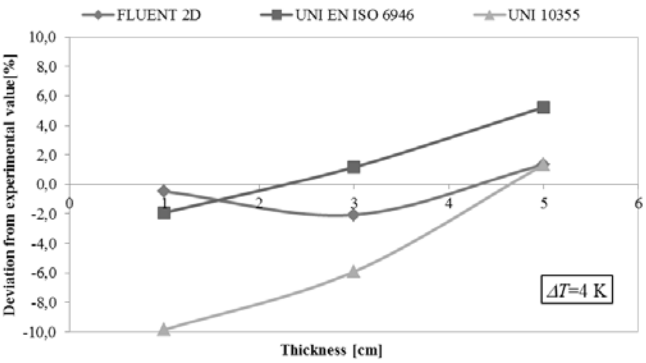

Fig. 7 – Deviation (%) the thermal resistance compared to the experimental measurement, ΔT=4 K.

The trend of the percentage deviations leads to think of a fault that could be in the models of the technical standards. Unfortunately it is not easy to determine whether the problem is in the model for calculating the contribution of the convective or radiative or both.

5. AIR CAVITIES IN HOLLOW BRICK BLOCKS

According to the results obtained it was decided to deepen the analysis by studying different geometries of air cavities separated by webs. Typical geometry of the blocks installed with horizontal perforations and with vertical perforations have been studied, considering some values of mean temperature and of temperature difference on the faces normal to the heat flux direction. The case studies here analyzed are shown in Table 1. The boundary walls of the cavity were supposed to be of brick with 5 mm thickness, thermal conductivity 0.41 W/(m K) and emissivity 0.9.

	b [cm]	d [cm]	L [cm]	T_m [K]	ΔT [K]
Vertical perforations	2	2	24.5	275	2.5
	4	4		285	5
	5	5		295	7.5
	6	6			
Horizontal perforations	2	2	24.5	275	2.5
	4	4		285	5
	6	6		295	7.5

Tab. 1 – Geometry and boundary conditions.

The reference solution was obtained with FLUENT 2D, modeling the radiation in the cavity with the DTRM method and the convection as in laminar regime. The boundary conditions are those summarized in Fig 3.

5.1 INSTALLATION WITH VERTICAL PERFORATIONS

The percentage deviations of the values of total resistance of the cavity (R) are reported in Figures 8.

Actually, both from the point of view of the convection and from that of the radiation, the most influential dimension should be the height L of the cavity. In order to test this, we redid the calculation according to the standards by using the ratio L/d in place of b/d.

Results, in terms of deviation from the 2D calculation, are shown in Figures 9.

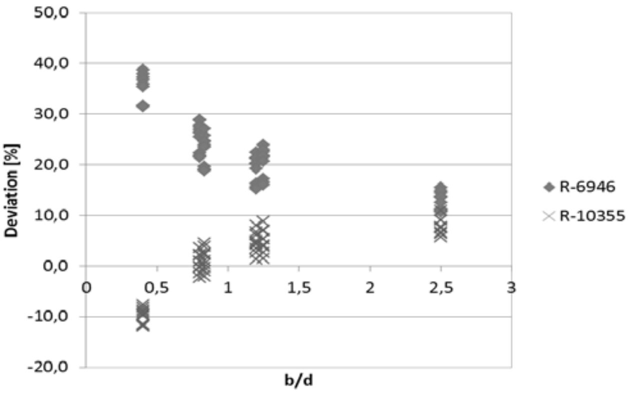

Fig. 8 – Deviation (%) of the value of total thermal resistance calculated by the standards, versus the ratio *b/d*.

Two faults are evident in the standards: 1) the model of radiation exchange of UNI EN ISO 6946 is lacking for low values of *b*/*d* (i.e. lesser width and greater thickness), a deviation of 30% was detected for *b/d*=0.4; 2) the model of convection exchange of UNI 10355 does not give an acceptable estimate of the exchange for all values of *b*/*d* (for very narrow cavity overestimates the convection, +29.7% for *b/d*=0.4, and for the other underestimates it, -39% for *b/d*=1.2).

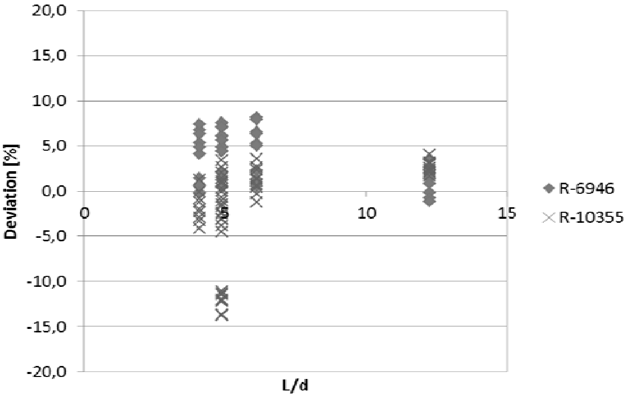

Fig. 9 – Deviation (%) of the value of total thermal resistance calculated by the standards, versus the ratio *L/d*.

It is confirmed that in the calculation of the radiation according to the UNI EN ISO 6946, the dimension that must be correlated to the thickness of the cavity is the greatest dimension of the isothermal faces normal to the heat flux direction. Furthermore, an imprecision of the convection calculation with UNI 10355 is evident for *L/d*=5 (+40%).

5.2 INSTALLATION WITH HORIZONTAL PERFORATIONS

In this mode of installation the largest dimension of the cavity is horizontal and coincident with the cutting length of the block. In Fig. 10 the percentage deviations of the total resistance *R* are shown.

Even in this case, faults are evident in the standards: 1) the model of radiation exchange of UNI 10355 is lacking for low values of *b*/*d*, +92% for *b/d*=0.5; 2) the model of convection of UNI EN ISO 6946 it overestimates the exchange for lower *b*/*d*, +32% for *b/d*=0.5, and underestimates it for higher values, -43% for *b/d*=2.

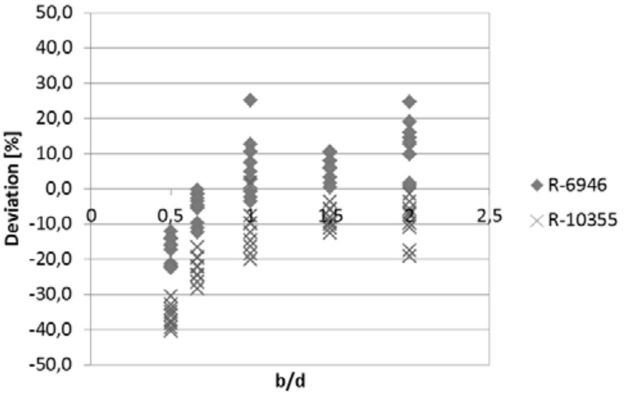

Fig. 10 – Deviation (%) of the value of total thermal resistance calculated by the standards, versus the ratio *b/d*.

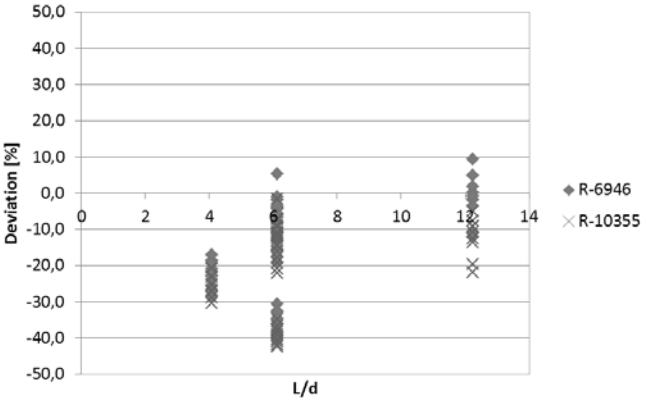

Fig. 11 – Deviation (%) of the value of total thermal resistance calculated by the standards, versus the ratio *L/d*.

The question arises, even in this case, whether the ratio *L*/*d* could not be the most suitable in the models of the standards.

The percentage deviations of calculation models versus the ratio *L/d* are reported in Figures 11.

It is evident a still large discrepancy between the actual convection and radiation exchange and the estimate of standards.

Looking at the distribution of temperature and air velocity in the cavity with *b* = 2 cm and *d* = 4 cm (Fig. 12) it is evident an asymmetry of temperature distribution on the horizontal walls that could have a major influence on the real heat exchange by radiation. The standards, in such a configuration, fail to model the real heat exchange.

Considering a wall of hollow blocks that are installed with horizontal perforations and the cavity of the type above described (results in Table 2), we can see how an approximate evaluation, according to the technical standards considered, leads to underestimate the thermal resistance of the wall with very important consequences.

Starting from a wall with thermal transmittance equal to the max value admitted by national law (Decree 311-06) of 0.4 W/m^{2}K, typical of the climatic Zone C, the calculation according to UNI 10355 would lead to a thermal transmittance of order 0.62 W/m^{2}K. That is, it would be an obvious problem for the proper evaluation of energy class of the building.

This estimation was done in a first approximation by assuming a wall of hollow blocks with 9 cavities of the type shown in Table 2 put in series in the heat flux direction.

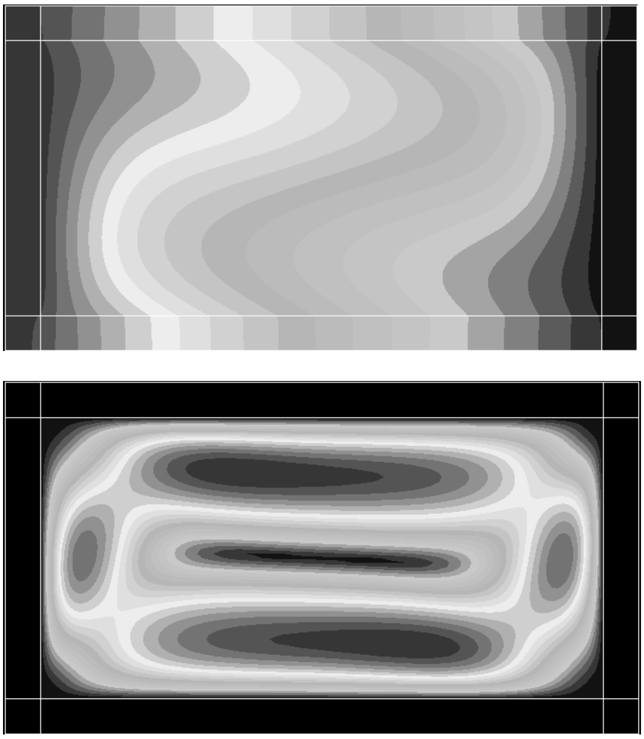

Fig. 12 – Temperature (top) and velocity (bottom) in the cavity with *b*=2 cm and *d*=4 cm. (T_m =295 K, Δ*T*=7,5 K.

	FLUENT 2D	UNI EN ISO 6946	UNI 10355
R(b/d)	0.259	0.218	0.169
R(L/d)		0.170	0.160
$h_a(b/d)$	1.349	1.429	1.168
$h_a(L/d)$		1.429	1.478
$h_r(b/d)$	2.507	3.164	4.764
$h_r(L/d)$		4.467	4.764

Tab. 2 Results for cavity with *b*=2cm, *d*=4 cm, *L*=24.5 cm, *Tm*=295 K, Δ*T* =7,5 K.

CONCLUSIONS

The thermal resistance of the cavity is routinely calculated in accordance with UNI EN ISO 6946 or UNI 10355. The experimental and numerical investigation carried out has pointed out that the use of the standards for estimating the thermal resistance of the air cavities can lead to large errors in some geometric configurations and boundary conditions.

For example, for cavity into hollow brick blocks installed with horizontal perforations, the thermal resistance could be underestimated in the order of 40%.

The error in estimating the thermal resistance of the single cavity affects significantly the assessment of the overall thermal performance of the wall of hollow blocks.

That is an extremely serious matter if one thinks of the importance of "certifing" the thermal transmittance values compared with the legal limits on the certification of energy performance, as well as the importance that the energy class of the building has from the point of view of its economic value, and from the point of view of the energy consumption estimate to achieve good indoor climate control.

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