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# Experimental and numerical thermal assessment of Lebanese traditional hollow blocks

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## Abstract

Hollow-core concrete blocks constitute the main method of construction for vertical walls in Lebanon where almost all walls are masonry and use the same block shape. The detailed investigation of the main parameters involved in the heat transfer in these blocks is thus of great importance for analyzing and understanding them and providing recommendations for their improvement.

This paper offers an experimental and numerical analysis of heat performance the Lebanese concrete hollow block. After validating the numerical model by comparing it to experimental results, a deep and detailed analysis is done for understanding the complexity of heat transfer phenomena inside the block. Then a parametric study is performed to understand the effect of various parameters on the overall thermal resistance of the block, these parameters include the concrete solid mixture, the cavities infill material, and the geometry configuration of the block.

## Keywords

Hollow block, heat modelling, buoyancy in cavities, thermal resistance, heat flow

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## **Introduction**

Energy savings in the building sector offer untapped potential in Lebanon because of the lack of national policies aimed at the energy efficiency of buildings on the one hand, and the lack of knowledge of good practices and know-how on the other.

Concrete hollow blocks offer a number of advantages compared solid blocks in terms of weight, thermal insulation, and acoustic insulation. Many research studies aim at developing new hollow blocks with improved thermal properties (Caruana et al. 2014).

In emerging countries such as Lebanon, concrete hollow blocks are widely used due to their advantages such as lifespan, low cost, low maintenance, fire resistance, and simplicity in implementation. The Lebanese buildings are characterized by their reinforced concrete structures and their vertical walls in single or double wall block masonry. This mode of construction dominates although new technologies have difficulty finding a place in this sector characterized by its high resistance to modifications because of the low-skilled labor force and the low costs of the materials currently used in this sector. The thermal performances of these walls remain until now unknown for lack of scientific thermal characterization method at different scales (material, wall, building, etc.).

The ever growing international concerns related to energy and resource conservation have led to many scientific and industrial efforts towards the improvement of masonry units in order to meet energy saving requirements. However, these changes cannot occur without understanding the detailed thermal behavior of these units and their thermo-physical properties.

Many authors studied the influence of hollow blocks configuration on their thermal performance. (Xamán et al. 2017) studied the thermal performance of four different configurations of hollow block materials for roofing in Mexico using a numerical approach based on the finite-volume method. The results showed the advantage of using the combination of insulating material and reflective coating on roofs with hot climates. (Urban et al. 2011) investigated different commercially available Concrete Masonry Unit (CMU) geometries and concrete mixtures using finite difference modeling to show their impact on R-values using six basic CMU shapes. (Fogiatto et al. 2016) determined the best cavity configuration for predefined external dimensions providing the best thermal resistance by examining 10 different block configurations using the software ANSYS®; the contribution of each heat transfer mode was also evaluated. (Coz Diaz et al. 2009) performed a numerical thermal analysis to optimize the thermal performance the lightweight hollow block design for internal floors using the finite element method. The number

the vertical and horizontal intermediate bulkheads were varied to create five different configurations with constant external dimensions (57 cm x 25 cm x 20 cm). Five different lightweight concrete mixtures have also been studied. The results showed that the main parameters influencing the thermal performance were the number of the horizontal intermediate bulkheads and thermal conductivity of the mixture. (Kus et al. 2012) conducted an experimental hygrothermal performance study on pumice aggregate concrete blocks by measuring temperature and humidity at the surfaces of the test wall and in the hollows of blocks. (Wang et al. 2017) found that modifying the thermal properties of hollow block walls used for solar greenhouses by filling soil and perlite in their cavities led to improving their thermal performance by increasing their thermal capacity and increasing their thermal resistance. (Zhang et al. 2014) used numerical and experimental approaches to evaluate the thermal resistance, decrement factor, and time lag of a hollow block wall. They found that the main factors influencing thermal performance, ranked in descending order, were: decreasing the thermal conductivity of block material, increasing the thermal capacity of block material, decreasing the equivalent thermal conductivity of the material inside holes, increasing block thickness (accompanying the increase of hole spacing), and increasing hole rows (maintaining small hole thickness).

Many studies discussed the potential of thermal, and/or mechanical improvement of building blocks by using recycled waste materials in the concrete mixture. (Xu et al. 2019) studied experimentally the effect of fibers content on the physical properties of autoclaved aerated concrete. He found that adding wood fibers into AAC was better than adding of polyester fibers. Increasing wood fibers content also led to increasing volume density and thermal conductivity, as well as increasing the mechanical properties and particularly the flexural strength. The Scanning Electron Microscope (SEM) observations revealed that the reinforcing mechanism of wood fiber was a physical interaction. (Caruana et al. 2014) provided an overview of testing methodologies for thermally improved hollow core concrete blocks by discussing testing methodologies for the load bearing as well as thermal characterization of hollow concrete blocks. (Caruana et al. 2017) also investigated the thermal properties of a new building block aiming at improving its thermal properties without compromising their compressive strength, physical dimensions or manufacturing process. Measurement techniques were applied to obtain comparative values of the thermal transmittance for standard and improved HCBs, using different EN and draft standards. (Fraile-Garcia et al. 2018) examined the thermal behavior of light concrete construction elements made with different amounts of rubber particles (0%, 10% and 20%) extracted from end-of-life tires. Three different closed test cells were built and subjected to several heating/cooling periods. The recordings of the temperature inside the cells and inside

their enclosures (walls, ceilings, floors) showed that the thermal behavior depended on the percentage of rubber particles. (Meng et al. 2018) provided a review on the use of various kinds of wastes (i.e. recycled concrete, crushed brick, soda lime glass, cathode ray tube glass, crumb rubber, ceramic and tile waste, etc.) in the production of concrete blocks. The results underlined a good potential for incorporating wastes as aggregate in concrete blocks without compromising the compliance of concrete blocks with standard requirements. (Mohammed et al. 2011) evaluated miscellaneous physical properties (compressive strength, thermal conductivity, acoustic absorption and transmission loss, and electrical resistivity) for crumb rubber hollow concrete blocks (39 cm x 19 cm x 19 cm) using different amounts (0%, 10%, 25% and 50%) of crumb rubber for replacing fine aggregates. (Zhu et al. 2015) defined an influence coefficient “c” for better explaining the effect of recycled concrete aggregate (RCA) on thermal conductivity of the recycled aggregate concrete (RAC). A modified formula for calculating the thermal conductivity of RAC based on that of normal concrete was also proposed. The results showed that the recycled coarse aggregate has the greatest influence on thermal conductivity of RAC.

This paper presents an experimental and numerical detailed description of the thermal performance of Lebanese traditional hollow block. The particularity of these blocks resides in their particular circular and elliptical hollow shapes.

After validation of the cavity and block thermal numerical models, the heat thermal transfer inside the block is determined numerically by assessing the influence of each heat transfer mode in this process.

An experimental validation of the model as well as a thermal characterization of the concrete solid matrix is performed in the lab using the Heat Flux Method.

Once the numerical model of the heat transfer in the block is validated, the improvement of the thermal behavior of the block is discussed based on three main parameters: the concrete mixture thermal conductivity, the air gaps infill with insulation materials, and the blocks internal shape (bulkheads configuration).

## **Experimental aspect**

### **Hollow blocks manufacture in Lebanon**

Masonry hollow block is nowadays the most used construction technology in the Lebanese context. These blocks are manufactured in a traditional craft way with unknown thermal properties.

In order to understand the specificities and manufacturing method of cinderblock in Lebanon, a case study for an industrial plant in Deir Shomra, Kesrouane in Mount-Lebanon is described in the following section. The site is located at the bottom of a valley.

The blocks mixture consists of small size aggregates (25% of total aggregate volume) and powdered aggregates (75% of the total aggregate volume). The aggregates are dosed using a container that contains 200 liters which is filled 5 times to form 1 m<sup>3</sup> of aggregates. 50 kg of cement are added to the aggregates (1 m<sup>3</sup>) from a silo and weighed using a hand-crafted system. Finally, 50 liters of water are added using a bucket of capacity 20 liters (2.5 full).



**Figure 1- Aggregate, cement, and water dosing**

The whole is mixed using a mechanical mixing system and the mixture is then transported with a large wheelbarrow to the various artisans working on in-line production presses.



**Figure 2- Work area of the craftsman and mold**

The 10 cm blocks are currently the most requested. Each mold can simultaneously manufacture two blocks as shown in Fig. 2.

After their manufacture, the blocks are watered twice: the night of the same day and the next morning.

In sunny season (April - October) the blocks can be delivered two days after their manufacture, while in cold season this can last between 3 and 4 days so that the blocks dry and take their mechanical properties.



**Figure 3- Storage and drying of the blocks**

## Experimental measurements

### *Experimental setup and samples*

In this part the aim will be to evaluate the thermal performances of the concrete hollow blocks used in the Lebanese constructions.

Two samples were investigated, the first one consisting of half a hollow block (20cm x 20cm x 10cm), and the other sample prepared by gluing two flat concrete pieces from the same mixture to have a thickness of 55 mm (Fig. 4).



**Figure 4- Experimented samples of the hollow block (left) and the solid mixture (right)**

Two experimental measurements were realized, the first one determining the thermal properties of the concrete mixture and the second one the equivalent thermal properties of the concrete block (including the cavities).

A thermal characterization device of construction materials will determine the thermal properties (thermal resistance and equivalent thermal conductivity) of the concrete hollow blocks.

The guarded hot plate method was considered for the experimental thermal characterization of the sample (Fig. 5). An imposed temperature change on each face of the sample is set and simultaneous measurements of the temperature and exchanged heat flux variations during heating and cooling processes allow the determination of the thermo-physical properties of the sample, namely the thermal conductivity  $\lambda$  and the specific heat capacity  $c_p$  (Younsi et al. 2011).



**Figure 5- Thermal characterization device for building materials**

### ***Characterization method***

#### a.) Thermal conductivity

The heat flux and the temperature on both sides of the sample are measured simultaneously. The application of Fourier's law for a unidirectional steady state heat transfer gives:

$$\varphi_1 = \frac{\Delta T}{R} \text{ and } \varphi_2 = \frac{\Delta T}{R} \quad (1)$$

The use of the generalized quantities  $\Sigma\varphi$  and  $\Delta T$  makes it possible to write:

$$\Sigma\varphi = 2 \frac{\Delta T}{R} \quad (2)$$

The advantage of using the generalized quantities  $\Sigma\varphi$  and  $\Delta T$  lies in the reduction of the measurement time. In fact, Fig. 6 shows that the sum of the heat fluxes ( $\Sigma\varphi$ ) stabilizes after 10 minutes while the steady state is reached after round 90 minutes for  $\varphi_1$  and for  $\varphi_2$ .

The thermal resistance is thus given by:

$$R = \frac{2\Delta T}{\Sigma\varphi} \text{ and } \lambda = \frac{e}{R} \quad (3)$$

#### b.) Specific heat

During the transient phase, the sample stores or releases heat energy  $Q$  as its temperature increases or decreases. This energy is related to the heat fluxes difference ( $\Delta\varphi$ ) according to the relation:

$$Q = \int_{t_i}^{t_f} \Delta\varphi \cdot dt \quad (4)$$

It can also be related to average temperatures  $\Sigma T_i/2$  and  $\Sigma T_f/2$ , where  $\Sigma T_i$  represents the sum of the temperatures on each face at the initial time  $t_i$ , and  $\Sigma T_f$  represents the sum of the temperatures on each face at the final time  $t_f$ .

$$Q = C \frac{\Sigma T_f - \Sigma T_i}{2} \quad (5)$$

The heat capacity of the sample is thus given by:

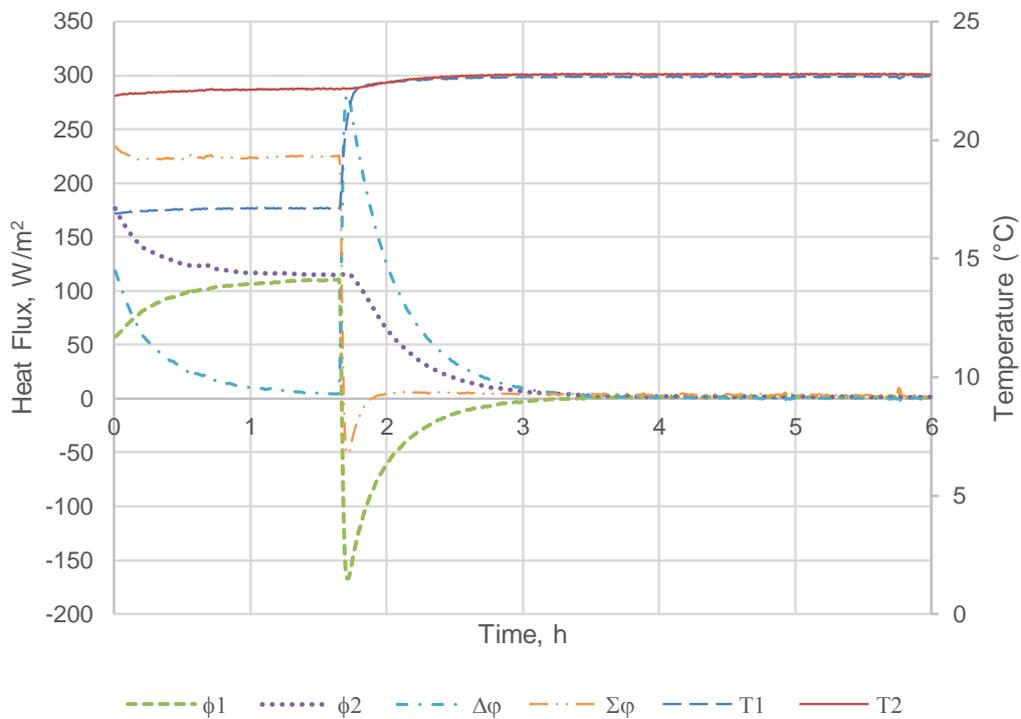
$$C = \frac{2 \int_{t_i}^{t_f} \Delta \phi . dt}{\Sigma T_f - \Sigma T_i} \quad (6)$$

Knowing the density of the sample and its thickness, the specific heat can be deduced:

$$c_p = \frac{C}{\rho e} \quad (7)$$

### Experimental results

Fig. 6 and Fig. 7 show the experimental measurements of heat flux and temperature for the concrete solid mixture and the concrete hollow block.



**Figure 6- Experimental results for the concrete mixture**

Table 1 represents the thermophysical parameters of the concrete mixture that were determined by applying Eq. 3 and Eq. 6 using the experimental measurements (Fig. 6).

The thermal conductivity and the heat capacity can thus be determined:

For  $t = 1h$ , Eq. 3 gives:

$$R = \frac{2 \times (22.11 - 17.14)}{224} - 0.005 = 0.0394 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$$

Where the contact resistance was considered equal to  $0.005 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$  (Tittlein et al. 2015).

$$\lambda = \frac{0.055}{0.0394} = 1.40 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$$

Eq. 6 between  $t=1.65h$  and  $t=4h$  gives:

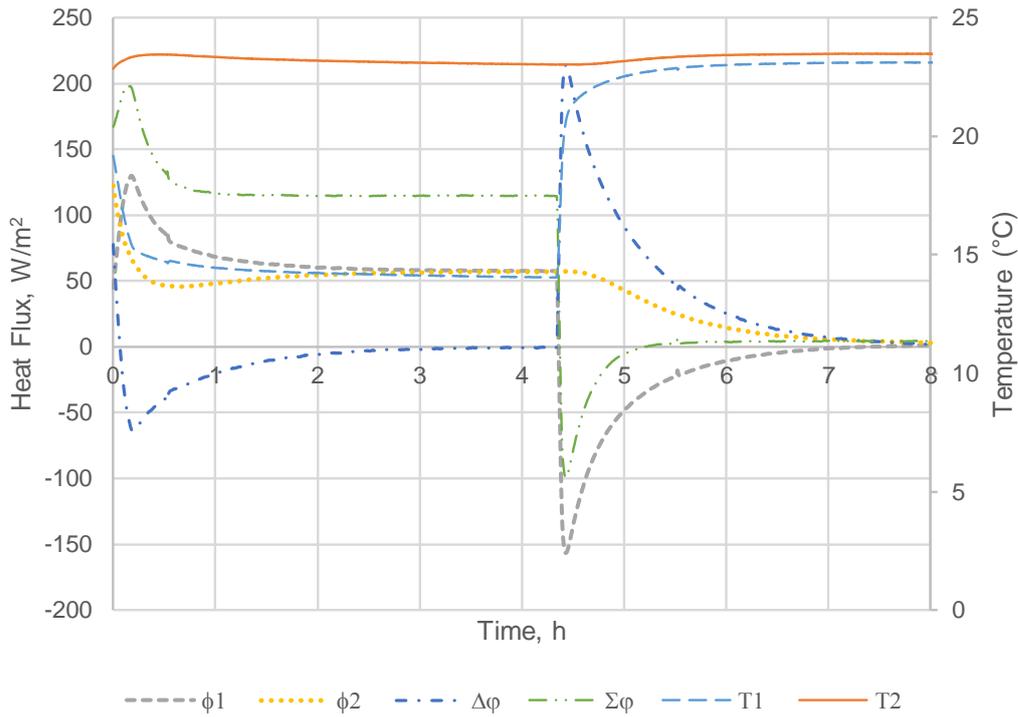
$$C = \frac{2 \times 416176}{45.4 - 39.3} = 136228 \text{ J} \cdot \text{K}^{-1}$$

Eq. 7 gives:

$$c_p = \frac{136228}{2240 \times 0.055} = 1106 \text{ J} \cdot \text{K}^{-1}$$

**Table 1- Thermal properties of the concrete mixture of the block**

	Thermal conductivity ( $\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ )	Density ( $\text{kg} \cdot \text{m}^{-3}$ )	Specific Heat ( $\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ )
Concrete mixture	1.4	2240	1106



**Figure 7- Experimental results of the block**

Similarly, the thermal resistance of the hollow block is determined using Eq. 3 and Fig. 7:

For  $t = 4\text{h}$ :

$$R = \frac{2 \times (23.04 - 14.05)}{115} - 0.005 = 0.151 \text{ m}^2 \cdot \text{K} \cdot \text{W}^{-1}$$

### **Numerical aspect**

The simulations were performed using the software COMSOL® version 5.3a. In this two-dimensional study, a structured mesh was considered using steady-state heat transfer.

### **Pre-test and model validation**

#### ***Validation of the cavity model***

Besides convection, thermal radiation was also considered using the discrete ordinates method (DO) due to its validity for radiation in any kind of gaseous medium. The air circulation inside the cavity promoting the natural convection, was considered as a laminar flow. By coupling the “Laminar Flow” model with the “Heat Transfer in Fluids” model in COMSOL Multiphysics, the

continuity equations, the Navier-Stokes equations, and the energy equations were accounted. The air density was assumed to be dependent of pressure and temperature varying according to the ideal gas relation.

The validity of the methodology was verified by comparison with benchmark results [5] for a cavity flow with Rayleigh number  $Ra=10^5$ .

For a square or rectangular-profile cavity, with four lateral insulated surfaces and two parallel faces with imposed temperatures, the Rayleigh number “Ra” is given by (Bergman et al. 2011):

$$Ra = \frac{g\beta(T_A - T_B)(H \times 10^{-3})^3}{\nu \cdot \alpha} \quad (8)$$

Where  $g$  [ $m/s^2$ ] is the gravity acceleration,  $\beta$  [ $K^{-1}$ ] is the expansion coefficient,  $T_A$  [K] and  $T_B$  [K] are the imposed temperatures on the two parallel sides,  $H$  [mm] is the cavity length,  $\nu$  [ $m^2/s$ ] is the kinematic viscosity and  $\alpha$  [ $m^2/s$ ] is the thermal diffusivity.

The air properties at 300 K can be obtained from reference tables (Bergman et al. 2011) and are reported in Table 2 as well as the boundary temperatures, the cavity length, and the Rayleigh number obtained from Eq. (1).

**Table 2- Values for calculation of Rayleigh number**

Variable	Units	Value
$g$	[ $m \cdot s^{-2}$ ]	9.81
$\beta$	[ $K^{-1}$ ]	0.0033
$T_A$	[K]	305
$T_B$	[K]	295
$H$	[mm]	48
$\nu$	[ $m^2 \cdot s^{-1}$ ]	$1.59 \times 10^{-5}$
$\alpha$	[ $m^2 \cdot s^{-1}$ ]	$2.25 \times 10^{-5}$
$Ra$	[-]	$10^5$

The pre-test was performed considering the same simulation conditions used for the blocks. The dimensionless temperature profile as well as the velocity fields (x and y components) are compared with the benchmark solution in Fig. 8-10.

Fig. 8 shows the isotherms obtained for  $Ra = 10^5$  in a closed rectangular cavity. Regarding the shape of the isotherms, the isotherms in the vicinity of the left wall ( $T_A > T_B$ ) are very tight in the lower part at  $y < H/2$  showing the start of air heating by convection. Beyond this part ( $y > H/2$ )

the isotherms disperse more and more in the cavity, which shows the increase in the temperature of the air in the cavity. On the other hand, at the right wall ( $T_B < T_A$ ) the isotherms take a reverse form compared to what has been said for the left wall. As the temperature of the right wall is lower than the left one, the air cools near this wall; the beginning of cooling begins in the upper zone and gradually progresses to cool the air further to the lower part of the left wall. In addition, as the rectangular cavity is isolated from the top and from the bottom, the isotherms have a symmetrical shape. These forms of isotherms translate the movement of convection in a clockwise direction. This recirculation is created due the air density difference at the hot wall vicinity. In fact, by receiving heat, the air becomes lighter and thereby ascends along this wall. On the other hand, it cools and becomes heavier, and thereby it goes down near the cold wall.

Fig. 9, and Fig. 10 show the horizontal (X) and vertical (Y) velocity fields respectively. It can be clearly seen that the vertical speed components are much higher than the horizontal ones; this explains that the natural convection recirculation movement is gravitational and caused by the variation of the fluid density in the cavity. The vertical component of the speed becomes very significant near the walls (left and right) and takes maximum values. In the middle of the cavity, the fluid is almost at rest, the horizontal and vertical speeds are almost zero.

It can be deduced that the numerical model developed using natural convection in closed cavities reproduces perfectly, qualitatively and quantitatively, the dynamic and thermal trends of the benchmark. This model has been adapted and developed for the work of natural convention inside the concrete hollow block cavities.

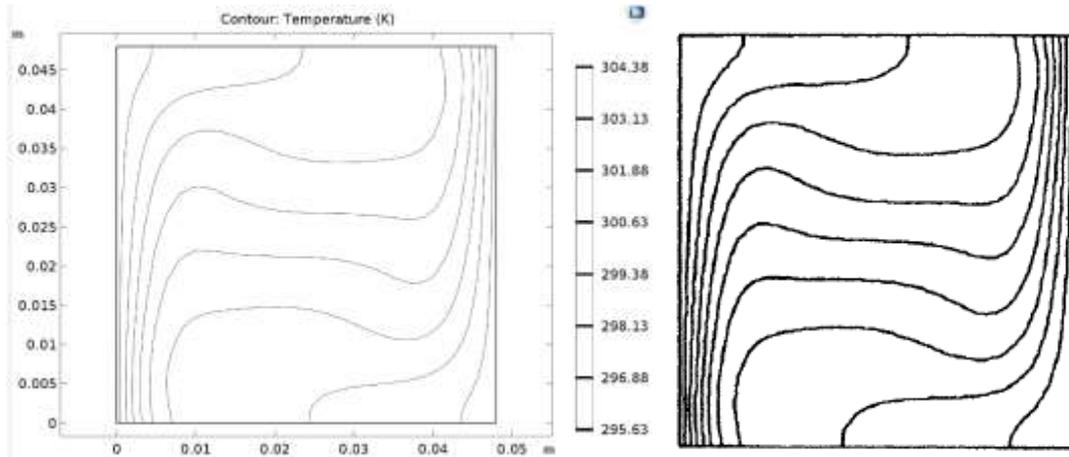


Figure 8- Temperature profiles: (a-left) this work; (b-right) benchmark

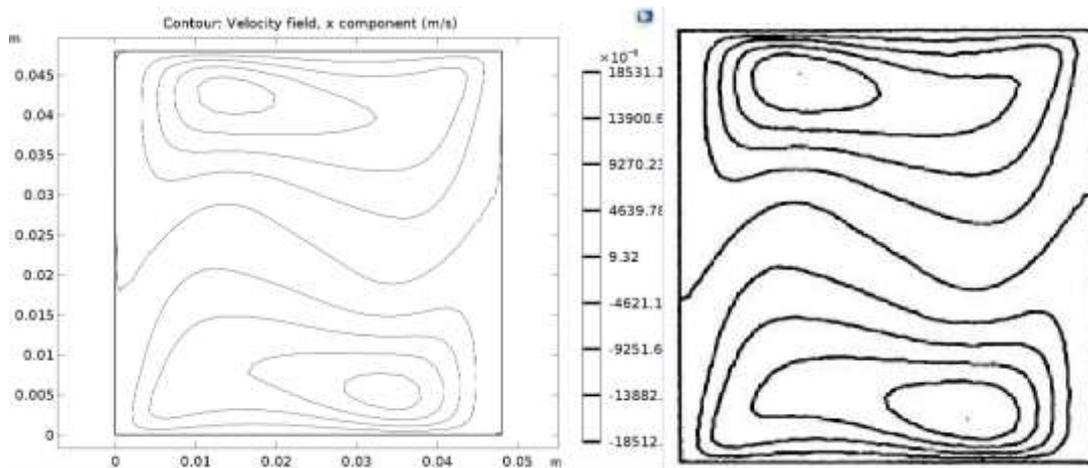


Figure 9- Velocity field (x component): (a-left) this work; (b-right) benchmark

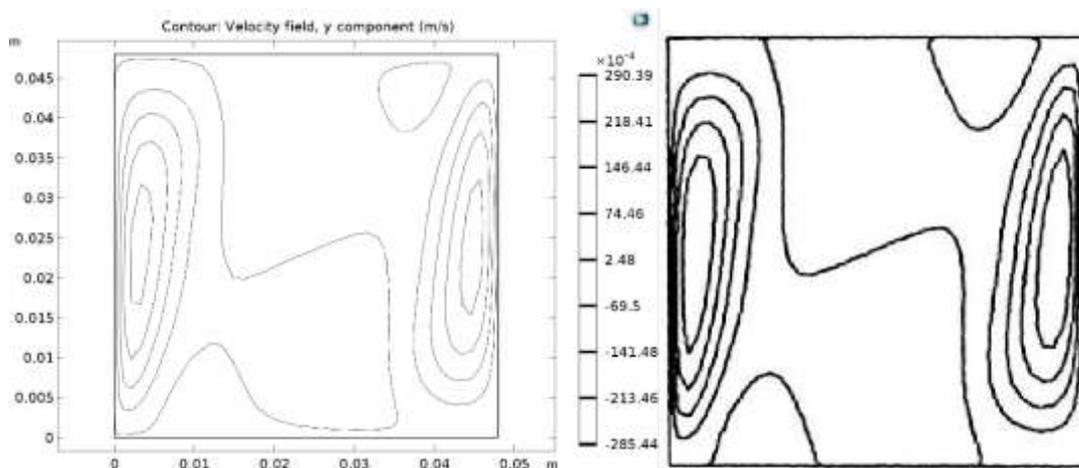


Figure 10- Velocity field (y component): (a) this work; (b) benchmark

### *Validation at the block scale*

The validation of the model was done by comparing the results with the ones obtained by Fogiatto et al. [6] . The same thermo physical properties for concrete and air used for the model validation are reported in Table 3.

**Table 3- Thermo-physical properties of concrete and air**

Property	Units	Air	Concrete
P	[kg/m <sup>3</sup> ]	Ideal gas	2300
c <sub>p</sub>	[kJ/(kg.K)]	0.0033	0.88
K	[W/(m.K)]	0.0263	1.50
E	[ ]	-	0.9
M	[N.s/m <sup>2</sup> ]	1.846 x 10 <sup>-5</sup>	-

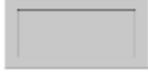
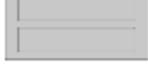
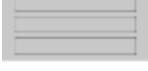
The 10 models described in the literature [4] were reproduced using the same assumptions and the equivalent thermal resistance was deduced by determining the total heat flux simulated for an imposed temperature difference of 20 °K.

The heat flux was determined numerically and the thermal resistance was deduced by the relation:

$$R = \frac{\Delta T}{\Sigma \varphi}$$

The comparison between the numerical model and the results of [6] is summarized in Table 4. The relative deviation is less than 10% for all the block configurations.

**Table 4- Comparison between simulated results and bibliography results for the 10 cases**

Bloc number	Bloc configuration	Thermal Resistance [6] ( $\text{m}^2\cdot\text{K}/\text{W}$ ) [4]	Thermal Resistance from the present study ( $\text{m}^2\cdot\text{K}/\text{W}$ )	Relative deviation (%)
#1		0.187	0.183	2.13
#2		0.178	0.175	1.68
#3		0.192	0.176	8.3
#4		0.196	0.179	8.67
#5		0.237	0.248	4.64
#6		0.273	0.299	9.52
#7		0.252	0.246	2.38
#8		0.284	0.289	1.76
#9		0.276	0.292	5.79
#10		0.108	0.108	0

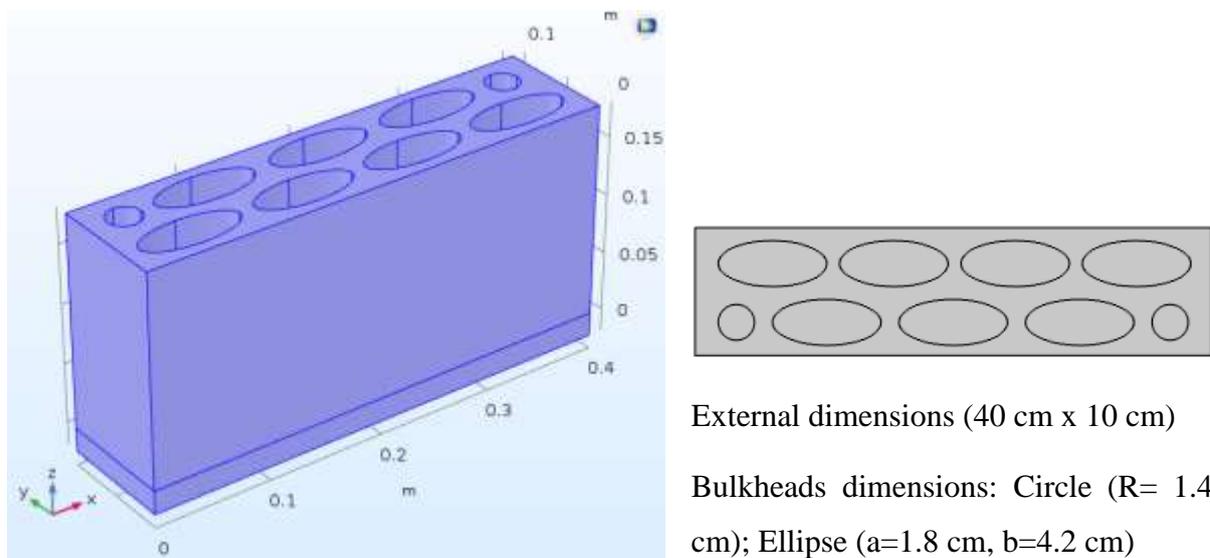
### 3D numerical modeling and simulation of the block

The dimensions of the studied wall are reported in Fig. 8. A temperature gradient of 20 K is imposed on the long lateral faces of the block (273 K – 293 K) while the two other faces are remaining adiabatic.

## Numerical results

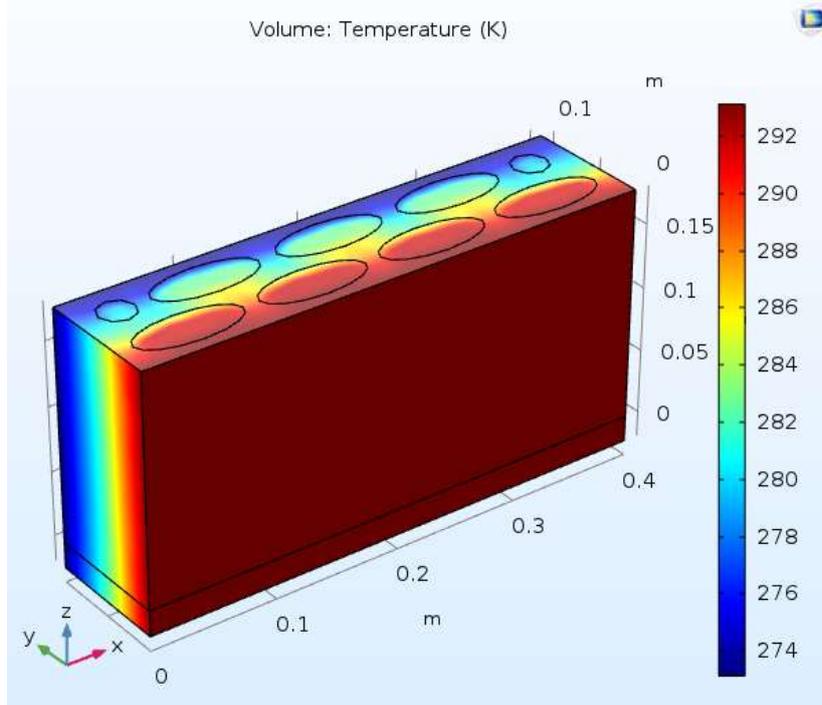
The numerical results for the 3D model allow a better understanding of the heat transfer and temperature distribution in the block in quantitative and qualitative manners.

It is composed of two rows of cavities, the first one made of four elliptical cavities and the second one of three elliptical cavities and two circular ones. The external dimensions of the blocks are  $40 \times 20 \times 10 \text{ cm}^3$ . The block dimensions as well as the simulation model are shown in Fig. 11.

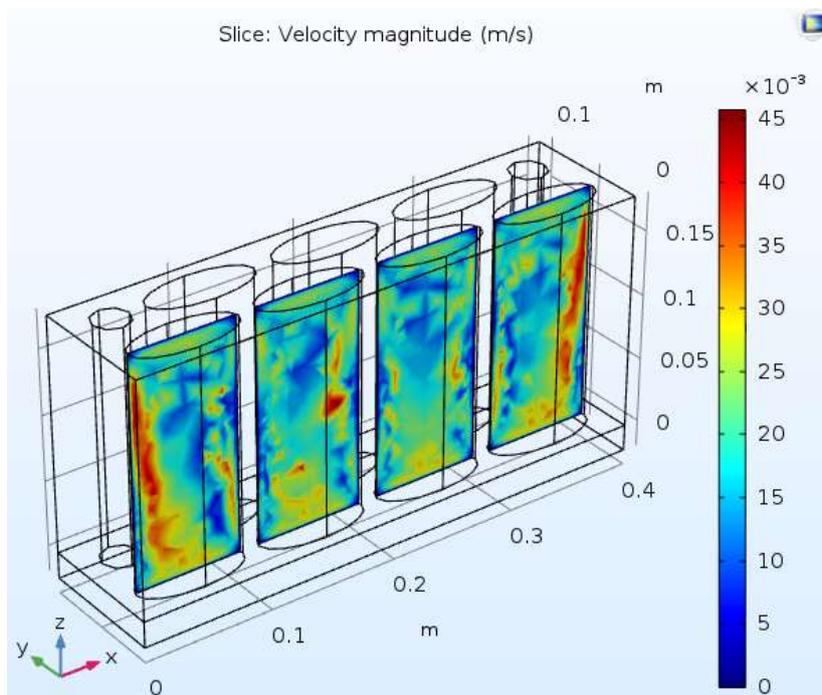


**Figure 11- Numerical model of the concrete hollow block**

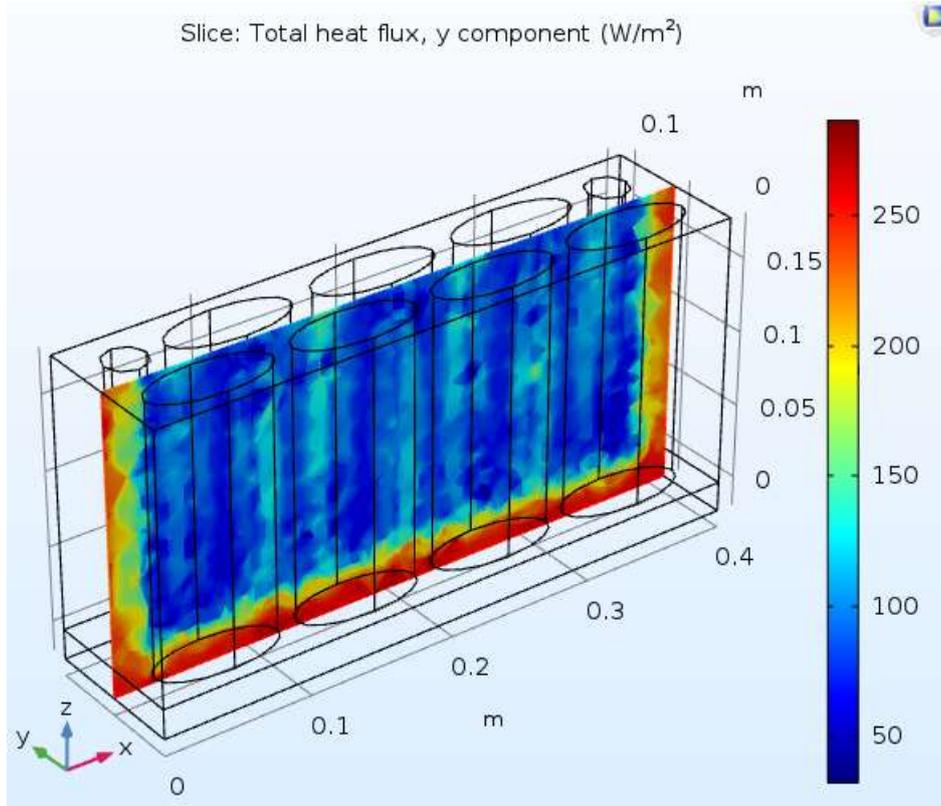
Fig. 12 shows that the temperature gradient within the block decreases progressively from the cold side to the hot side. The air velocity inside the cavities reaches maximum values of around 4 cm/s (Fig.13) which shows that convective heat exchanges are taking place. The maximum heat flux is noticed at the edges of the block where there are no cavities preventing conductive transfer, the solid matrix is thus the domain of the main heat flow in the block (Fig. 14).



**Figure 12- Temperature distribution inside the hollow block**



**Figure 13- Air velocity inside the cavities of the block**



**Figure 14- Heat flux distribution across the middle plan of the block**

3D numerical modeling and simulation offer a lot of potential for better understanding different thermal transfer phenomena in the hollow block where conduction, convection and even radiation take place simultaneously. The solid concrete mixture is the domain of the conductive heat transfer while convection and radiation occur in the cavities of the block.

### **Comparison between experimental and numerical results**

The simulated average heat flux crossing the block is  $127.5 \text{ W.m}^{-2}$ . The equivalent thermal resistance of the block is thus given by:

$$R = \frac{\Delta T}{\phi} = \frac{20}{127.5} = 0.159 \text{ m}^2 \cdot \text{K} / \text{W}$$

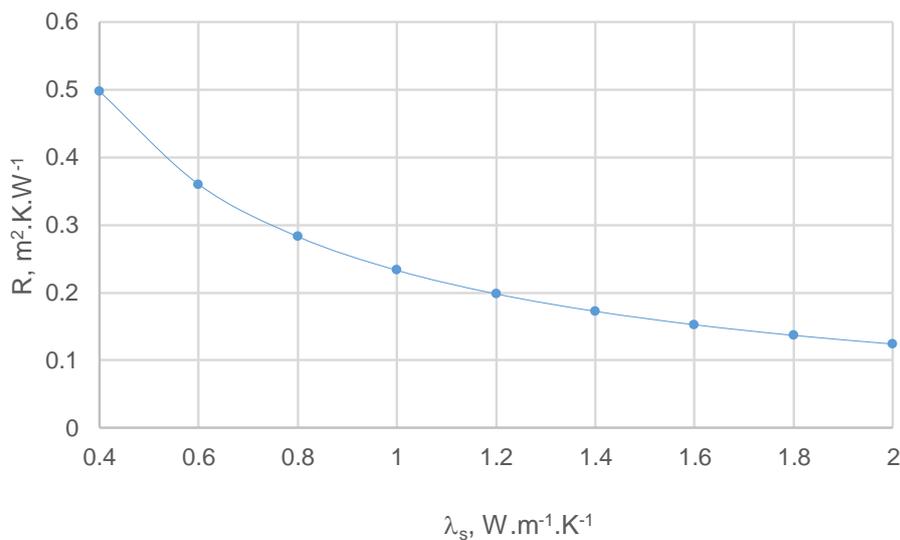
The difference between experimental ( $0.151 \text{ m}^2 \cdot \text{K} / \text{W}$ ) and numerical ( $0.159 \text{ m}^2 \cdot \text{K} / \text{W}$ ) results is around 5%.

## Parametric analysis of the block

### Parametric analysis by modifying the solid matrix

One of the possible improvement scenarios of the hollow concrete block is to improve the thermal conductivity of concrete solid matrix by incorporating some materials to its composition like recycled solid wastes for example.

The relation between the solid material thermal conductivity and the global hollow block composition was obtained numerically and is presented in Fig. 15. The results show that reducing the thermal conductivity of the concrete mixture from 1.4 to 0.4 will increase the thermal resistance of the block by more than 3 times from 0.17 to 0.5  $\text{m}^2.\text{K}.\text{W}^{-1}$ . This can be practically done by reducing the thermal resistance of the concrete mixture by replacing the normal standard concrete mixture by lightweight concrete or by replacing a part of the aggregates by other aggregates having a better thermal resistance such as wood or Expanded polystyrene EPS.

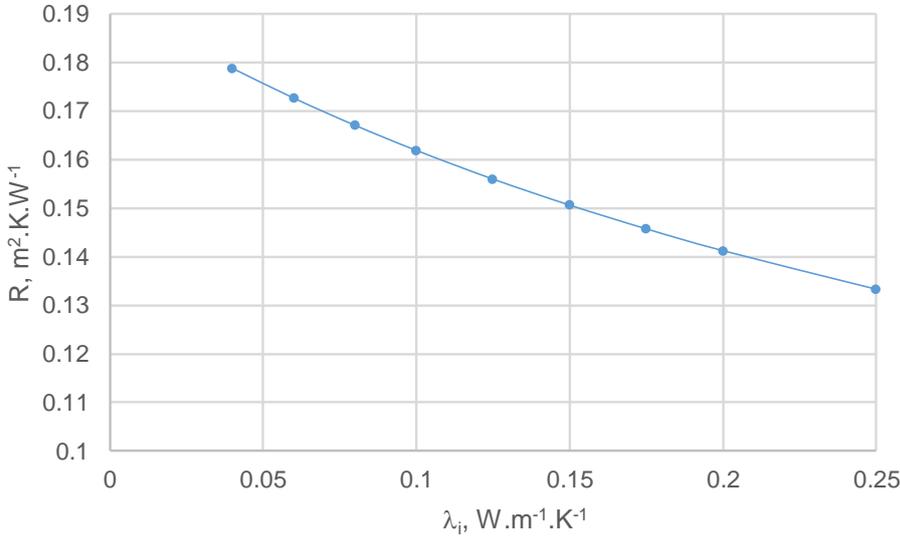


**Figure 15- Relation between the thermal conductivity of the solid mixture and the equivalent thermal resistance of the hollow block**

### Parametric analysis by filling the hollow part

Another possible way to improve the thermal performance of hollow blocks is to fill its air gaps by insulation materials. Fig. 16 shows that the minimum thermal conductivity needed to increase the thermal resistance of the blocks is below  $0.2 \text{ W}.\text{m}^{-1}.\text{K}^{-1}$ ; in other words, any material having

a higher thermal conductivity will be useless for this application. It can also be noticed that an improvement of around 40% in thermal resistance can be achieved by filling the air gaps by an insulation material of around  $0.04 \text{ W.m}^{-1}.\text{K}^{-1}$  (which is the case of most insulation materials (Bergman et al. 2011)).



**Figure 16- Relation between the thermal conductivity of the air gap infill and the equivalent thermal resistance of the hollow block**

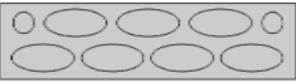
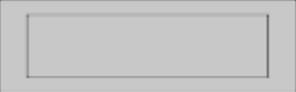
**Parametric analysis by modifying the geometry**

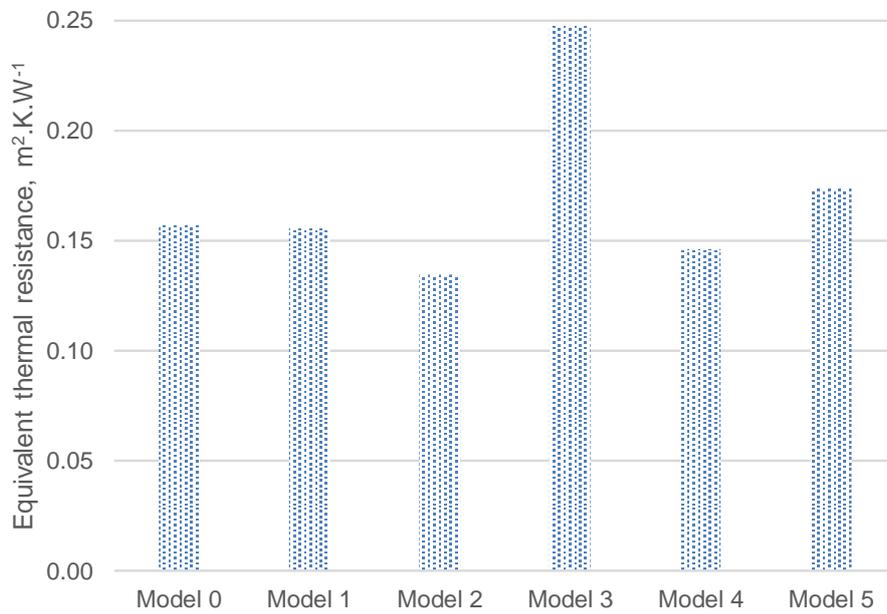
The last improvement that will be discussed is the effect of modifying the block internal geometry by maintaining the same external dimensions (Total Area:  $400 \text{ cm}^2$ ), and the same concrete mixture quantity represented by the solid cross section  $A_s$  (Solid Area:  $221.52 \text{ cm}^2$ ).

The Lebanese hollow block configuration (Model 0), will be compared with 6 different rectangular cavity shapes by maintaining a uniform concrete matrix thickness “t”.

The comparison was made by assessing the 2D heat transfer for the different cases and comparing the equivalent thermal resistance for the different configurations.

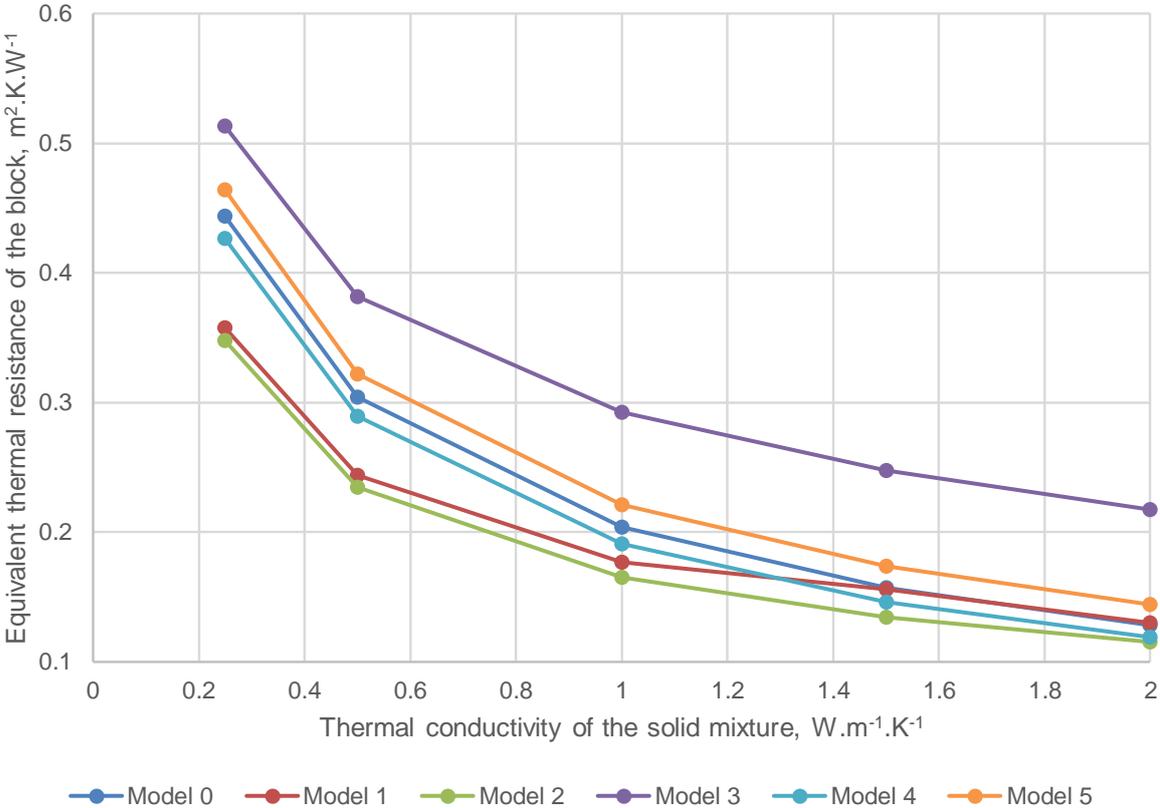
**Table 5- Dimensions of the different blocks configurations**

	Shape	Cavity width (l)	Cavity length (L)	Concrete thickness (t)
		cm	cm	cm
Model 0		-	-	-
Model 1		5.09	35.09	2.46
Model 2		5.39	16.55	2.30
Model 3		2.44	36.59	1.71
Model 4		5.97	7.48	2.02
Model 5		2.75	8.12	1.50



**Figure 17- Equivalent thermal resistance for different configurations**

The comparison of the equivalent thermal resistances of the different configurations presented in Fig. 17 shows that the best configuration is the one presenting two air cavities in series with respect to the heat flux direction (Model 3). On the other hand, the worst configuration is the one presenting two air cavities in parallel with respect to the heat flux direction (Model 2). These results are not surprising since it is commonly known that the parallel model provides the upper bound of effective thermal conductivity in heterogeneous media while the series model gives the lower bound (Xu et al. 2016). The air cavities play an important role of damming the heat flux through the block while the concrete solid matrix plays the role of thermal bridge allowing the heat to go through the block. Fig. 18 shows how the series configuration (Model 3) remains by far the best configuration for different thermal conductivities of the concrete mixture. This configuration is to be recommended when for reaching high thermal resistance values. The Lebanese configuration (Model 0) does not offer any particular advantage from a thermal perspective and its shape is mainly due to manufacturing considerations and implementation in construction site.



**Figure 18- Equivalent thermal resistance vs concrete mixture thermal conductivity for different configurations**

## **Conclusions and recommendations**

The free convection model inside the block cavities was validated by comparing temperature and velocity profiles to benchmark values available in the literature. Then the validation of the block model was performed by comparing the results of 10 block models available in the literature (Fogiatto et al. 2016).

A 3D block modeling and simulation was performed and a slight difference of nearly 5% was found between the thermal resistance of the experimentally determined block and the numerically simulated block. Then a numerical analysis was performed for understanding the main heat transfer phenomena inside the concrete hollow block. Finally, a parametric study is performed to understand the effect of various parameters on the overall thermal resistance of the block, these parameters include the concrete solid mixture, the cavities infill material, and the geometry configuration of the block. The conclusions drawn from this work will provide a good basis for further explorations for improving concrete hollow blocks by incorporating new materials in their composition and by preserving the same shape and dimensions of prototype block for ergonomic reasons as well as local workmanship techniques.

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