MAIN PATHWAYS FOR THE EMERGENCE OF OPTIMIZED AIR CAVITY BRICK WALLS

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The application of innovative construction techniques, such as the use of bricks with interconnected and well-arranged cavities, can promote enhanced insulation. Two hundred and forty-four different configurations were investigated thermally to improve their thermal performance and to promote some design guidelines. A configuration will then be selected to evaluate the thermal performance of facade walls based on several geometric morphologies, according to which they are either single or double walls. The selected house has been subjected to the climatic conditions of Ghardaia, which are hot and very severe during certain periods. The method for calculating the building's energy needs was applied to assess the energy required for heating and cooling according to the level of building compactness. The results initially indicated that longitudinal cavities improve the thermal resistance of hollow bricks and thus reduce the heat flow passing through the façade walls, while transverse walls decrease the thermal performance of these hollow bricks by creating thermal bridges within their structure. Adopting construction techniques that promote insulation, such as double walls can be beneficial. For buildings requiring thermal comfort, double-wall structures or more advanced insulation systems are generally recommended. The double-wall design helps reduce heating and cooling needs, resulting in significant energy savings of up to 36%. A compact design can lead to energy savings and a reduction in insulation needs, while still maintaining adequate thermal comfort.

Key words*: Hollow brick, Air cavity, Thermal resistance, Heat loss, Double wall, Heating, Thermal insulation, Cooling, Compactness.*

1. Introduction

The building envelope has been the subject of numerous studies by both scientists and architects. Experimental measurements and numerical calculations focused on the behavior of building materials as a function of the external climate and design approaches, taking into account thermal and geometric aspects. Cavity walls have a significant advantage over solid masonry walls because they protect against external weather conditions in addition to complete protection against rain penetration. The use of hollow block walls is, therefore, one approach to improving the thermal performance of the building envelope due to their lightweight and high thermal performance. In this context, the impact of structural cavity configurations on the thermal performance of a hollow block wall has been analyzed by several scientific researchers.

The U-value of hollow clay walls was investigated by varying the clay and mortar thermal conductivities, the geometric configuration of the cavity grid and the thickness of the bricks. The results indicated that the increase in the brick thickness led to a U-value decrease from 0.761 $W/m^2.K$ to 0.563 $W/m^2.K$. On top of this, lowering the thermal conductivity results in a negligible decrease in the wall's U-value **[1]**.

However, heat transfer through a wall system can be significantly reduced by adding thermal insulation that prevents heat from escaping in winter and entering in summer **[4]**, using double or triple-glazed windows with spaces filled with inert gas (such as argon) coupled with hollow brick walls, which effectively reduce heat loss through conduction and convection **[3]**, and applying reflective films on the exterior surfaces of brick walls or inside cavities that can help reflect or weaken the flow of radiant heat **[2]**. On the other hand, some involved mechanisms are the percentage decrease of the solid material **[5]**, the change of heat conduction paths and the lowering of the thickness of the inner and outer walls of the brick unit **[6]**. The mechanical and thermal properties are also linked to the thickness of the wall, the thickness of the ribs, the number of holes and the arrangement of the holes in the bricks. The mechanical and thermal properties are also dependent on the thickness of the wall, the thickness of the ribs, the number of holes and the arrangement of the holes in the bricks **[7]**. In a further project, the experimental performance of a new type of porous brick has been revealed and measured by considering the number of air cavities. A reduction in density, thermal conductivity and a slight reduction in compressive stress were achieved by this configuration **[8]**. However, eighteen types of clay brick and two types of concrete brick have been analyzed from the point of view of their thermal performance. An analysis of the results showed that the equivalent thermal conductivity depends not only on the material and the brick configuration but also on the brick thickness. In general, thinner bricks have a lower conductivity than thicker ones **[9]**.

The recommendations of EN ISO 6946 have been applied for the first time to the calculation of the thermal performance of hollow bricks, considered as building elements composed of thermally homogeneous layers. An iterative algorithm based on the equivalent thermal resistance network has been described in detail and then applied to various hollow bricks **[10]**. Furthermore, the booklet "Th-Bat-Parois opaques" published by the French government has been used in thermal regulation applications to evaluate the energy consumption of buildings. European standards have been served to calculate the thermal performance of building envelope elements. In this context, the NF EN ISO 13789 standard was used to assess the transmission loss coefficient, which systematically reflected the thermal performance of buildings. Regarding thermal resistance and thermal transmittance, they were based on the NF EN ISO 6946 standard **[11]**.

The main contexts to be studied in this article primarily concern thermal properties due to the air trapped in the cavities, familiarization with the construction standards governing the use of hollow bricks, particularly regarding strength and insulation, and architectural applications by examining its various uses, whether for load-bearing walls, partitions, or facades. The main issue with brick walls with air gaps concerns their thermal performance and durability. These walls, which are often used to enhance a building's insulation, can present several challenges, including thermal insulation. Although these walls are designed to improve insulation, their effectiveness depends on the design and implementation. Poor design can diminish the expected thermal benefits. The issue of air cavities in hollow bricks lies in their impact on thermal insulation. Air cavities can improve the thermal insulation of hollow bricks, but their effectiveness depends on the design and size of the cavities. If the cavities are not properly sized or are poorly filled, this can lead to thermal bridges, thereby reducing the energy efficiency of buildings. In addition, due to their cavities, they may have lower mechanical strength compared to solid bricks. This requires special attention during the design of structures to ensure that they meet safety and durability standards. Knowing that still and stable air is a poor conductor of heat, we will also examine to what extent the morphology of air cavities in hollow bricks can help minimize the cost of the thermal insulation required for walls to meet the required thermal standards. Several studies fall within the same context. The first **[12]** deals with the geometry and thermal coefficient of bricks, which can affect their ability to transfer heat through the wall. The second contribution **[13]** essentially tackles the same issue but combines air-filled cavities with a number filled with thermal insulation. The same work was conducted by Magrini et al. **[14]**, with a study primarily focused on the economic impact and overall feasibility of systematic insulation and filling actions based on the wall surface area and the thickness of the air cavities in hollow walls. The deployed method generally relies on the use of thermal modeling techniques based on the characteristics of materials, configurations, and the analysis of air cavities. It presents a combined approach that allows for a deep understanding of the thermal performance of hollow bricks with air cavities and optimizes their design for specific applications. Unlike previously published research, some assumptions have been carefully taken into account. The thermal conductivity of the materials making up the bricks, as well as the mechanisms of heat transfer through conduction and convection in the air cavities, have been considered based on reliable default values established by reputable organizations. The random and significant variation in climatic conditions has been taken into account in the assessment of energy needs throughout the entire year. The interaction with other building elements (insulation, coatings, etc.) has been rigorously considered, as they can influence the overall thermal performance of the building envelope. Unlike existing numerical models in the literature, the calculations carried out were purely analytical. They did not require mathematical assumptions. The evaluation of the thermal performance of hollow bricks with air cavities and the optimization of their use in construction has therefore been undertaken with precision. The optimization of the air cavity configuration in hollow bricks can have several objectives and bring significant innovations in the field of construction and building materials. The integration of new manufacturing techniques may soon allow for geometrically more complex and efficient cavity designs, particularly by drawing inspiration from natural structures (such as honeycombs or bones) to create air cavities that maximize strength while minimizing weight.

This paper aims to propose new bricks suitable for building the walls of a house with good thermal performance. In Algeria, hollow bricks have horizontal and vertical perforations, making them lighter than solid bricks and therefore easier to transport. The best configurations will be adapted to the new building material by varying the shape and size of cavities. The wide range of shapes available means it can meet all kinds of energy needs. The set of cases represents different inner shape configurations and preserves the same external dimensions (30 cm × 20 cm × 15 cm). The originality of this work also relates to an Algerian computational method that produces new results to expand their knowledge base in the field of building physics. The calculation rules have been established to conform to the standards stipulated in the Algerian thermal regulation (Regulatory Technical Document DTR.C3-4). The second objective is to optimize the configuration of the cavities which therefore minimizes heat loss through the walls and systematically leads to more efficient energy management within a building. The main purpose is to reduce the energy used and the costs associated with it. However, the correct insulation of cavity walls through an intelligent geometric optimization of internal cavities can trap warm or cold air and prevent unwanted air from circulating through the cavity. This type of work greatly improves the performance of buildings and their interior comfort. The method for calculating the building's energy needs quantifies the energy required for heating and cooling. The results obtained will then be used to test the energy reliability of these cavity walls by comparing them with a conventional single wall.

2. Materials and methods

A methodology based on classical formulas, such as those adopted in rules issued by the scientific community or in official technical documents, has been introduced to achieve the objectives outlined. Heating and cooling energy needs and heat loss through the walls have been estimated and quantified using numerical simulation. Checking the accuracy of resolution models is a crucial step to ensure that they faithfully represent the phenomena or systems under study.

The verification step has already been carried out for the calculation of thermal resistances, as formalized by a decree published in the Official Journal of the People's Democratic Republic of Algeria. This regulatory technical document D.T.R C 3.2/4, titled "Thermal Regulation of Buildings" has been prepared by a specialized technical group **[15]**. It essentially defines the general regulatory principles of thermal design for buildings and provides professionals with assessment methods, including energy needs for winter and summer periods. It also provides a detailed response to issues related to building thermal performance and concerns regarding energy management. The methods outlined in this document are generally based on validation through:

- Experimental data by comparing model predictions with real data and using statistical techniques to assess the quality of the fits.
- Examining the differences between observed and predicted values to detect patterns or trends that may indicate that the model is not capturing certain aspects of the phenomenon.
- Consistency tests by checking each time that the model adheres to the fundamental principles of physical laws

Regarding the energy needs assessment model for heating and cooling published by research team colleges in prestigious international journals **[16-18]**, its accuracy has thus been proven and maintained through:

- A peer review. The new model proposed by our team is a combination of the most appropriate mathematical approaches with results that have been submitted for peer review in the field to obtain critical feedback and suggest improvements. Relevant revisions have been considered to better align with the data or theories.
- The use of up-to-date data that feeds the model and comes from reliable and recognized sources such as government agencies, international organizations, and highly reputable academic studies.
- The comparison of the model's results with those of other recognized models that have dealt with the same phenomenon, enables us to evaluate and eliminate inconsistencies in the results by

identifying in each case potential significant divergences. These procedures were previously carried out by ourselves.

- The evaluation of the model's performance by comparing past forecasts with actual observed data and calculating error indicators. This may include short, medium, and long-term forecasting periods.
- The sensitivity analysis that identifies the most influential variables by testing how variations in input parameters affect the model's results. This procedure has also been carried out previously by the entire research team, and finally
- Several tests were conducted to evaluate its ability to generalize to other encountered situations.

However, based on these steps, this evaluation is considered complete as it has confirmed the accuracy and reliability of the mathematical models deployed in this manuscript.

Hollow bricks were selected to investigate the impact of cavities on their thermal performance. This building material is made from terracotta, which is a mixture of clay and sand (natural additives). This mixture is ground, moistened, molded and dried before being fired at between 900°C and 1200°C for around thirty hours.

2.1. Properties and thermal-electrical analogy

The concept of the electrical-thermal analogy has been formalized to calculate equivalent electrical resistances. It provides a simple but effective solution to this type of problem **[19]**. The thermal resistance R ($m^2.K/W$) depends on the geometric and thermal characteristics of the materials constituting the hollow brick. The layers are considered to be homogeneous, on top of each other and perpendicular to the heat flow. Temperature seems to be a thermal potential. The terms $1/h$ ($m^2.K/W$) and e/λ ($m^2.K/W$) correspond respectively to the thermal resistances of an air layer with a flat wall of thickness e, thermal conductivity λ and surface area S. h is the convective exchange coefficient between the air cavity and the vertical surface. The thermal resistance of surface exchanges represents default values provided on page 12 of the reference **[15]**. The method to be adopted for the calculation of the equivalent resistance of the air cavity is deduced from the Regulatory Technical Document **[15]**. It is approximate because it assumes one-dimensional heat transfer and involves empirical correlations for estimates of natural convection within the holes and for radiative exchange between hole surfaces. The thermal resistance of an air gap can be obtained from the table indicated in Figure 1. The method for calculating the overall heat transfer coefficient of opaque walls is standard; it is detailed on page 22 of reference **[15]**. To apply this analogy, the resistances have been divided by the area of the heat exchange section to obtain the elementary resistance of the brick, expressed as (K/W), to deduce the equivalent resistance of the wall in question. The idea is to calculate the equivalent thermal resistance of each geometric configuration, bearing in mind that the thermal conductivity of terracotta is 1.15 W/m.K. The external dimensions of the hollow brick are 15 x 20 x 30 cm^3. The exact dimensions and overall diagram of the equivalent circuit for this type of brick are given in reference **[19]**. At the beginning of the study, the effect due to the mechanical properties of the structure, consisting of identical and symmetrical vertical cavities, was neglected. Then, symmetrical cross-sectional walls have integrated progressively to take into consideration parameters related to mechanical properties such as mechanical resistance to traction, during compression and compression modulus of elasticity. This initiative aims to provide clear guidance on the priorities for the creation of air cavities. The example in Figure 2 has been an arbitrary choice. The configuration corresponds to a hollow brick in the vertical position, made up of four columns of cavities separated by one symmetrical cross-sectional wall.

Thickness of the air gap (mm)	Thermal resistance value
05 to 07	0.11
08 to 09	0.13
10 to 11	0.14
12 to 13	0.15
14 to 24	0.16
25 to 50	0.16
55 to 300	0.16

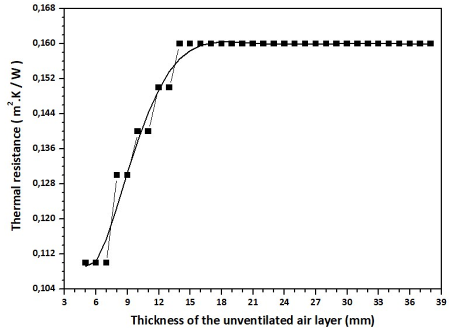


Figure 1: Thermal resistance of unventilated vertical air layers (page 23 of the reference **[15]**)

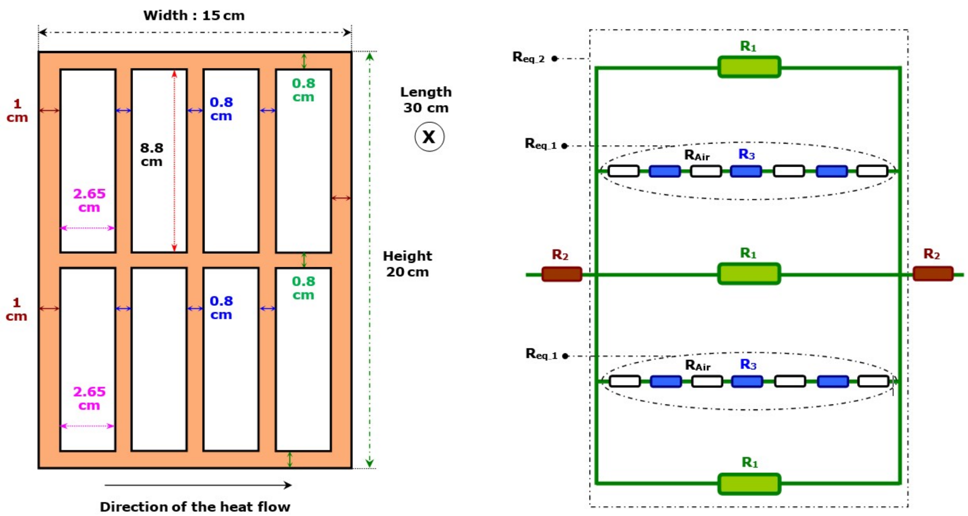
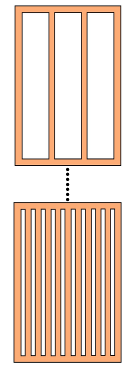


Figure 2: Geometry of the masonry unit and resistor network, case of a hollow brick with 8 identical vertical rectangular cavities of dimensions 2.65 cm x 8.8 cm

The number of test cases for a hollow brick in a vertical position will be 112 configurations. The number of cavity columns varies from 3 to 10, while the number of symmetrical cross-sectional walls can go up to 13 (from 0 to 13). If the hollow brick is in the so-called "horizontal" position, i.e. the height will be 15 cm and the width becomes 20 cm, the wall's resistance will logically increase. Under these circumstances, 120 geometric configurations correspond to the number of cases to be studied. The number of cavity columns can range from 3 to 14, while the number of symmetrical cross-sectional walls can be limited to just 10. Using this reasoning, we will be able to obtain a database that can serve as a reliable data sheet for the rigorous study of the influence of cavities and their optimization. The volume and mass of the hollow brick will be taken into account when reading, interpreting, analyzing and drawing conclusions from the results obtained. A solid brick of the same dimension weighs 13.3929 kg and has a volume of 9000 cm^3. Two different examples have been described for a better understanding. The cases to be studied corresponding to rectangular cavities without symmetrical cross-sectional walls with a height of 18.2 cm were summarized in the first (Table 1).

Table 1: Characteristic data relating to hollow bricks with vertical cavities, without symmetrical cross-section walls

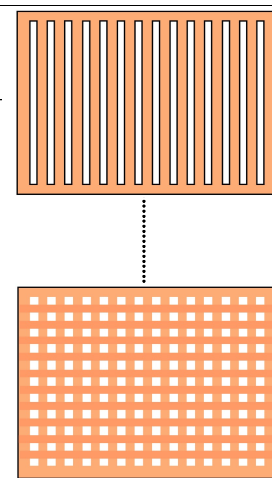
Number of cavity columns	Number of air cavities	Cavity dimensions Height x Width (cm^2)	Volume of the hollow brick (cm^3)	Weight of the hollow brick (kg)
3	3	18.2 x 3.8	2775.6	4.1304
4	4	18.2 x 2.65	3212.4	4.7804
5	5	18.2 x 1.96	3649.2	5.4304
6	6	18.2 x 1.5	4086.0	6.0804
7	7	18.2 x 1.17	4528.3	6.7385
8	8	18.2 x 0.925	4959.6	7.3804
9	9	18.2 x 0.733	5398.0	8.0328
10	10	18.2 x 0.58	5833.2	8.6804



Unlike the first example, in the second (Table 2), the hollow brick has been laid horizontally. The number of cavity columns was set at 14, but the number of transverse symmetrical walls to be retained varied from 0 to 10.

Table 2: Characteristic data relating to hollow bricks with horizontal cavities, without symmetrical cross-section walls

Number of cavity columns	Number of air cavities	Cavity dimensions Height x Width (cm^2)	Volume of the hollow brick (cm^3)	Weight of the hollow brick (kg)
0	14	13.4 x 0.543	5944.0	8.8452
1	28	6.3 x 0.543	6126.4	9.1167
2	42	3.93 x 0.543	6311.2	9.3916
3	56	2.75 x 0.543	6491.3	9.6597
4	70	2.04 x 0.543	6673.8	9.9312
5	84	1.567 x 0.543	6855.8	10.2020
6	98	1.229 x 0.543	7038.0	10.4732
7	112	0.975 x 0.543	7221.1	10.7457
8	126	0.778 x 0.543	7403.1	11.0165
9	140	0.62 x 0.543	7586.0	11.2887
10	154	0.491 x 0.543	7768.2	11.5599



2.2. Calculation of the building's energy needs for heating and cooling

The calculation of the building's energy needs (Wh) for heating and cooling is mainly based on the following basic equations **[16-18, 20-21]**:

$$E_{Envelope} = 24\ Dj_{Heating/Cooling}\ HL_{Envelope} \pm Int\ Heat \pm Sol\ PG \tag{1}$$

$Int\ Heat:$ The internal heat gains from starting up the equipment and machines, lighting systems, heat production by occupants and their activities...

The average occupancy time is estimated at 18 hours: 26 minutes, knowing that the average irradiated heat flux per occupant is of the order of 125.23 W. If the number of occupants living in the family home is 5, the internal heat gains result in a value of 923.36 Wh. The daily value of the remaining internal heat gains is approximated to be 497.15 Wh.

Sol PG : Passive solar gain. It will not be taken into account in this case. This is to avoid being an active factor in improving the envelope's thermal performance.

$Dj_{\text{Heating/Cooling}}$: Heating and cooling degree days by definition are measures that reflect the amount of energy needed to heat or cool a building to a comfortable temperature, given how cold or hot it is outside.

HL_{Envelope} : The sum of heat losses through walls, windows, doors, ceilings and roofs, thermal bridges, floors and ventilation, in W/K.

$$\begin{aligned} HL_{\text{Enveloppe}} = {} & HL_{\text{Walls}} + HL_{\text{Ceilings and Roofs}} + HL_{\text{Windows}} + HL_{\text{Doors}} \\ & + HL_{\text{Thermal bridges}} + HL_{\text{Floors}} + HL_{\text{Ventilation}} \end{aligned} \tag{2}$$

The heat loss of each building element can be estimated using the following general equation:

$$HL_{\text{Building element}} = \sum_{i=1}^{i=n} b_{\text{Building element\_i}} \; S_{\text{Building element\_i}} \; U_{\text{Building element\_i}} \tag{3}$$

n : Total thermal zones in the building

i : The thermal zone number

$S_{\text{Building element\_i}}$: The total area of the building element (m^2)

$U_{\text{Building element\_i}}$: Thermal transmittance value U-value ($W/m^2.K$)

$b_{\text{Building element\_i}}$: The heat loss reduction coefficient

This coefficient is calculated based on the surface of the walls separating the unheated space from the heated spaces, from the outside, from the ground or another unheated space, the type of unheated space (garage, attic, circulation, etc.), the insulation state of both the walls of the unheated space and the walls overlooking the unheated space. For an exterior wall, and an underground wall or a floor on a crawl space, the retained values of $b_{\text{Building element\_i}}$ are respectively 1 and 0.8. For adjacent non-residential buildings, b = 0.2. In other cases, the coefficient b values, given in the references, are used by default **[21]**.

Thermal bridges are areas in the building envelope from which heat can escape more easily than from the surrounding parts of the building. Linear joints are the most common form of thermal bridge. They form at the junctions between the lower floor "LF" and the external wall "EW", the intermediate floor "IF" and the external wall, the upper floor "UF" and the external wall, the slab "SL" and the balcony "BA", and between the shear wall "SW" and the external wall.

$$\begin{aligned} HL_{\text{Thermal bridges}} = {} & \sum_{i=1,j=1}^{i=m,j=n} b_{LF\text{-}i\,/\,EW\text{-}j}\,\lambda_{LF\text{-}i\,/\,EW\text{-}j}\,L_{LF\text{-}i\,/\,EW\text{-}j} + \sum_{i=1,j=1}^{i=o,j=p} b_{IF\text{-}i\,/\,EW\text{-}j}\,\lambda_{IF\text{-}i\,/\,EW\text{-}j}\,L_{IF\text{-}i\,/\,EW\text{-}j} \\ & + \sum_{i=1,j=1}^{i=q,j=r} b_{UF\text{-}i\,/\,EW\text{-}j}\,\lambda_{UF\text{-}i\,/\,EW\text{-}j}\,L_{UF\text{-}i\,/\,EW\text{-}j} + \sum_{i=1,j=1}^{i=s,j=t} b_{SL\text{-}i\,/\,BA\text{-}j}\,\lambda_{SL\text{-}i\,/\,BA\text{-}j}\,L_{SL\text{-}i\,/\,BA\text{-}j} \\ & + \sum_{i=1,j=1}^{i=u,j=v} b_{SW\text{-}i\,/\,EW\text{-}j}\,\lambda_{SW\text{-}i\,/\,BA\text{-}j}\,L_{SW\text{-}i\,/\,EW\text{-}j} \end{aligned} \tag{04}$$

λ : Thermal conductivity (W/m K)

b : The heat loss reduction coefficient

L : The length of the thermal bridge (m)

Heat loss from the ventilation system is estimated based on the average air change rate in the dwelling as can be seen in Table 3. In the case of multi-residential apartment buildings, the air renewal rate will be estimated using the regulatory flow rate calculator. In other cases, the air exchange rate may be a function of the number of occupants living in the house.

Table 3: Values retained for the average renewal rate of the ventilation system [22]

	Kitchen	Bathroom	Shower	Toilet
In multi-residential apartment buildings	60 m^3/hour per enclosed space	40 m^3/hour per enclosed space	40 m^3/hour per enclosed space	40 m^3/hour per enclosed space
Other cases	60 m^3/hour per occupant			

2.3. House description

For this article, a multi-zone house will be the focus of the thermal performance study. The floor area of the house is 126.69 m^2, which consists of a living or dining area, kitchen, two bedrooms, bathroom, and toilet. It is not equipped with air-conditioning cooling and heating) or a mechanical ventilation system. The technical specifications, in particular the composition of the masonry and the thermo-physical properties of the construction elements are given in Table 4 below.

Table 4: Building masonry description and thermo-physical properties

Masonry elements			Thickness mm	Thermal conductivity W/m K	U-value W/m².K
Façade walls	Façade rendering: cement and sand-based mortar		18	1.4	Study cases
	Hollow bricks (with holes)		Study cases		
	Indoor wall cladding: ready-made mortar with cement, sand and water		10	1.4	
	Smoothing coating (in plaster)		02	0.35	
Roof High-floor	Type 1: single-story house	Cement mortar screed	50	1.4	Type 1 In contact with the outside 2.8050
	Type 2: house in a residential building	Granite floor stone	20	2.1	
		Cement mortar screed	30	1.4	
	Compression slab: hollow core slab of dimensions 20 cm thick x 16 cm wide x 53 m long		200	1.45	Type 1 In contact with a premise area 2.4894
	Cement mortar rendering		10	1.4	
	Smoothing plaster		02	0.35	
Low floor on solid ground	Granite floor stone		20	2.1	1.1370
	Cement mortar screed		30	1.4	
	Reinforced concrete slab		200	1.75	
	Solid ground: set of layers promoting the stability and drainage of the paving)		/	/	
Single-glazed windows					5
Metal entrance door					5.8

This single-story house is moderately spacious and well-arranged. Its total surface area is ideally distributed to preserve the privacy of each occupant. The sleeping area is grouped in one wing of the house and includes the master suite with its 16 m² dressing room and a bedroom of the same size to be arranged out with large wardrobes. The other wing of the house has a 24m² living room with many advantages. It is flooded with light, especially the kitchen, which is open and airy. This space is therefore well lit in both summer and winter, with direct access to the outside (Figure 3).

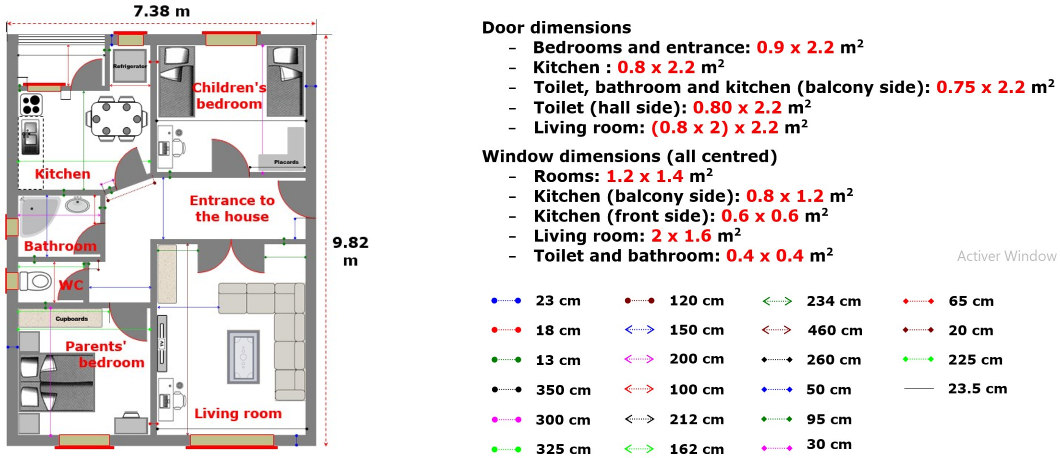


Figure 3: House plan view

3. Results and discussion

3.1. General overview of the climatic region

Ghardaïa is located in the M'zab Valley in the northern Sahara of Algeria, characterized by extreme temperatures, a hot and dry climate in summer and low precipitation and a cold climate in winter. Its altitude is 503 m above sea level, its Latitude: 32°29'27" North and its Longitude: 3°40'24" East. Summers are particularly harsh, with daytime temperatures often exceeding 40°C, while nights can be cooler. Winters are milder, with daytime temperatures ranging from 15°C to 20°C and colder nights that can drop to around 5 °C. The region is also subject to strong winds, particularly during the summer months, which can lead to dust storms. Overall, the climate is typical of a hot desert environment, with significant temperature variations between day and night. The information database reveals a period, which extends from January 1, 2004 to December 31, 2015. They correspond to a typical year of 12 typical months. In Ghardaïa, the clearness index varies significantly by month. Some of the site data are summarized in Table 5.

Table 5: Site data corresponding to temperatures, horizontal solar irradiations and clearness index

Month	Temperature °C	Average daily solar irradiance kWh/m²	Clearness index %
January	11.84	3.39	84.76
February	12.31	4.46	88.81
March	17.67	5.47	83.64
April	21.93	6.78	87.25
May	26.43	7.34	88.08
June	31.64	7.88	93.45
July	35.18	7.79	95.95
August	33.96	7.12	96.88
September	28.48	5.82	87.80
October	23.49	4.62	93.64
November	16.28	3.57	86.72
December	11.99	3.10	79.47
Annual mean value	22.66	5.62	88.87

3.2. Thermal performances

In the building construction sector, minimizing heat transfer and developing the morphological concept of bricks are the key to optimizing the thermal resistance of bricks. According to Tables 6 and 7, the results obtained in this section show that the thermal resistance increases with the number of cavity columns regardless of the number of cross-sectional walls perpendicular to the cavity columns. Its value will be systematically reduced by increasing the width of the cavity.

Table 6: Thermal resistance (K/W) of the vertical hollow brick according to the morphology of the air cavity.

	Number of cavity columns							
Number of symmetrical cross-walls	3	4	5	6	7	8	9	10
0	6.774	8.227	9.452	10.499	10.946	11.024	10.788	11.408
1	6.152	7.254	8.135	8.854	9.152	9.203	9.047	9.455
2	5.638	6.494	7.148	7.665	7.875	7.911	7.802	8.086
3	5.208	5.883	6.382	6.766	6.919	6.946	6.866	7.072
4	4.841	5.382	5.770	6.063	6.178	6.198	6.138	6.292
5	4.526	4.963	5.270	5.497	5.586	5.601	5.555	5.673
6	4.251	4.608	4.853	5.032	5.101	5.113	5.078	5.169
7	4.010	4.303	4.501	4.644	4.699	4.708	4.680	4.752
8	3.796	4.038	4.199	4.314	4.358	4.365	4.343	4.400
9	3.606	3.806	3.938	4.031	4.066	4.072	4.054	4.100
10	3.435	3.601	3.709	3.785	3.813	3.818	3.803	3.841
11	3.281	3.419	3.507	3.569	3.592	3.596	3.584	3.615
12	3.141	3.256	3.328	3.378	3.397	3.400	3.391	3.415
13	3.014	3.108	3.167	3.209	3.224	3.227	3.219	3.239

Table 7: Thermal resistance of the horizontal hollow brick according to the morphology of the air cavity.

	Number of cavity columns											
Number of symmetrical cross-walls	3	4	5	6	7	8	9	10	11	12	13	14
0	9.310	11.316	13.008	14.456	15.707	16.801	17.260	17.583	17.786	18.004	17.930	18.462
1	8.548	10.077	11.296	12.291	13.119	13.818	14.106	14.305	14.466	14.563	14.476	14.840
2	7.905	9.090	9.993	10.704	11.279	11.753	11.945	12.077	12.183	12.247	12.190	12.428
3	7.356	8.285	8.967	9.491	9.904	10.238	10.372	10.464	10.537	10.581	10.542	10.706
4	6.882	7.617	8.140	8.532	8.837	9.080	9.176	9.242	9.295	9.326	9.298	9.414
5	6.468	7.053	7.459	7.757	7.985	8.165	8.236	8.284	8.323	8.346	8.325	8.410
6	6.104	6.570	6.887	7.116	7.289	7.424	7.478	7.514	7.542	7.559	7.544	7.607
7	5.781	6.153	6.401	6.578	6.710	6.813	6.853	6.880	6.901	6.914	6.903	6.950
8	5.492	5.789	5.982	6.119	6.220	6.299	6.329	6.350	6.366	6.376	6.367	6.403
9	5.233	5.467	5.618	5.724	5.801	5.861	5.884	5.900	5.912	5.919	5.913	5.940
10	4.999	5.182	5.299	5.379	5.438	5.483	5.501	5.513	5.522	5.527	5.522	5.543

An example of a hollow brick without cross-sectional walls is shown in Figure 4 below. However, the increasing inclusion of the cross-sectional walls results in a significant weakening in the thermal resistance. An example corresponding to the case of a hollow brick with 3 cavity columns is shown in Figure 5 below.

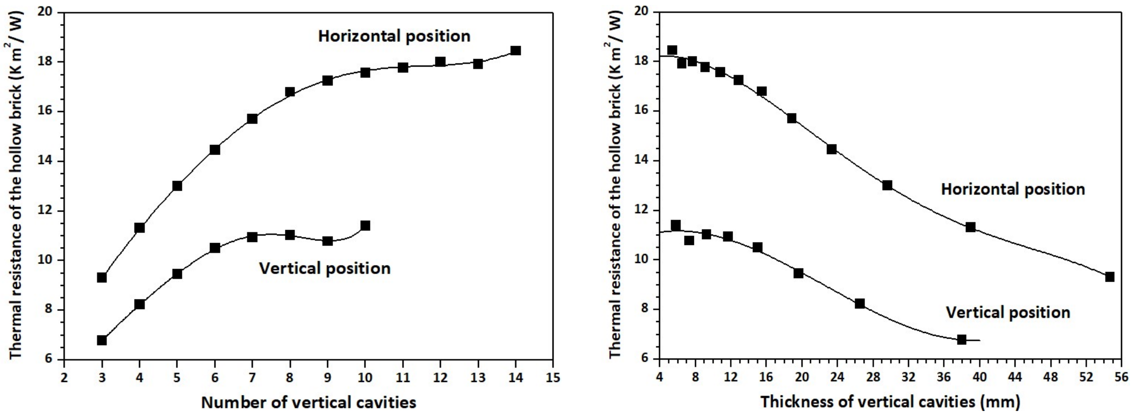


Figure 4: Variation in thermal resistance as a function of the: (a) number of air cavity columns, (b) air cavity width, case of a hollow brick without cross-sectional walls.

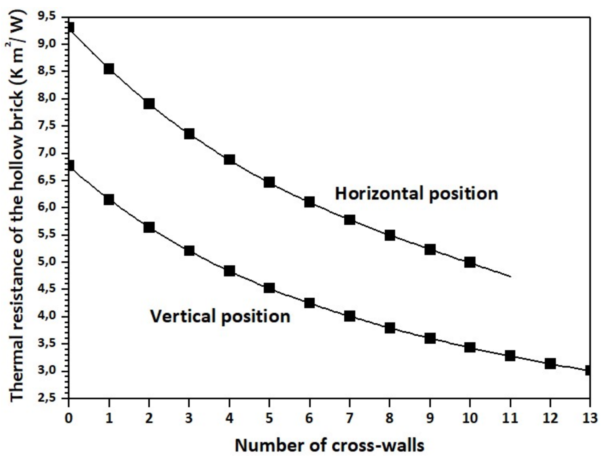


Figure 4: Variation in thermal resistance according to the number of cross-sectional walls, case of a hollow brick with 3 air cavity columns. The corresponding thickness of the air cavity is 38 mm if the brick is in the vertical position and 54.67 in the horizontal position.

3.3. Heat loss, heating and cooling energy needs according to the building's compactness

Furthermore, to compare hollow bricks of different geometric configurations, the reference case of a façade wall with a total thickness of 23 cm was selected, as shown in Figure 3. The choice was focused on heavy, hard limestone because it is locally available and the most widely used in the region. The choice was focused on heavy, hard limestone, the most widely used in the region and available locally. The thermal conductivity of the stone layer (20 cm) is 2.4 W/m K. The U-value will be the criterion for assessing wall performance. Its values are 3.58 W/m^2.K for all opaque walls in the case of the single-story house. If the east and west walls are in contact with an adjacent room, the U-value for the south and north façade walls remains the same but is changed to a value of 3.04 W/m^2.K for the east and west walls. The RT 2020 thermal regulations do not have a defined overall thermal resistance R. It will depend not only on the housing zone but also on the surface area to be insulated. On average, the R coefficient for RT 2020 is greater than 5 m² K/W.

As a result, according to all previous cases, the findings further that, bricks alone in the wall will not comply with the thermal regulation standards. On the other hand, tests and calculation programs have shown that all configurations can improve the thermal performance of walls. The heat loss through walls is affected by the dwelling's compactness. For this reason, the total heat loss through the building envelope, the wall heat losses, their share in the total heat losses and the heating and cooling energy needs are given in Table 8 according to the compactness index. It should be remembered that the compactness index is inversely proportional to the compactness. The stone will therefore be compared to a selected hollow brick which promotes good mechanical resistance and good choice for use in building construction. It corresponds to a brick in a horizontal position and has 80 cavities (10 air cavity columns and 7 cross-sectional walls) with a thickness of 10.8 mm a height of 9.75 mm, and a volume of 6472.8 cm³, corresponding to a weight of 9.6321 kg.

Table 8: Comparison between stone and hollow brick walls according to the building compactness, case of a comfort temperature between 21 and 26 °C

			1st case : single-story house		2nd case : east and west facing in contact with unheated areas		3rd case: high floor, east and west facing in contact with unheated areas	
			Stone	hollow brick	Stone	hollow brick	Stone	hollow brick
Compactness	Classic index: $S_{external\ heat\ loss}$ / Volume (m^{-1})		0.77		0.50		0.20	
	Index adapted to the architecture: Living area / Volume (m^{-1})		2.62		1.69		0.69	
Total heat loss (W/K)			833.20	642.21	563.68	474.50	472.69	383.52
Heat loss through walls (W/K)			377.66	208.55	182.59	104.36	182.59	104.36
Wall loss rate			45.33%	32.48%	32.40%	22.00%	38.63%	27.22%
Energy needs		Heating (kWh)	23 945.84	18 450.01	16 190.35	13 624.23	13 572.19	11 006.08
		Cooling (kWh)	19 479.94	15 043.21	13 219.01	11 147.42	11 105.40	9 033.81
		Total (kWh)	43 425.78	33 493.22	29 409.35	24 771.65	24 677.59	20 039.88

Firstly, the results have indicated that heat losses from the façade walls are high compared to the total heat losses, especially in the case of stone walls. Low compactness systematically leads to higher losses. This is fully in line with the insufficient and inadequate wall thickness (23 cm) to cope with external heat flows. Secondly, a significant reduction in wall heat loss was achieved in this case by using hollow bricks. They were estimated at 44.78% in the first case and 42.84% for the second and third. These values correspond to a substantial reduction of 22.87% in total heat losses and envelope energy needs (heating and cooling) for the first case, 15.77% for the second and 18.79% for the third. Referring to equation 1, the rate of decrease in total heat loss, heating, cooling and total energy needs is the same due to these losses which are linearly increasing with the energy needs (heating, cooling and their sum).

The other advantage consists in the importance of reducing weight. The elementary mass of a heavy stone wall with the same dimensions as this hollow brick is between 21.15 and 23.22 kg, knowing that its density is generally between 2350 and 2580 kg/m^3 **[22]**. However, the mass of the hollow brick in this case is equivalent to 9.63 kg, which represents a significant reduction of between 54.47% and 58.53% compared to the heavy stone.

This study has concluded that the thermal regulation standards could only be reached by increasing the thickness of the hollow bricks, creating non-ventilated air layers or incorporating an additional layer of thermal insulation. However, the structure of thicker hollow bricks can be similar to that of a monomur brick. So the characteristics of this type of brick are more suitable than in the previous cases. For an alternative solution, a more in-depth study will be proposed to test a wide range of cases. A variety of construction methods have been considered and used to investigate the thermal performance and achieve an optimum building wall system. Four such designs are shown in Figure 6. Hollow brick with 80 cavities was used as a masonry element.

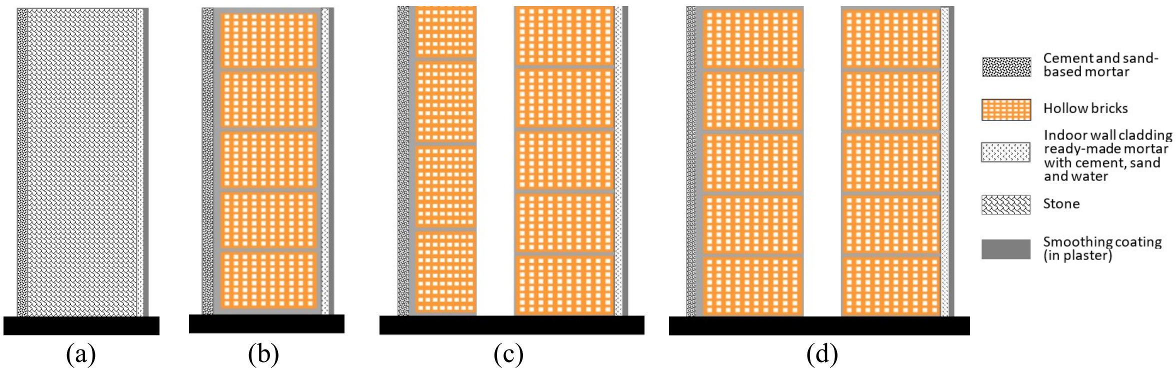


Figure 6: House wall configuration, a: stone façade walls (reference case), b: façade walls with single hollow brick, c: double-wall façade with horizontal and vertical hollow bricks, d: double-wall façade with horizontal hollow bricks

Double wall facades are therefore becoming increasingly popular in building envelope design due to their high efficiency in heating, cooling and sound insulation. The air gap in double-wall façades must be, for example, 3 cm thick to be efficient. The U-values of the façade walls were obtained by applying the thermal-electrical analogy method according to Table 9.

Table 9: Heat loss through walls and total energy required for ongoing heating and cooling for selected houses, case of a comfort temperature between 21 and 26 °C.

		U-values	Heat loss through walls (W/K)	Annual energy needs for heating and cooling (kWh)
Stone façade walls	1st case	3.58 W/m^2.K for all façade walls	377.66	43 425.78
	2nd case	3.58 W/m^2.K for south and north-facing walls and 3.0390 W/m^2.K for east and west-facing walls	182.59	29 409.35
	3rd case		182.59	24 677.59
Façade walls with single hollow brick	1st case	1.98 W/m^2.K for all façade walls	208.55	33 493.22
	2nd case	1.98 W/m^2.K for south and north-facing walls and 1.80 W/m^2.K for east and west-facing walls	104.36	24 771.65
	3rd case		104.36	20 039.88
Double-wall façade with horizontal and vertical hollow bricks	1st case	1.10 W/m^2.K for all façade walls	115.85	28 204.47
	2nd case	1.10 W/m^2.K for south and north-facing walls and 1.04 W/m^2.K for east and west-facing walls	59.17	22 109.76
	3rd case		59.17	17 377.99
Double-wall façade with horizontal hollow bricks	1st case	1.03 W/m^2.K for all façade walls	108.10	27 592.83
	2nd case	1.03 W/m^2.K for south and north-facing walls and 0.98 W/m^2.K for east and west-facing walls	55.31	21 882.69
	3rd case		55.31	17 150.92

The monthly energy needs for heating and cooling have demonstrated their dependencies on several factors, such as the building compactness and the thermal insulation, as shown in Figure 7.

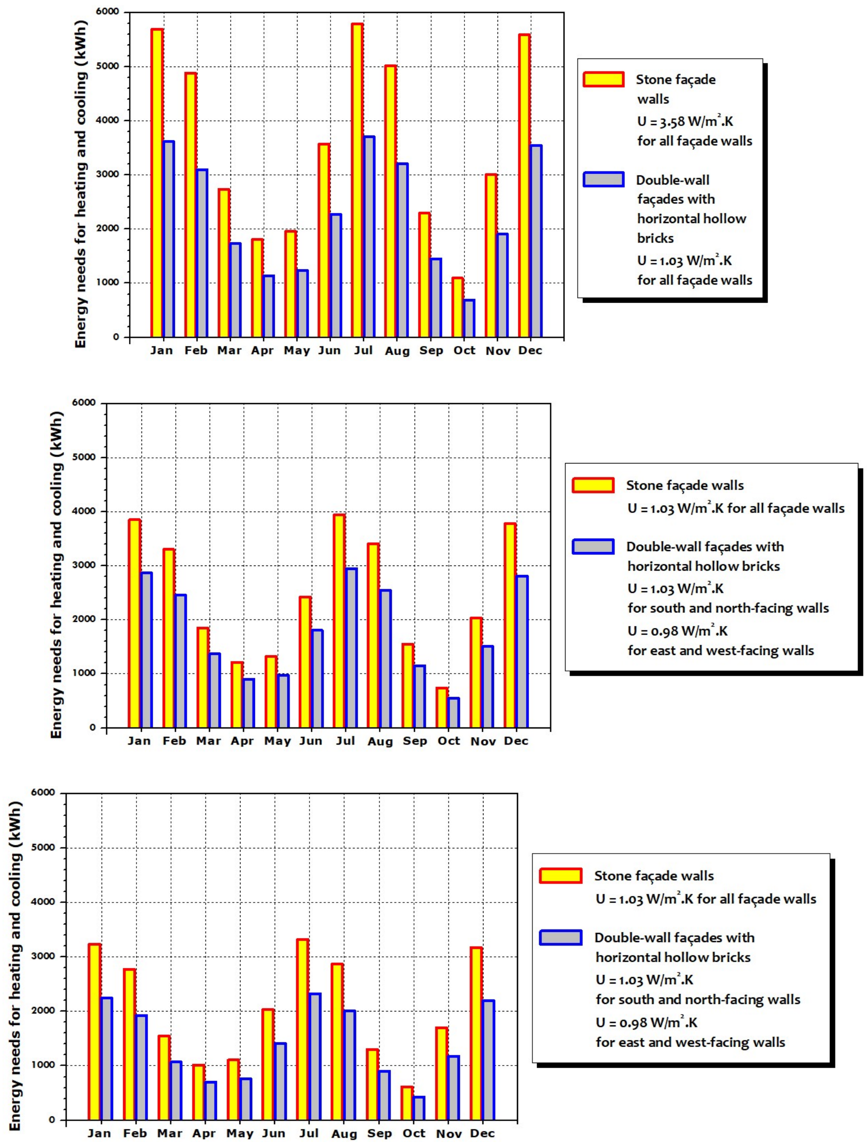


Figure 7: Monthly energy requirements for a comfortable temperature between 21 and 26 °C, a: case of a single-story house, b: the case of east and west facing in contact with unheated areas, c: the case of high floor, east and west facing in the contact with unheated areas

Firstly, it was found that the results obtained were highly dependent on the level of compactness of the dwelling. According to the table, it should be remembered that compactly designed buildings often require less energy for heating and cooling. For example, a decrease of 51.65% in heat loss through walls and a reduction of 43.17% in heating and cooling energy requirements can be achieved by comparing a low-compact stone house with a conventional index of 0.77 and a suitable index of 2.62 with a house with much lower indices of around 0.20 and 0.69 respectively. In the second configuration, heat loss and energy requirements for heating and cooling will be reduced by 49.96% and 38.39% respectively. In the case of double-wall façades with horizontal and vertical hollow bricks, a reduction of 48.92% and 40.17% respectively has been generated. The latter case corresponds to a 48.83% reduction in heat loss and a 37.84% reduction in heating and cooling requirements.

Secondly, unlike the single wall, the double-wall façade with horizontal hollow bricks is a construction technique that offers several advantages in terms of thermal insulation and durability.

This passive concept refers to a design and construction strategy that improves thermal comfort and energy efficiency, sometimes without active mechanical air conditioning systems. Heating and air conditioning energy savings can be reduced by up to 36% compared with a single-skin wall.

In addition, heavy stones do not provide the same effective thermal insulation as hollow bricks, despite their good thermal inertia. Thanks to its cavities, hollow brick offers better thermal and even acoustic insulation properties, which can contribute to greater comfort in buildings. This is because hollow bricks have cavities that trap air, reducing heat conduction and improving the energy efficiency of buildings. These cavities provide better thermal insulation, which can help reduce heating and cooling costs.

To further improve thermal insulation, hollow bricks can be combined with other insulating materials. For example, adding thermal insulation to the space between walls is a common technique for improving the building's energy efficiency.

In very hot climate areas such as Ghardaïa, thermal regulations impose specific requirements in terms of the thermal resistance of walls to ensure optimum thermal comfort and reduce energy consumption. Thermal regulations give maximum U or minimum R values for walls, according to climatic zones **[23]**. Generally, to limit heat loss in winter and minimize heat gain in summer, the thermal resistance of walls should be high enough, at least 5 m^2.K/W. However, the best thermal resistance obtained from the previous configurations is only 1.02 m^2.K/W, which is still insufficient. Injected polyurethane, for example, can be selected as it is particularly well-suited to hard-to-reach areas, which explains its success in the renovation of buildings lacking thermal insulation.

4. Conclusion

There are different types of hollow bricks with different insulation properties. So it's important to choose those that meet current thermal insulation standards. Innovations in brick manufacture have also led to more efficient designs, optimizing cavities to meet the specific needs of modern construction projects. When designing façade walls, it is essential to consider the thickness of the bricks, the arrangement and the layout of the air cavities to maximize the effectiveness of the thermal insulation.

Cavity design can also be important. Well-distributed and appropriately sized cavities can maximize the insulating effect, while cavities that are too large or poorly arranged may reduce the effectiveness of the insulation. The thermal resistance is therefore influenced by its internal structure and the number of cavities. As a general rule, a brick with a greater number of cavities can provide better thermal insulation. This can be explained by the cavities that trap air, which is a good insulator. The air contained in these spaces reduces heat conduction through the material, which improves the overall thermal resistance of the brick.

The cavity columns are generally more appropriate for hollow bricks. They provide better load distribution and improved thermal and compressive resistance, which is essential for masonry structures. The cavity lines can also be used, but they are often less effective in terms of strength and stability. The significant number of cross walls in hollow bricks can create thermal bridges, where heat can transfer more easily from one side of the brick to the other.

This reduces the effectiveness of thermal insulation. These circumstances lead to consider other morphologies that avoid straight transverse walls.

Unlike hollow bricks, heavy stone is generally more expensive due to extraction, transportation, and implementation costs.

Adopting construction techniques that promote insulation, such as double walls or frame construction systems, can also be beneficial. For permanent residences or buildings requiring thermal comfort, double-wall structures or more advanced insulation systems are generally recommended. The double-wall design helps reduce heating and cooling needs, resulting in significant energy savings of up to 36%.

The innovations in this field of study aim to improve not only the energy efficiency of buildings but also their comfort and sustainability while meeting increasing environmental requirements. They mainly concern:

- Improving thermal performance without increasing wall thickness by suggesting avenues for proposing innovations in the design of the cells.
- The development of lighter hollow bricks, while maintaining their strength, facilitates handling and reduces the weight of structures, which can be particularly advantageous for multi-story construction projects.
- The addition of insulating materials combined with air cavity morphologies allows for minimizing the required thickness of insulation compared to conventional cases and further increases the energy efficiency of hollow walls.
- The modular construction technology using hollow walls will, consequently, be more in demand due to its simplicity, enhanced insulation, and very affordable cost.
- The possibility of combining these structural integration morphologies with more advanced technologies such as breathable membranes or vapor barriers, not only to enhance the level of thermal insulation but also to regulate humidity and prevent mold issues.
- The innovation in breakthrough technologies for thermal bridges is a construction technique that creates connecting elements between different parts of the structure, allowing for a reduction in heat transfer through walls with air cavities.

The compactness of a building, which refers to purely geometric indices, plays a crucial role in thermal insulation. In general, a more compact building tends to have better thermal performance, which can result in lower thermal insulation requirements. This could allow for the use of thinner insulation while maintaining the same thermal comfort. Building codes and energy efficiency standards can therefore play a role in determining the thickness of insulation based on compactness. More compact buildings may be subject to different regulations that take their design into account. In summary, the compactness of a building has a significant impact on the thickness of the required thermal insulation. A compact design can lead to energy savings and a reduction in insulation needs, while still maintaining adequate thermal comfort.

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Paper submitted: 13.03.2025

Paper revised: 19.04.2025

Paper accepted: 25.04.2025