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Relationship between Geometric Shapes of Hollow Bricks and their Thermal Efficiency: Case of a Single-family House in Hot Desert Climates

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Abstract

Air cavities play a crucial role in energy efficiency. Well-designed air cavities serve as an insulating barrier and minimize thermal bridges. The investigation aims to explore several aspects, including the impact of the number of cavities and their geometric shapes on thermal resistance. The calculation guidelines have been established by the standards outlined in the Algerian Regulatory Technical Document DTR.C3-4. The number of test cases for a hollow brick in a vertical position will consist of 12 configurations, all with the same external dimensions of 20 cm × 15 cm × 30 cm. The goal is to prioritize the design of air cavities within the hollow bricks to improve their thermal efficiency. The internal structure and the number of cavities significantly impact thermal resistance. Cavity columns are typically better suited for hollow bricks, as they enhance load distribution and offer superior thermal and compressive resistance, crucial for masonry structures. The multiple cross walls in hollow bricks might create thermal bridges, which can enhance heat transfer between the sides of the brick.

Keywords: Air cavities; Geometric shapes; Hollow bricks; Electrical analogies; Thermal resistance; Energy needs.

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1. Introduction

Energy requirements for cooling and heating are responsible for nearly 40% of the total electric energy consumption in Algeria [1-2]. This situation is typical in regions of harsh climatic conditions with extremely hot and cold climates [3]. Building envelopes made of hollow bricks with air cavities are an innovative approach. These materials are designed to enhance thermal insulation, reduce energy consumption, and improve overall building performance. Hollow bricks, often made from clay or concrete, feature internal voids that create air cavities, which serve as thermal barriers. This design helps to minimize heat transfer between the interior and exterior of a building, contributing to energy efficiency [4-6]. Bekkouche et al. [1] highlighted that, in arid regions, hollow bricks offer an optimal balance of thermal comfort compared to heavy stone and cinderblock. Similarly, Bellahcene et al. [7] emphasized that the thermal performance of hollow bricks largely depends on the number and geometric configuration of their cavities, which significantly influence the insulation and thermal resistance of walls. Consequently, hollow bricks exhibit favorable thermal and physical properties, effectively minimizing heat transfer through the building envelope and reducing energy consumption across all seasons.

According to previous studies [8], it can be inferred that several factors must be taken into account when designing façade walls. These include the thickness of the bricks, the configuration of the air cavities, and their overall arrangement, all of which are crucial for optimizing thermal insulation performance. Cavity columns are typically better suited for hollow bricks due to their advantages in load distribution. They enhance thermal performance and compressive strength, both of which are crucial for the integrity of masonry structures. Additionally, their design contributes to more efficient weight distribution and improved resistance to thermal fluctuations, making them an ideal choice for such applications. Cavity lines may also be utilized, but they are frequently less efficient regarding resistance and stability. The large number of cross walls in hollow bricks can lead to thermal bridging, making it easier for heat to transfer from one side of the brick to the other. It is precisely at this point that the idea of this work is situated. We want to change several configurations of air cavity bricks to observe the influence of thermal bridges on the thermal characteristics of this building material. For this, 12 geometric shapes for hollow bricks, based on steady-state heat transfer, have been suggested. The purpose of the investigation was focused on the effect of the cavities number and their geometric shape on their thermal resistances.

The distinctive nature of this study is also linked to an Algerian computational technique that produces innovative results, enriching the understanding of building physics. The calculation guidelines have been developed to meet the standards mandated by the Algerian thermal regulation (Regulatory Technical Document DTR.C3-4). The second goal is to optimize the cavity configuration, which reduces heat loss through the walls and consequently improves energy management in the building. However, by intelligently optimizing the geometry of internal cavities, effective insulation of cavity walls can capture warm or cold air and inhibit the circulation of undesired air through the cavity. This approach significantly enhances building performance and interior comfort. The energy needs calculation method assesses the energy required for heating and cooling. The resulting data will be utilized to evaluate the energy efficiency of these cavity walls in comparison to a standard single wall.

2. Materials and Methods

A refined methodology, rooted in established classical formulas and aligned with standards endorsed by the scientific community and official technical documentation, was employed to fulfill the outlined objectives. Hollow bricks were purposefully selected as the subject of the investigation to assess the influence of internal voids on thermal performance. These bricks are crafted from terracotta , a natural composite of clay and sand undergoing a meticulous process of grinding, moistening, molding, and drying, followed by firing at high temperatures ranging between 900°C and 1200°C for approximately thirty hours.

A. Thermal and electrical analogies

The electrical-thermal analogy has been established as a practical approach for determining equivalent thermal resistances. The thermal resistance R ($m^2.K/W$) is influenced by both the geometric configuration and the thermal properties of the materials making up the hollow brick. In this context, the material layers are assumed to be uniform, stacked vertically, and aligned perpendicularly to the direction of heat transfer. The terms 1/h ($m^2.K/W$) and e/λ ($m^2.K/W$) represent the thermal resistances of an air layer and a flat wall, respectively where e is thickness, λ is thermal conductivity, and S is surface area. The convective heat transfer coefficient, h, quantifies the exchange between the air cavity and the adjacent vertical surface. The procedure used to estimate the air cavity's equivalent resistance follows the guidelines outlined in the Regulatory Technical Document [9]. This approach is approximate, assuming one-dimensional heat flow and incorporating empirical formulas to account for natural convection and radiative heat exchange within and between cavity surfaces. Thermal resistance values for air layers can be referenced from the chart presented in Table 1. The thermal conductivity of the terracotta that constitutes the hollow brick is 1.15 W/m.K.

Table 1. Thermal Resistance of the Air Layer as a Function of its Thickness.

Air gap thickness (mm)	5 to 7	8 to 9	10 to 11	12 to 13	14 to 300
Thermal resistance value m².K/W	0.11	0.13	0.14	0.15	0.16

Figure 1 below depicts the electrical diagram of the hollow brick.

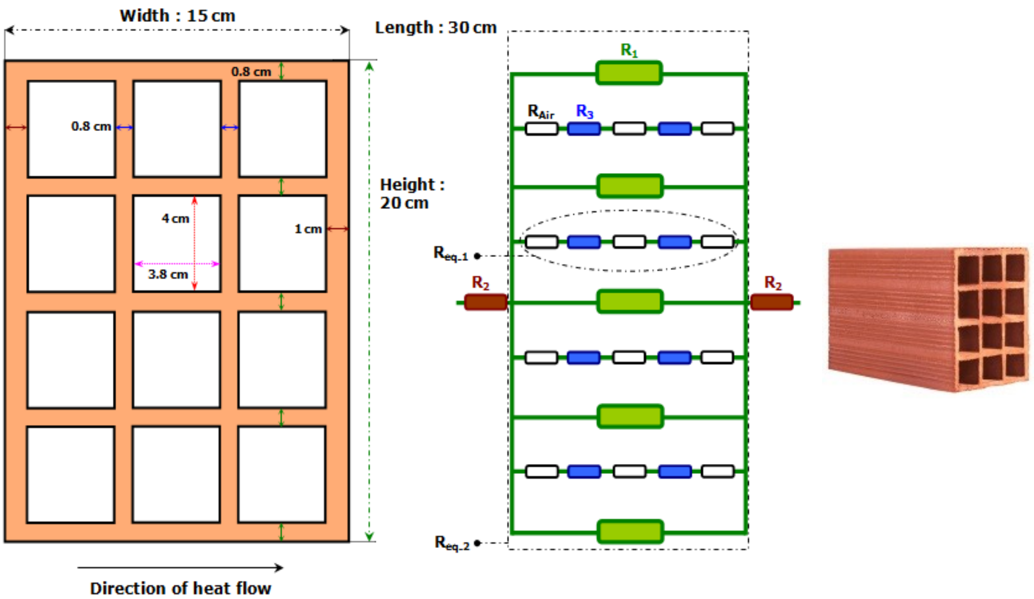


Figure 1. Configuration of the masonry unit and resistor network, case of a hollow brick with 12 identical vertical rectangular cavities of dimensions 4 cm x 3.8 cm

B. Geometric configurations of the studied hollow bricks

The number of test cases for a hollow brick in a vertical position will be 12 configurations. As illustrated in Figure 2, were analyzed, all sharing identical external dimensions of 20 cm × 15 cm. The objective of this analysis is to offer a systematic basis for prioritizing the design of air cavities in hollow bricks, thereby enhancing their thermal performance. The assumptions made are:

- Heat transfer across the walls is considered unidirectional, moving perpendicular to the brick's vertical facades.
- Heat transfer occurs by conduction in the solid body and by convection in the air cavities.
- The temperature distribution on the external and internal surfaces of the bricks is assumed to be uniform, in accordance with the principle of the nodal method.
- It is also assumed that the thermo-physical properties of the bricks remain constant throughout the process.

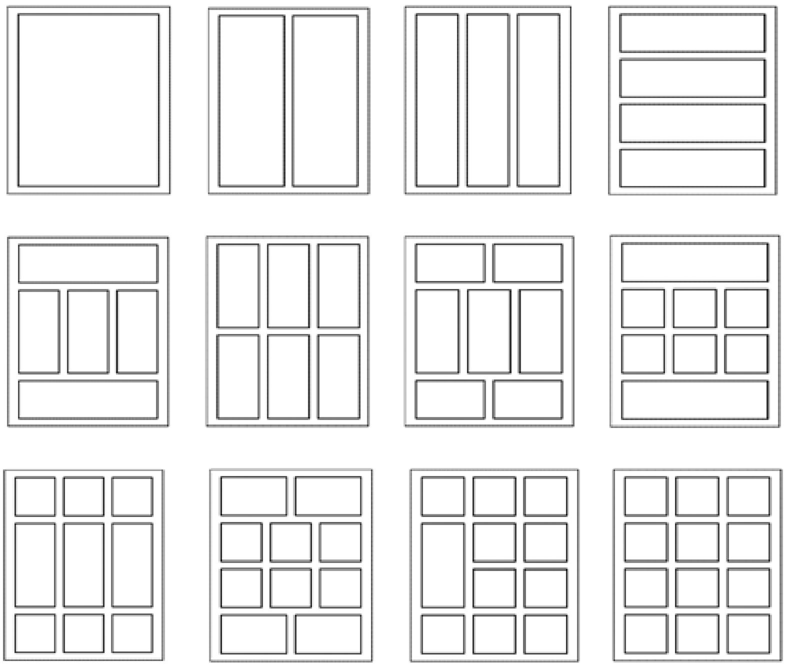


Figure 2. Pre-suggested configurations

C. Summary calculation method for heating and cooling requirements

The energy efficiency of a building is defined by its thermal balance, which involves managing heat gains and losses to maintain comfortable indoor conditions. The calculation of the building's energy needs (Wh) for heating and cooling is mainly based on the following basic equations. The building's energy needs for heating and cooling, typically expressed in kilowatt-hours (kWh), are calculated on the basis of the following basic equations [10-12]:

$$\mathbf{E_{Envelope} = 24\ Heating\ and\ cooling\ degree\ days \times HL_{Envelope} \pm Intermal\ heat\ gain \pm Passivesolar\ gain} \quad \mathbf{(1)}$$

$HL_{Envelope}$ is the sum of heat losses through walls, windows, doors, ceilings and roofs, thermal bridges, floors and ventilation, in W/K. represents the total heat losses occurring through walls, windows, doors, ceilings, roofs, thermal bridges, floors, and ventilation, calculated in watts per kelvin (W/K).

$$\mathbf{HL_{Envelope} = HL_{Walls} + HL_{VCeilings\ and\ Roofs} + HL_{Windows} + HL_{Doors} + HL_{Thermal\ bridges} + HL_{Floors} + HL_{Ventilation}} \quad \mathbf{(2)}$$

Each building component's heat loss can be assessed through the following general expression:

$$\mathbf{HL_{Bulding\ element} = \sum_{i=1}^{i=n} b_{Bulding\ element-i} S_{Bulding\ element-i}\ U_{Bulding\ element-i}} \quad \mathbf{(3)}$$

The variable n represents the total number of thermal zones within the building. The variable i denotes the thermal zone number. The variable $S_{Building\ element\_i}$ indicates the total surface area of the building element (m^2). The thermal transmittance, indicated by $U_{Building\ element\_i}$, is quantified as the U-value ($W/m^2.K$). Finally, $b_{Building\ element\_i}$ serves as the coefficient that measures heat loss reduction.

D. Overview of the building masonry and its thermal-physical characteristics.

This house has a total floor area of 126.69 m² and includes a living or dining area, kitchen, two bedrooms, a bathroom, and a toilet as depicted in Figure 3. It is not equipped with an air-conditioning system (for cooling or heating) nor with a mechanical ventilation system. The technical specifications, particularly the composition of the masonry and the thermo-physical properties of the building elements, are detailed in Table 2.

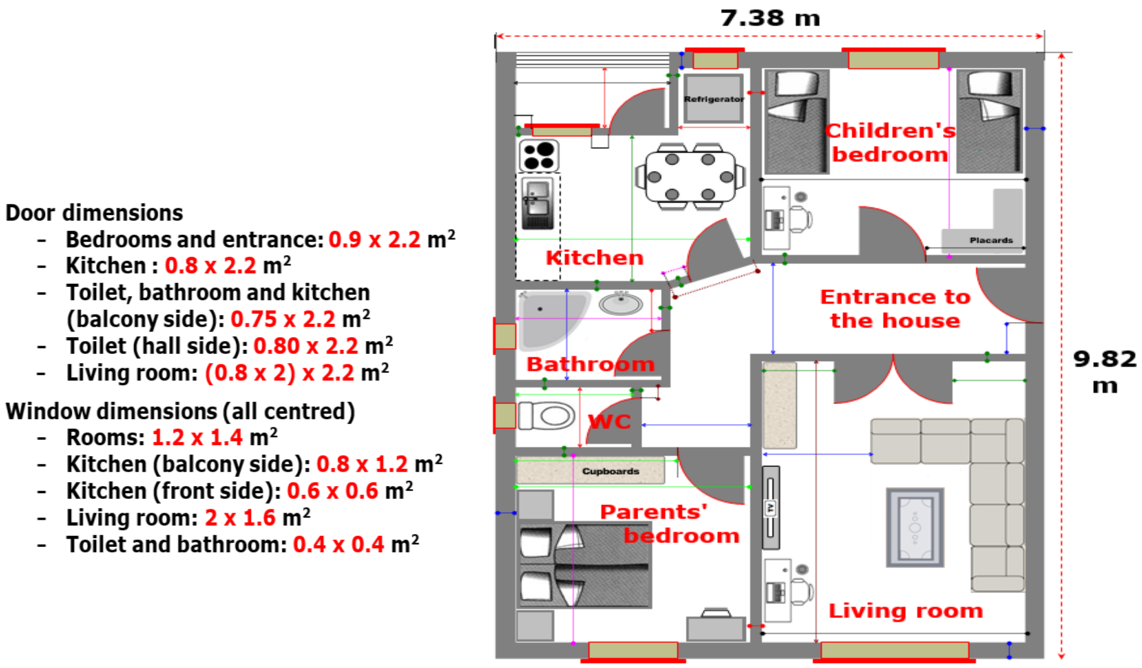


Figure 3. Residential plan illustration

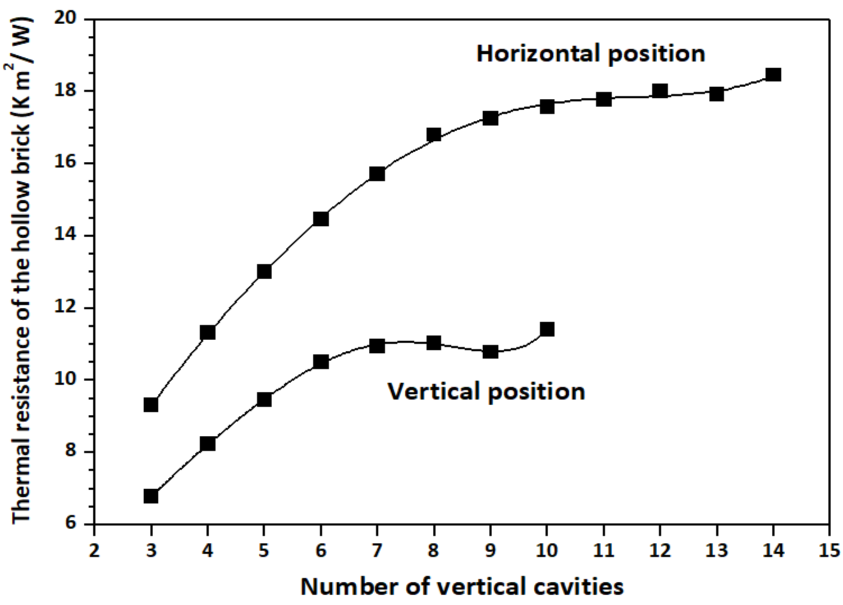
Table 2. Masonry Materials Used in Buildings and Their Thermal Properties

Masonry materials		Thickness Mm	Thermal conductivity W/m K	U-value W/m².K
Building façades	Exterior rendering	18	1.40	According to the case study
	Bricks designed with cavities	/	/	
	Indoor surface cladding	10	1.40	
	Plaster smoothing layer	02	0.35	
Upper-level roofing	Cement-based mortar screed	50	1.40	2.80
	Hollow core slab 20 x 16 x 53 cm³	200	1.45	
	Cement mortar rendering	10	1.40	
	Finishing plaster for sleek surfaces	02	0.35	
Floor on solid ground	Granite layer for flooring	20	2.1	1.14
	Cement mortar screed	30	1.4	
	Reinforced concrete slab	200	1.75	
	Ground: Firm foundation	/	/	
Single-glazed windows				5.00
Metal entrance door				5.80

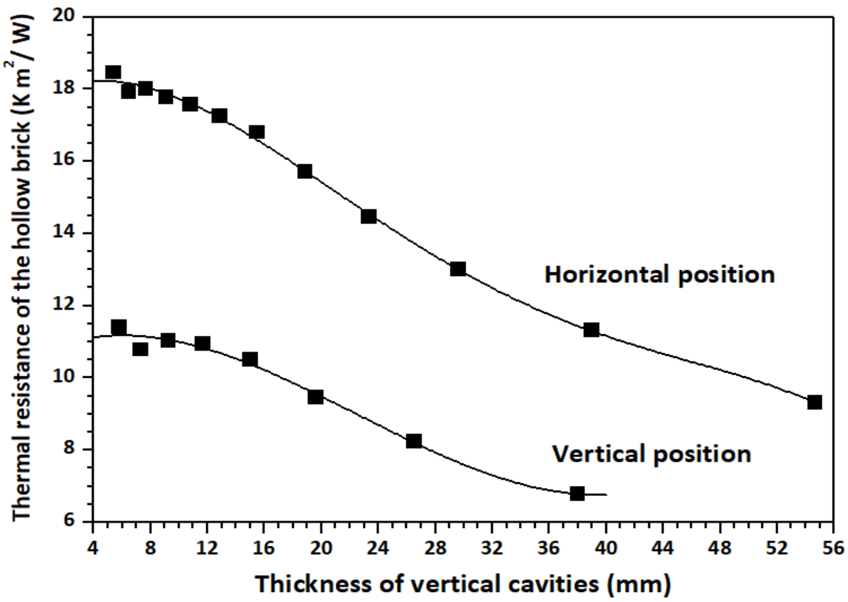
3. Findings and Analysis

In the building construction industry, enhancing thermal resistance in bricks can be achieved through several strategies, including reducing heat transfer and innovating the design of bricks. The findings presented in this section indicate that thermal resistance improves as the number of cavity columns increases, irrespective of the number of cross-sectional walls that are oriented perpendicular to these columns. Additionally, it is important to note that increasing the width of the cavity will consistently lead to a decrease in thermal resistance. Hollow bricks are among the building materials that exhibit good thermal resistance, due to their composition and geometry.

Figure 4 below illustrates a hollow brick that lacks cross-sectional walls; however, as the number of cross-sectional walls increases, the thermal resistance is notably compromised.



(a)



(b)

Figure 4. Variation in thermal resistance in relation to: (a) the number of air cavity columns, (b) the air cavity width, case of a hollow brick without cross-sectional walls [8].

To provide a comparison, Figure 5 illustrates the thermal resistance of a hollow brick that includes three 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.

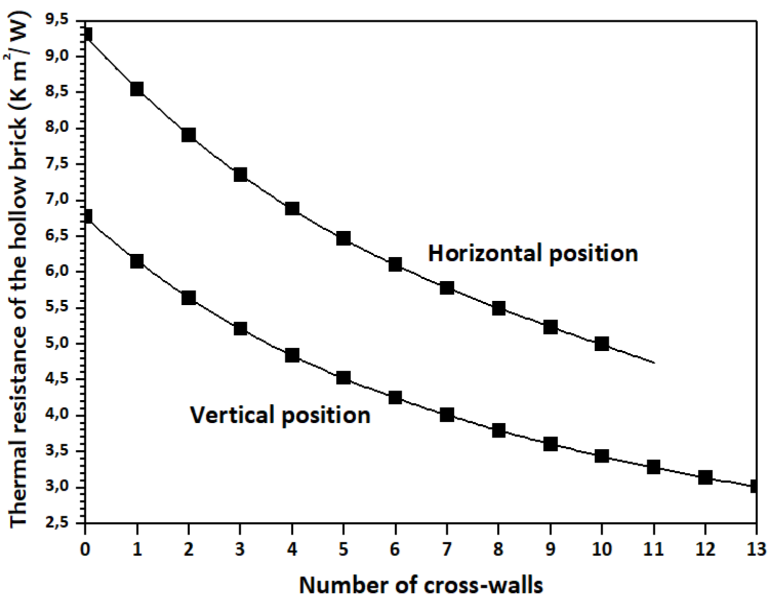


Figure 5. Variation in thermal resistance according to the number of cross-sectional walls, case of a hollow brick with 3 air cavity columns [8].

The bar graphs the effect of the geometric shape of hollow bricks on their thermal resistance. According to the bar graphs (Figure 6), the results obtained in this section show that the number of cavities and their geometric arrangement significantly influence thermal resistance. The key takeaway is that incorporating vertical air cavities, aligned perpendicularly to the direction of heat flow, is more effective in enhancing the bricks thermal resistance.

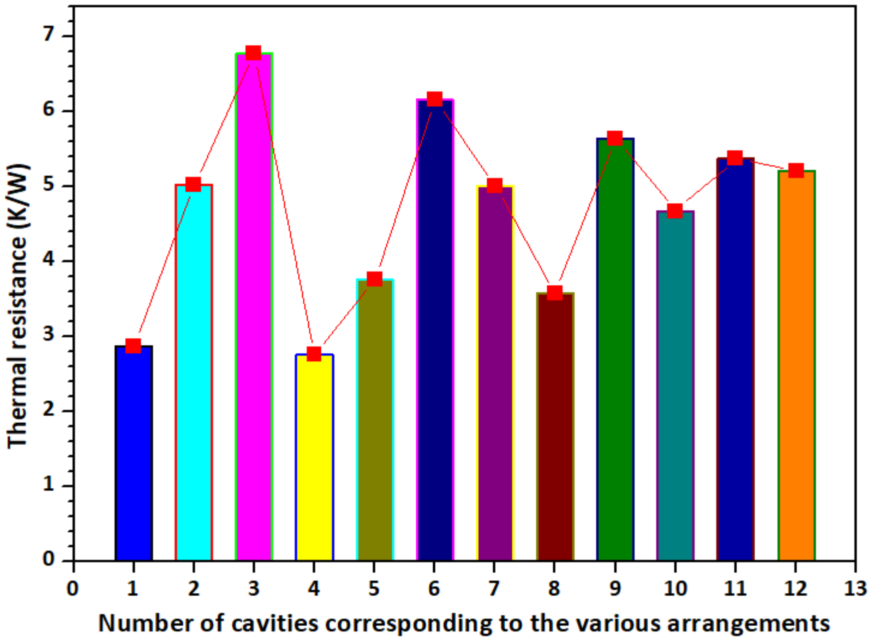


Figure 6. Thermal resistances of hollow bricks according to the various configurations, expressed by the number of air cavities.

As a result, and in line with all previous cases, the findings indicate that the engineering of hollow bricks plays a significant role in enhancing the thermal performance of walls, thereby contributing to a reduction in energy consumption. This is evident in the monthly heating and cooling energy demands, as illustrated in Figure 7.

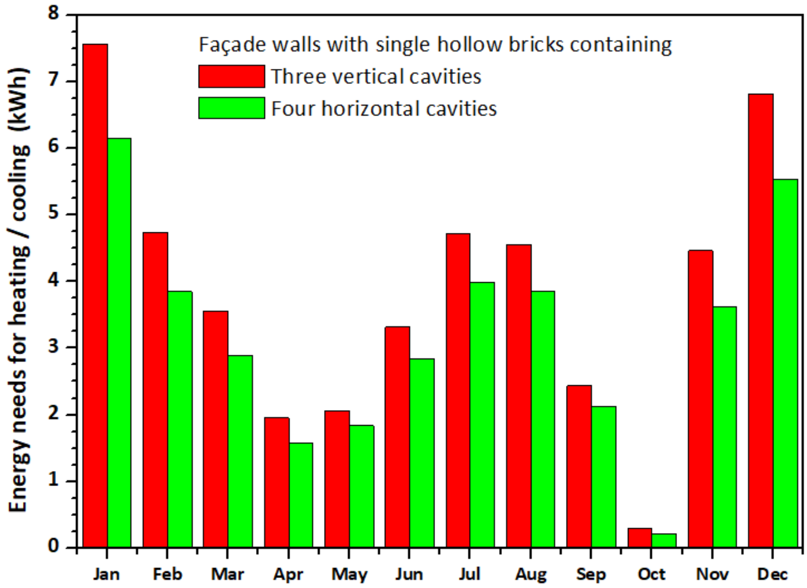


Figure 7. Monthly energy requirements for a temperature between 20 and 28 °C

The results clearly demonstrate that the thermal performance of walls is highly influenced by the geometry of hollow bricks. As illustrated in the bar charts, using 3-cavity hollow brick walls instead of 4-cavity ones led to a notable 17.16% reduction in heating and cooling energy requirements. Hollow bricks enhance both thermal and acoustic insulation, contributing significantly to indoor comfort. This improvement is primarily due to the air trapped within the cavities, which reduces heat conduction and enhances the overall energy efficiency of buildings. To further optimize thermal insulation, alternative geometric configurations can be explored and developed based on the current findings, aiming to increase thermal resistance and reduce the U-value of walls. Such advancements would help ensure better thermal comfort and lower energy consumption, ultimately reducing heating and cooling costs.

4. Conclusion

A well-designed building envelope considers local climatic conditions, thermal performance, and environmental sustainability. In many buildings, overheating is primarily caused by heat absorbed through the walls. The number and shape of cavities in hollow bricks are crucial in improving insulation and thermal resistance.

Cavity design is significant; properly sized and evenly distributed cavities can enhance insulation, whereas oversized or poorly configured cavities may diminish its effectiveness. The internal structure and the number of cavities significantly impact thermal resistance. Cavity columns are typically better suited for hollow bricks, as they enhance load distribution and offer superior thermal and compressive resistance, crucial for masonry structures. The cavity lines can also be used, they tend to be less effective regarding strength and stability. Additionally, the numerous cross walls in hollow bricks may lead to thermal bridges, facilitating easier heat transfer between the brick's sides.

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