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Analysis of heat fluxes in ceramic block type building pieces

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Abstract. In Norte de Santander, Colombia, there is a ceramic cluster made up of 59 companies dedicated to the production of construction materials derived from clay, a vernacular material with a wide extraction potential in the region. Fired clay products in different hollow block presentations represent 15% of industrial production, these construction pieces are low cost and show a high demand in the local masonry market, therefore, their thermo-physical characteristics largely build the thermal envelope of "Cucuteña". This research comparatively evaluates the thermal behavior of four types of ceramic blocks with different perforations, applying the finite element method in thermal simulations that consider a conductivity of 0.407 W/m°C in the ceramic to establish the influence of the shape on the temperature distribution and heat flow profiles of each piece subjected to environmental conditions of a warm semi-arid climate, with average maximum temperatures of 33 °C and an average maximum solar radiation of 796.8 Wh/m² under extreme climatic conditions in the city of San Jose de Cúcuta, Colombia. The results of the study allow identifying the ceramic block of 6 rectangular holes as the product that, due to its physical characteristics, presents a better alternative to be applied in constructions that seek thermal efficiency.

1. Introduction

In the department of Norte de Santander, the richness of the location defines the constructive materiality with which its architecture is built, the clay, as a material wealth, is a vernacular resource with excellent physical and chemical characteristics for the manufacture of ceramic pieces for construction. Therefore, in this northeast area of Colombia there is an industrial cluster that is responsible for its exploitation and transformation, bringing together 59 companies dedicated to the production of construction ceramics [1], which make up one of the most important subsectors of the local economy, representing 21% of the manufacturing sector, producing 38% of employment and contributing 12.8% of the GDP in the region [2,3], the goods derived from this production process generate a large supply of materials for the construction sector such as blocks, bricks, tiles, slabs, among others.

The present research seeks to evaluate the thermal behavior of the most demanded ceramic pieces for masonry in the region of Norte de Santander, where ceramic blocks represent 15% of the total products manufactured by clay companies [4,5], its demand is related to its constructive functionality and low cost in the market, which makes it an accessible piece and, therefore, a molding element of the thermal loads of the local envelope, a particularly relevant factor in a context of warm semi-arid climate [6,7].

From this perspective, the evaluation of heat fluxes on the physical properties of the parts can determine those products that present better thermal advantages for enclosures in a warm climate with average temperatures between 27 °C and 33 °C without large variations throughout the day, a location with low cloud cover and high solar radiation incidence that can reach 796.8 Wh/m².

2. Methodology and materials

The research selects a specific typology of ceramic piece, block type products of measures length: 300 mm, width: 100 mm and height: 200 mm to analyze 4 constructive units with different shapes in the horizontal cavities Figure 1, the H10 block with six rectangular cavities (B-A), Figure 1(a), the H10 block with 8 rectangular cavities (B-B), Figure 1(b), the H10 block with 4 rectangular cavities whit 2 circular cavities (B-C), Figure 1(c), and the H10 block with 8 circular cavities (B-D), Figure 1(d).

In the study, the same thermal conductivity is applied to all the pieces, obtained through the linear transient flow method of 0.407 W/m°C for clay fired at 1000 °C [8-10], and the influence of the internal shapes of the partitions and the area of the air chambers on the thermal behavior of the products is evaluated; traditional pieces for ceramic masonry are taken as a sample, their characteristics are presented in Table 1.

| (a) | (b) | (c) | (d) |
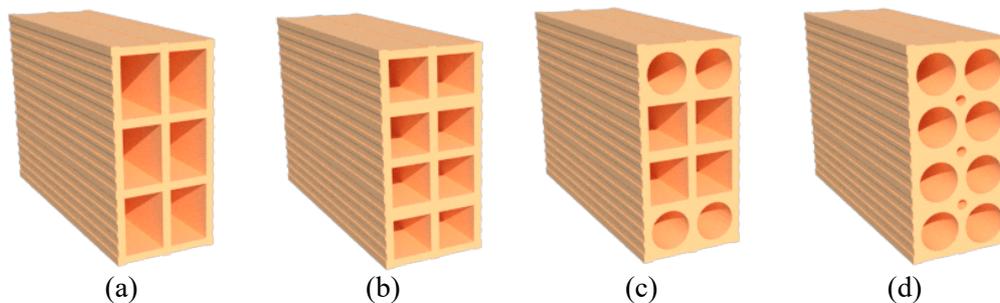
Figure 1. Ceramic block (a) B-A, (b) B-B, (c) B-C and (d) B-D.

Table 1. Characteristics of the types of ceramic blocks.

Vacuum percentage per air chamber			
B-A	B-B	B-C	B-D
64%	57%	55%	46%

The finite element method is used to develop thermal simulations in ANSYS R16 software, implementing parameters specific to the climate of the city of San José de Cúcuta, Colombia, to establish the thermal behavior by heat transfer of the parts in conditions of 33 °C as average maximum temperature, determining the temperature distribution and heat flows related to the shape and dimension of the parts.

The environmental data used are taken from the IDEAM [11] for a geographic location of latitude: 7.9 °N, longitude: 72.5 °W, altitude: 298 m.a.s.l. in San José de Cúcuta, Colombia, taking as a reference point for the temporality the month of September as the period that presents the highest temperatures throughout the year, considering average maximum climate variables from 12:00 hours to 13:00 hours of a typical day, where, a wind flow presents a speed of 4 m/s and an average maximum solar radiation of 796.8 Wh/ m².

The data used for the conductivity of the materials, k Clay = 0.407 W/m°C; in relation to the calculated data, the convective heat transfer coefficient is the value that depends on the wind speed and the temperature and pressure conditions in which it is found, is calculated by the Equation (1) [12].

$$h = \frac{Nu*k}{Lc}, \qquad (1)$$

where, h is the convective heat transfer coefficient, Nu is the Nusselt number, k is the thermal conductivity of air, Lc is the assumed characteristic length of 20 cm. The Nusselt number is a dimensionless value that describes the increase in heat transfer over a surface [12]. For a rectangular cross-section and crossflow, is represented by Equation (2).

$$\text{Nu} = 0{,}102\text{Re}^{0,675} * \text{Pr}^{1/3}, \tag{2}$$

where Re is the Reynolds number, Pr is the Prandtl number. The Reynolds number is a dimensionless value that describes the behavior of the air flow over the surface of the block and is calculated by the Equation (3) [12].

$$\text{Re} = \frac{\rho * V * Lc}{\mu}, \tag{3}$$

where ρ is the air density, V is the wind speed, μ is the dynamic viscosity of the air. The properties of air for a temperature of 33 °C are described as, $\rho = 1.1526\,\text{Kg/m}^3$, $k = 0.026102\,\text{W/m°C}$, $\mu = 0.000018858\,\text{Kg/m.s}$, $Pr = 0.72736$.

Replacing the values in order of Equation (1), Equation (2) and Equation (3), results in a convective heat transfer coefficient of $h = 17.5154\,W/\text{m}^2.°\text{C}$ to be applied to the outer section of the geometry, where the wind speed takes effect, and assumes a heat transfer by natural convection of 5 W/m²°C and a heat flux of 796.8 W/m², for surfaces that are not enclosed as internal air chambers, a heat transfer coefficient by natural convection of $h = 5\,W/\text{m}^{2°}C$ [12]; the conditions to which the products are subjected are shown in Figure 2.

A	Convection 1: 5 W/m².°C
B	Convection 2: 17,5154 W/m².°C
C	Flujo de calor: 796,8 W/m²
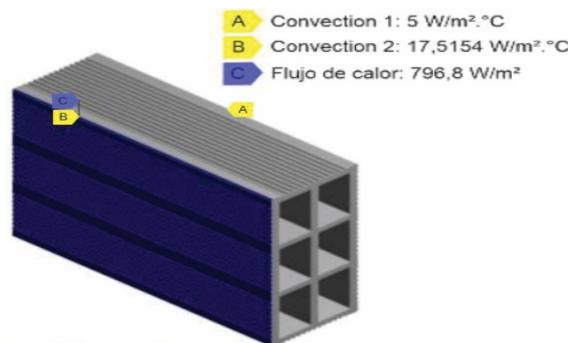
Figure 2. Conditions applied to the models.

3. Results and discussion
The results of the thermal simulations allow a comparative analysis of the heat fluxes and temperature distribution profiles across the bridges and partitions of each piece in relation to the influence exerted by the rectangular and circular geometric shapes of the horizontal air chambers.

3.1. Heat flow results
The Figure 3 shows the results of heat flow profiles in each piece, where the horizontal partitions function as direct thermal bridges, piece B-A (Figure 3(a)) contains 4 direct thermal bridges and B-B (Figure 3(b)), B-C (Figure 3(c)), and B-D (Figure 3(d)) 5 direct heat paths, where, B-C (Figure 3(c)) and B-D (Figure 3(d)) by using a circular geometry increases the percentage of ceramic mass of the thermal bridge and facilitates heat transfer by conduction.

Comparing the shape of the partitions in the rectangular geometries an average heat flow of 149.0 W/m² is found and in the circular shapes there is an average of 174.1 W/m² with little significant differences. However, if the heat flow in the final wall surface of the pieces is compared higher percentages are observed in B-C (Figure 3(c)) and B-D (Figure 3(d)) as they present less contact with

the air chamber, which increases the final heat transferred in the pieces with average values of 100 W/m^2, while geometries such as B-A (Figure 3(a)) and B-B (Figure 3(b)) with greater area exposed to the air chamber decreases the thermal transfer presenting heat flows in the final surface closer to 30 W/m^2; the heat flow results are presented in Table 2.
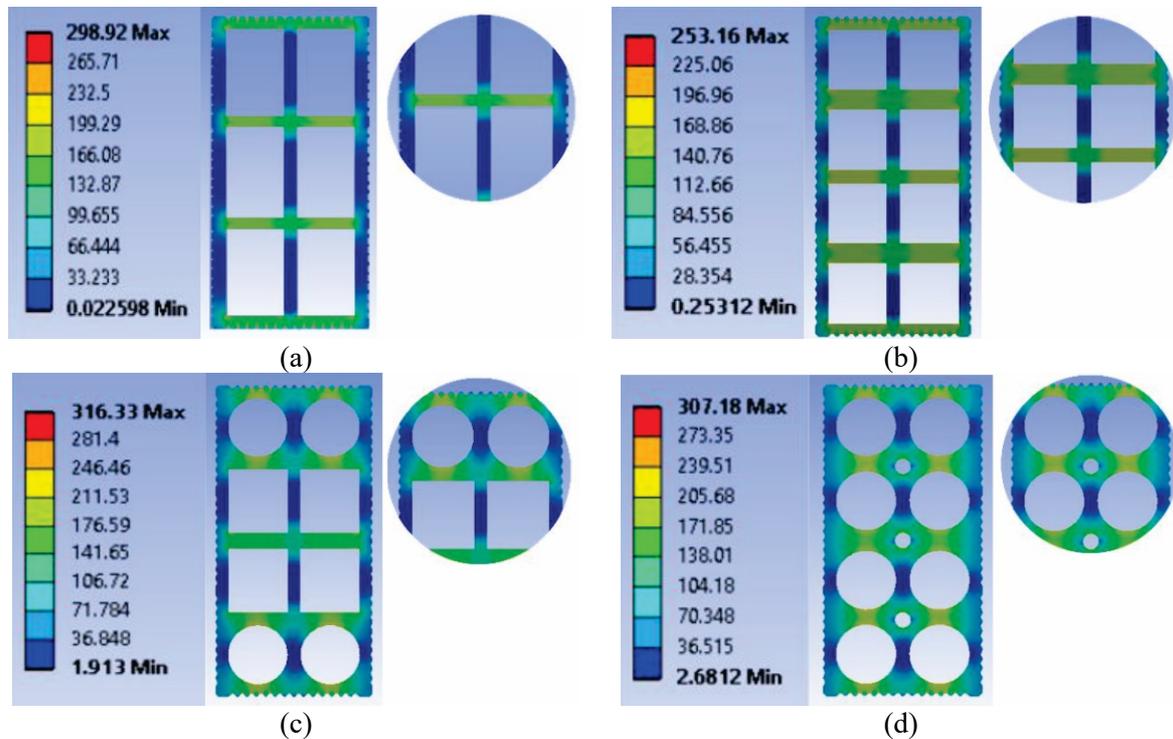
Figure 3. Heat flow results of products type (a) B-A, (b) B-B, (c) B-C and (d) B-D.

Table 2. Heat flow results.

Product	Type	B-A	B-B	B-C	B-D
Average heat flux in partitions (W/m^2)	Rectangular	146.0	140.7	141.6	
	Circular			176.5	171.8

3.2. Temperature distribution results

The temperature transferred to the interior of a B-A Figure 4 product under 33.0 °C conditions present a profile of 37.9 °C, with high temperatures that cross the thermal bridge and reach the internal surface at average temperatures of 41.0 °C; and in those layers that cross air chambers, a transmittance of 38.2 °C is recorded in the final temperatures.
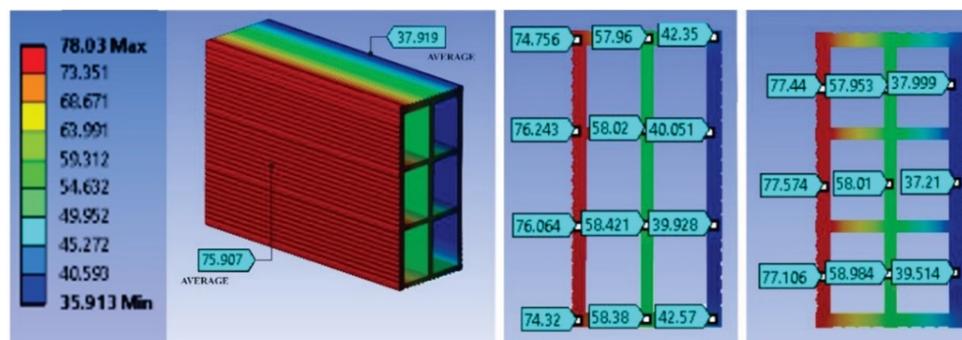
Figure 4. Temperature distribution results for product B-A.

In the Figure 5 the temperature distribution profiles show higher average values in those parts containing circular internal shapes; products such as B-C (Figure 5(b)) containing mixed shapes show temperatures of 38.9 °C and B-D (Figure 5(c)) whose internal cavities are completely curved show temperatures of up to 42.3 °C, product B-B (Figure 5(a)) shows final temperatures of 39.2 °C due to a reduction in the percentages of internal air and an additional thermal bridge with respect to B-A (Figure 4), which shows the lowest final temperature of 37.9 °C, a significant decrease in the final temperature with respect to the other pieces, of approximately 1.0 °C and up to 4.4 °C between B-A (Figure 4) and B-D (Figure 5(c)); the temperature distribution results are presented in Table 3.

(a)

(b)

(c)
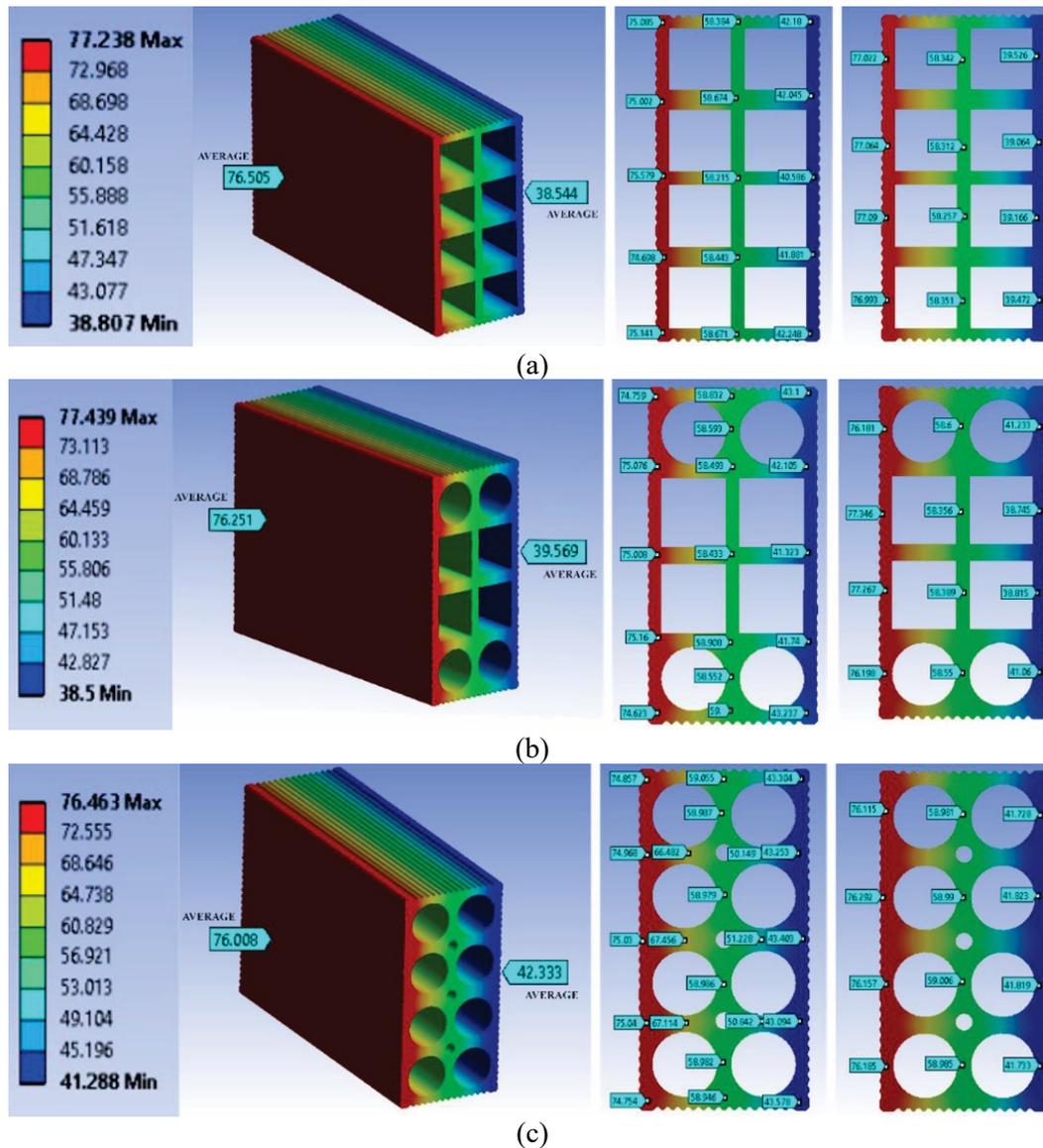
Figure 5. Temperature distribution results of products type (a) B-B, (b) B-C, and (c) B-D.

Table 3. Temperature distribution results.

Average	B-A	B-B	B-C	B-D
Temperature initial surface (°C)	75.90	76.50	76.25	76.00
Temperature final surface (°C)	37.91	38.5	39.5	42.33

With the results compiled in Table 4, it can be observed that the B-C and B-D pieces that contain cylindrical cavities can present temperatures between 1° C and 2 °C above a B-C piece in the final thermal conditions of the partitions' path, and if the paths through the initial wall, the air chamber, the intermediate wall, the air chamber and the final temperature of the internal wall are analyzed, the results can be from 2.7 °C to 5.0 °C above a B-A type piece. These results allow us to identify the B-A type as the one that, due to its physical characteristics of rectangular cavities and fewer thermal bridges, achieves better thermal performance results for a hot tropical climate.
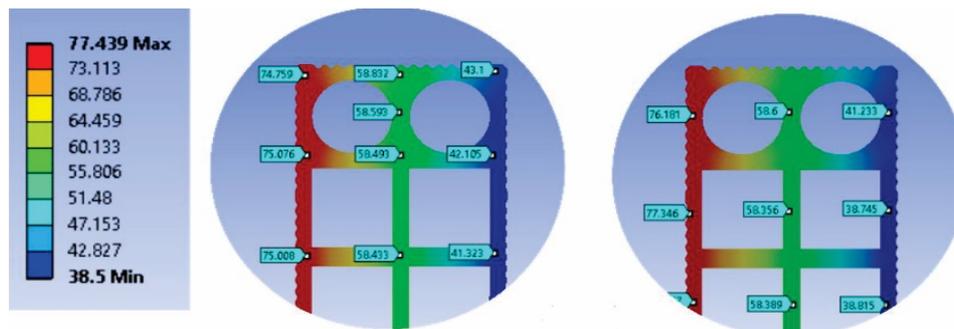
Figure 6. Detail of the results of temperature distribution in part B-C.

Table 4. Final surface wall temperature distribution results.

Average	B-A	B-B	B-C	B-D
Across thermal bridge or partition wall (°C)	41.0	41.7	42.2	43.2
Through wall and air chamber (°C)	36.5	39.2	39.9	41.7

4. Conclusions

One aspect that may be of interest in the selection of materials for the construction of masonry in the area of influence of the ceramic companies in the Norte de Santander, Colombia, is the thermal behavior of the products that build these enclosures. This research has determined the influence of the internal physical characteristics of the ceramic block type pieces on the heat transferred to the final surfaces of the envelope, finding a difference greater than 2 °C with the modification of the number of thermal bridges, the density of the piece and a rectangular or circular shape in its cavities.

The results of thermal simulations demonstrated that B-A, a light piece with 6 rectangular cavities is the most viable product within the available options for constructions in hot semi-arid climates by presenting only three direct thermal bridges, a higher percentage of interior air volume and a rectangular shape. On the other hand, circular shapes and larger mass have shown to obtain temperatures up to 4 °C higher than a B-A block, making it an inefficient system for the envelope in the city of San José de Cúcuta, Colombia.

This comparative study can serve as a basis for the correct selection of building envelope materials in an extreme hot climate, as well as for the definition of design guidelines in the development of new products that can effectively contribute to the reduction of thermal loads of ceramic building systems, a particularly relevant issue in the mitigation of energy consumption in buildings.

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