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Exploration of types of ventilated air chambers to improve thermal efficiency of bricks in fired clay

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Abstract. The products and construction systems for facades regulate energy transfer in the architectural envelopes. Therefore, this paper developed an exploration of types of ventilated air chambers to improve thermal efficiency of brick for masonry walls in fired clay, taking into account their role in buildings. The methodology involves three fundamental stages: design, simulation and analysis of results. The design stage proposes 3 brick typologies with ventilated air chamber. The second stage simulates the behavior of the heat transfer and heat fluxes of the models in extreme climatic conditions of San José de Cúcuta, Colombia, in September in Ansys software through the finite element method. Finally, the analysis of results studies the relationship between the incorporation of the ventilated chamber, shape of the product and heat transfer of proposed models, in comparison with the multi-perforated brick. The results indicate that thermal benefit varies between 2.52 °C and 3.64 °C in the interior surfaces of proposed bricks. Moreover, incorporation of ventilated air chamber mitigates heat transfer and reduces energy concentration in the interior sides of new bricks design. In conclusion, innovation in brick design proves that new forms proposition generates added values such as thermal benefits related to comfort. This aspect is important to consider because it establishes a transformative perspective for brick industry through an innovative market that is committed to sustainability of architectural envelopes in order to reduce energy consumption of buildings.

1. Introduction

The best strategy for regulating energy consumption in construction is to control transfer of energy loads from the envelope as an active connector between interior and exterior of the building [1]. Furthermore, to analyze logical relationships between geometry, proportion and orientation of an elementary architectural element as modifiers of the microclimate [2].

The design of the facade must be considered as a passive system capable of identifying determinants that interact a space, in order to improve the energy performance of a building [3]. Taking into account, the processes and design parameters such as the type of construction, materials, shape of the building and composition of the envelope with regard to solar orientation, ventilation and natural lighting, shading, air tunnels, thermal insulation, resistance of materials to humidity, condensation, storms and floods [4-8]. Studies are redirecting their approaches towards the shape and manufacture of geometries of architectural envelopes through patterns, due to the environmental impact of their energy behavior with respect to their surroundings [9,10], considering that decisions of the architect in design stage affect the energy efficiency of the building and those who inhabit these spaces [11].

In this order of ideas, the product design must be complementary and consider criteria that add mitigation of solar incidence and generate thermal insulation. The main factors to consider are the alteration of exterior surfaces for the generation of their own shadows [12,13], modification of hollows distribution in order to create longer thermal paths that delay heat conduction [10,14,15], treatment of mortar joints to reduce thermal bridges caused by high conductivity of the material [14-16] and finally, the incorporation of ventilated air chambers [13].

Such as, proposing dynamic and sensitive facades to climate changes that exposed a building is the new target of designers, architects and engineers to reduce energy consumption [1]. The purpose of this paper is to explore types of ventilated chambers in fired clay bricks. The process begins with design of 3 perforated bricks with ventilated air chambers (B-VAC) to validate thermal properties in ANSYS software through the finite element method. To finish the analysis of the simulation results, it discusses the relationship between product shape of B-VAC and their thermal performance obtained from the temperature distributions and energy fluxes.

2. Methodology
The methodology for the exploration of types of ventilated air chambers is contemplated in three stages: product design, thermal validation and analysis of results.

2.1. Product design
In the first place, product design for masonry is based on criteria and formal logic that contribute to the proposition of new sustainable solutions aligned with the current market offer in the ceramic industry of Norte de Santander, Colombia. Taking into account the above, the format of the products consists of vertical perforations like the multi-perforated brick (MB). The first stage develops the technical drawing of the 3 designs and MB as reference pattern in 2 and 3 dimensions (2D, 3D) in AutoCAD software.

2.2. Thermal validation: simulation of heat transfer and fluxes
Thermal validation begins with the export in IGES formats of the modeling of MB and B-VAC in the ANSYS software; the following subsections describe data required on the conductivity of materials, climatic conditions of a specific environment and types of fluxes that affect the surfaces of the bricks, in order to evaluate thermal performance of the exploration of B-VAC design. Further, Figure 1 illustrates materials used and types of fluxes involved in heat transfer of bricks.

2.2.1. Conductivity of materials. Figure 1 illustrates mapping of clay and mortar materials in the two-dimensional view of MB and B-VAC proposals. The main focus of the paper is to identify thermal behavior from the shape, therefore, only 2 materials will be used in the simulation. First material is clay, its thermal conductivity is 0.30 Wm°C. It will be used in the entire body of bricks and it is represented with color blue and lilac in Figure 1. Second material is mortar for vertical joints that connect the exterior-interior path between bricks (horizontal direction). Its conductivity is 0.88 Wm°C [17] and it is represented with color grey in Figure 1.

2.2.2. Climatic conditions of environment. The selected scenario for thermal validation of B-VAC typologies is the city of San José de Cúcuta, Norte de Santander, Colombia. The selected period is the most critical of the year, which is the month of September between 12:00 and 13:00. The data provided on the climatic conditions of the environment for thermal validation are average maximum solar radiation (796.8 Wm^2), average maximum temperature (33 °C) and average wind speed corresponding to the environment (4 m/s) [18].

2.2.3. Types of fluxes according to the mechanisms of heat transfer by radiation and convection. Finally, the types of fluxes applied to the surfaces of bricks are classified according to the heat transfer mechanism. Figure 1 also identifies the fluxes applied by radiation and convection on the corresponding

surfaces of each element. First, solar radiation (796.8 Whm^2) acts as heat flux on the outer surfaces corresponding to the ventilated air chamber, identified by the dashed blue line in Figure 1.

In the second place, the convection acts externally on the interior surfaces of hollows whose function is the ventilated air chamber, under a convection heat transfer coefficient of 25.903 Wm^2°C, represented by yellow line in Figure 1. By last, the natural convection on the interior surfaces of product with a 5 Wm^2°C, identified with orange line in Figure 1. In Figure 1(a) show of the materials and fluxes applied to MB, in Figure 1(b) show the B-VAC 1, in Figure 1(c) show the B-VAC 2 and Figure 1(d) show the B-VAC.

(a)	(b)
(c)	(d)
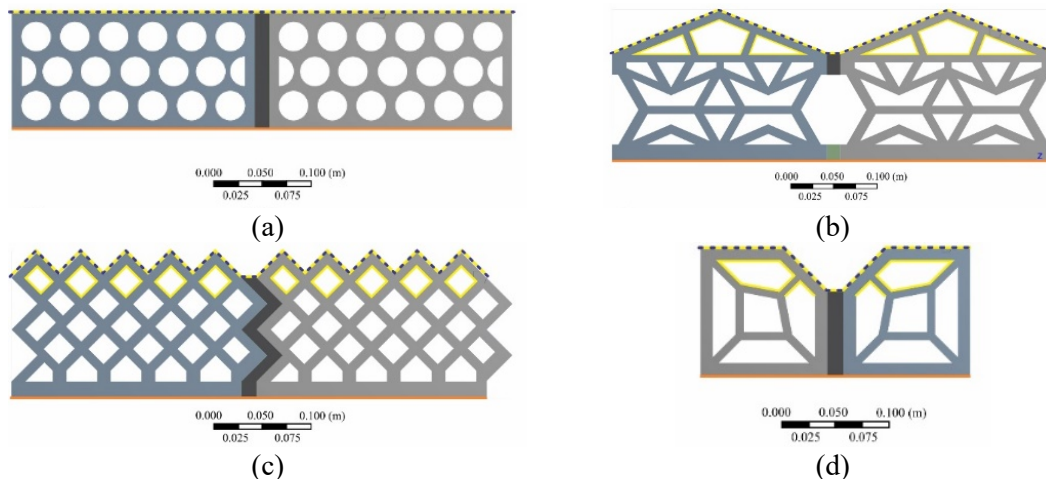
Figure 1. Materials and fluxes applied to MB (a), B-VAC 1 (b), B-VAC 2 (c), B-VAC 3 (d). Colors blue and lilac represent clay and grey represents mortar joint. Dashed blue line: solar radiation; yellow line: exterior convection. Orange line: interior convection.

2.3. Analysis of results

Analysis of results debates thermal behavior of B-VAC according to the relationship between shape and materiality, distribution of exterior and interior temperatures, energy fluxes and influence of the ventilated air chamber. Furthermore, heat fluxes are analyzed from Equation (1), corresponding to Pearson's correlation coefficient [18]. Equation (1) identifies the correlation of the exterior, interior and exterior-interior surface of bricks and their mortar joints through the following Pearson correlation coefficient, Equation (1).

$$r_{xy} = \frac{\sum Z_x Z_y}{N}. \tag{1}$$

3. Results and discussion

This section presents three types of clay bricks that incorporate design concepts in order to improve thermal performance and evaluate main aspects that influence energy concentration. The analysis of results examines values obtained from heat transfer and flow simulations according to B-VAC shape.

3.1. Product design

The exploration in the design of ventilated air chambers yielded 3 typologies that vary in size and shape of the perforations or hollows, geometry of the surface exposed to solar incidence, mortar joint and brick format. The starting point for the design of the new proposals is MB in fired clay (Figure 2), which is a traditional product of the ceramic industry in Norte de Santander and Colombia. MB is a brick manufactured by extrusion, with a rectangular base with multiple vertical and cylindrical perforations [19]. Figure 2(a) shows principal components of MB design in 2D: Does not consider ventilated air

chamber (VAC) on the external surface, regular mortar joint and regular geometry of hollows, while Figure 2(b) shows 3D model of MB.
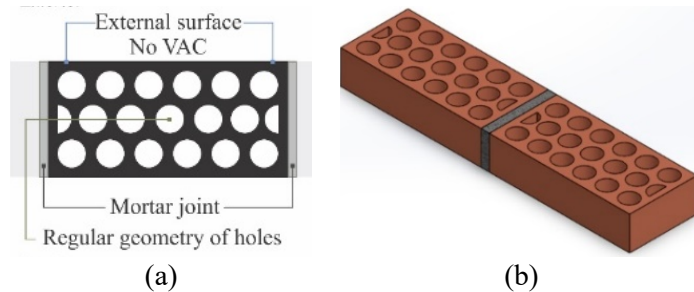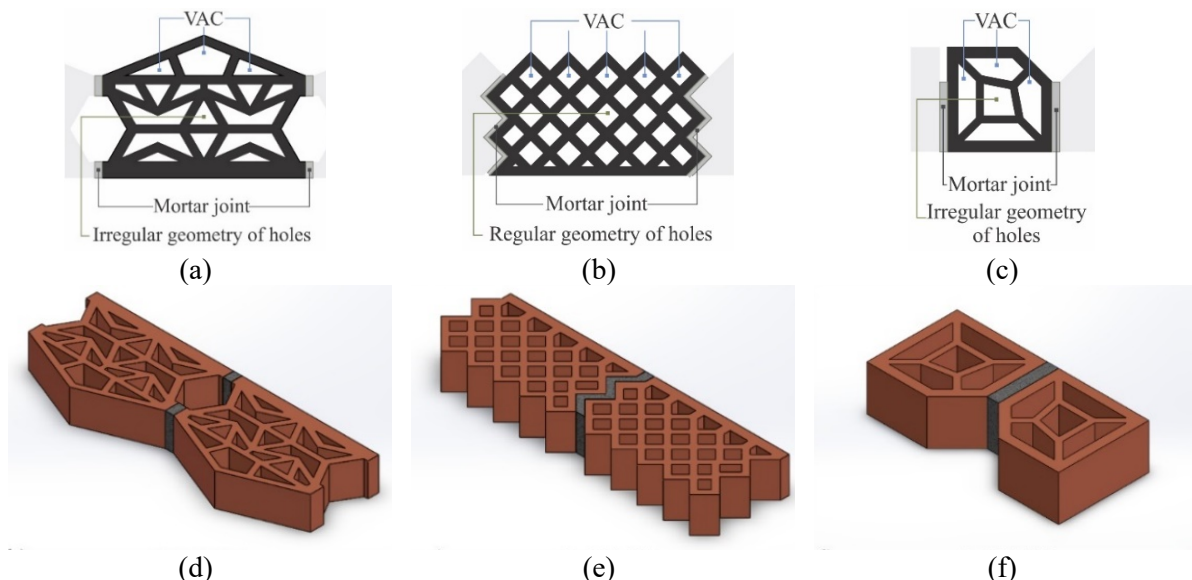

Figure 2. MB design: 2D section and shape description (a) and 3D model of MB (b).

3.1.1. B-VAC 1. The first proposal is B-VAC 1, shown in Figure 3(a), Figure 3(d). Its design has 3 hollows ventilated air chamber that alters the geometry of the surface with 2 inclined planes. The distribution of interior hollows responds to a geometry of triangles and irregular polygons patterns. There are 12 perforations. Additionally, another cavity between bricks is added as a treatment of mortar joint, to block the direct heat conduction through this material with high conductive properties.

3.1.2. B-VAC 2. The B-VAC 2 design has 10 inclined planes on the outer surface that form 5 cavities of ventilated air chamber. Figure 3(b), Figure 3(e) shows the regular geometry of hollows, formed by perforations with a square and rectangular base. A the same as the outer surface, B-VAC 2 side faces also form inclined planes to alter the path of the mortar joint.

3.1.3. B-VAC 3. Finally, B-VAC 3 proposal is a square format with an inclined plane on the outer surface, which forms the ventilated air chamber with just one cavity, as it is seen in Figure 3(c), Figure 3(f). The irregular hollows (4 units) in this design revolve around a central hollow. As its format is small compared to the other products, the mortar joint is longitudinally reduced, and it remains direct as MB.

Figure 3. B-VAC design: 2D section and description of principal components of design: B-VAC 1 (a), B-VAC (b) and B-VAC 3 (c) and 3D model of B-VAC 1 (d), B-VAC 2 (e) and B-VAC 3 (f).

3.2. Thermal validation: simulation of heat transfer and fluxes

The energy transfer simulations of the products yield 2 types of values: temperature distribution in °C and heat fluxes in Wm2. Next, Table 1 registers values of temperature distribution of exterior surfaces

and interior of MB and types of B-VAC. Moreover, Table 1 includes heat fluxes values of bricks and mortar joint outdoors and indoors. As mentioned above, MB values are the reference standard to contrast performance of BVAC typologies, in order to discuss energy efficiency of the implementation of sustainable design criteria of bricks.

The analysis of results of heat transfer and heat fluxes is validated with values in Table 1 obtained from the simulations and it is also complemented with Figure 4 and Figure 5, which illustrate thermal and energy concentration profiles of MB and B-VAC typologies according to their shape.

Table 1. Values of temperature distribution and heat fluxes of MB and B-VAC.

Brick	Temperature distribution (°C)		Average heat fluxes (Wm²)			
	Exterior surface	Interior surface	Exterior surface		Interior surface	
			Brick	Mortar joint	Brick	Mortar joint
MB	63.00	37.56	27.47	120.95	27.47	120.95
B-VAC 1	60.56	33.92	190.51	79.55	0.289	16.14
B-VAC 2	62.00	35.04	171.45	233.11	1.86	32.69
B-VAC 3	60.61	34.80	169.81	207.19	20.27	38.96

3.2.1. Heat transfer: temperature distribution. Figure 4 illustrates temperature distribution between exterior and interior of extrusion sections of MB Figure 4(a) and brick typologies with ventilated air chamber, B-VAC 1 Figure 4(b), B-VAC 2 Figure 4(c), B-VAC 3 Figure 4(c). Thermal benefit of B-VAC typologies is reflected in the decrease in temperatures of interior surfaces, according to Table 1. The best performance is B-VAC 1 Figure 4(b), with 3.64 °C less than the inner surface of MB Figure 4(a); while, B-VAC 2 and B-VAC 3 decrease by 2.52 °C, Figure 4(c) and 2.76 °C, Figure 4(d), respectively. According to the above, thermal behavior reduces interior temperatures between 6.70% to almost 10% in the best of cases, Figure 4(b).

According to the temperature distribution in Table 1 and thermal profiles in Figure 4, it is verified that thermal efficiency of bricks is related to the consideration of concepts such as treatment of mortar joints, reduction of thermal bridges, alteration of exterior surface and generation of long thermal paths through the modification hollows distribution [10,12-14,20].


(a)   (b)   (c)   (d)
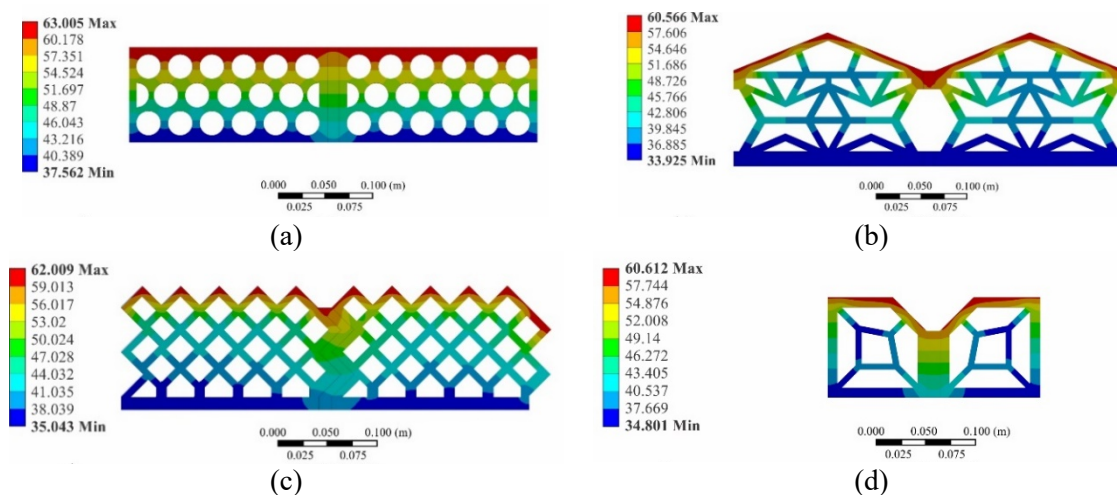
Figure 4. Thermal profiles of bricks (°C): MB (a), B-VAC 1 (b), B-VAC 2 (c), B-VAC 3 (d).

3.2.2. Heat fluxes: energy concentration. Heat fluxes represent the concentration of energy transferred from exterior to interior according to the shape of the product and the conductivity of material. Figure 5 shows heat fluxes of 3D models of MB Figure 5(a) and brick typologies with ventilated air chamber, B-VAC 1 Figure 5(b), B-VAC 2 Figure 5(c), B-VAC 3 Figure 5(c). Moreover, Figure 5 highlights the 3 common areas in all bricks: exterior surface or ventilated air chamber, mortar joints and holes or

hollows. In order to thoroughly examine heat behavior according to the implementation of passive design strategies: ventilated air chamber [12], treatment of mortar joint [13,15] and modification of hollows distribution [10,13,14].

Taking into account values in Table 1, the main variation of energy concentration according to the shape is identified thanks to the Equation (1) obtained between the heat fluxes of outer and inner surface of brick and mortar joint, recorded in Table 2. There is a negative correlation between heat fluxes of exterior-interior surfaces of bricks (-0.79). Since the difference in heat fluxes registered on the exterior surface of B-VAC increases with the implementation of ventilated air chamber and correspondingly, it mitigates transfer of heat fluxes to the interior surface. The modification of hollows distribution complements the decrease in heat fluxes, Figure 5(b), Figure 5(c), and Figure 5(d), shows how the holes of B-VAC typologies contain minimum values (between 0.28 Wm^2 to 1.86 Wm^2) compared to the outer surface of each element and MB section, Figure 5(a).

In the case of the mortar joint (-0.18), the exterior-interior correlation is also negative but to a greater extent, since the difference between exterior and interior heat fluxes is less because conductivity of the mortar is higher in this study and therefore, more energy is concentrated at this point. The best treatment mortar joint to mitigate heat transfer is the generation of an air chamber to block the direct passage of the material [10,14] such as B-VAC 1, Figure 5(b).
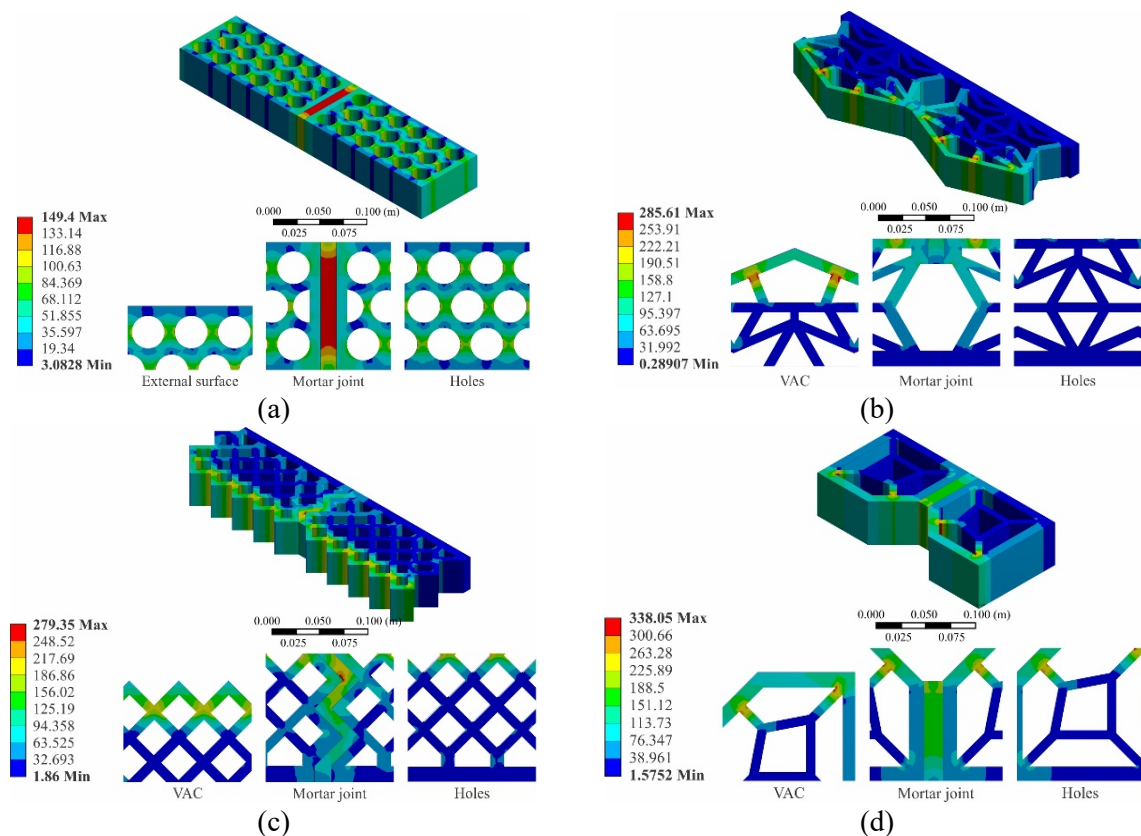
Figure 5. Heat fluxes profiles of bricks (Wm^2): (a) MB, (b) B-VAC 1, (c) B-VAC 2, (d) B-VAC 3.

According to Table 2, there is a positive correlation between heat fluxes of outer surface of B-VAC and mortar joint (0.25) and the inner surface of B-VAC and their mortar joints (0.83). The exterior correlation is lower because the difference in heat fluxes transferred by solar radiation varies according to the conductivity of the material, *i.e.*, exterior values of the joint are higher (between 79.55Wm^2 to 233.11 Wm^2). Instead of surface of the brick mitigates the solar incidence with the convection generated by the ventilated air chamber (27.47 Wm^2 to 190.51 Wm^2).

Conversely, outer surface of the brick mitigates solar incidence with convection generated by the ventilated air chamber (27.47 Wm^2 to 190.51 Wm^2). On the contrary, interior values are better correlated because variation of heat fluxes is less because values decrease proportionally by the shape of products in brick and mortar joints [10,12-16,20], and there is not difference between fluxes values of interior surfaces of B-VAC and mortar joints. According to Figure 5, it is excellent because energy concentration of interior surfaces of B-VAC is very low and therefore, it does not transfer heat to living spaces built with this type of product.

Table 2. Heat flux correlation coefficient of exterior and interior surfaces of MB and B-VAC and their mortar joints.

Exterior	Interior	Exterior	Interior
Brick	Mortar joint	Brick	Mortar joint
0.25	0.83	-0.79	-0.18

4. Conclusions

Design innovation demonstrates that the exploration of shapes generates added values of temperature reduction related to thermal comfort, fundamental for the construction of sustainable cities and communities. Results indicate a considerable reduction in the energy concentration, thanks to the mitigation in the transfer of heat from the ventilated air chambers, modification of interior hollows and treatment of the mortar joint. The improvements vary between 2.52 °C and 3.64 °C in the temperatures of interior surfaces of B-VAC types.

Similarly, the correlation of heat fluxes between exterior brick surfaces and their mortar joints (0.25) indicates that it is less than the correlation of heat fluxes between interior brick surfaces and their joints (0.83), because conductivity of materials, treatment of mortar joints and incorporation of ventilated air chambers affect the mitigation of solar incidence impact on the exterior surfaces and therefore, on the energy concentration of interior surfaces.

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