

STUDY OF THE ENERGY EFFICIENCY OF VENTILATED CERAMIC FAÇADES

**⁽¹⁾ G. Silva, ⁽¹⁾ V. Cantavella, ⁽¹⁾ À. R. García, ⁽¹⁾ E. Bou,
⁽²⁾ A. Miralles, ⁽²⁾ E. Uviedo**

⁽¹⁾ Instituto de Tecnología Cerámica (ITC).

Asociación de Investigación de las Industrias Cerámicas (AICE).

Universitat Jaume I. Castellón. Spain.

⁽²⁾ Asociación Española de Fabricantes de Azulejos y Pavimentos Cerámicos.
Castellón. Spain

ABSTRACT

The progressive changes in the regulations on building construction are affecting some aspects that have so far been given little consideration, such as safety of use, insulation, and especially the energy efficiency of the buildings.

Although the literature seems to recognise the advantages of different types of ventilated envelopes, based on the use of thermal solar energy, for energy saving, hardly any information or scientific studies are available that endorse their efficiency and allow the advantages of ventilated façade envelopes to be promoted in a quantitative manner. This is why the criteria and computer programs used for ascribing the energy efficiency of buildings consider that the use of ventilated façades hardly improves the building's thermal performance whereas, in practice, their advantages, especially in environments with a warm climate, have been confirmed to prevent heat accumulation and reduce cooling costs.

In this work, an experimental study has been carried out in actual exposure conditions throughout a full year-long cycle, using a prototype fitted with instruments, which simulated a ventilated façade with a real height equivalent to the distance between building decks. Monitoring its energy performance in different atmospheric conditions and seasonal periods has allowed a mathematical model for estimating ventilated façade performance in different climate zones and with different façade orientations to be developed and validated.

In parallel, and with a view to verifying the influence of other non-scalable variables with the prototype, such as the continuity of the ventilated chamber on the vertical of the building and the types of access openings to the convection channel, actual buildings have been respectively fitted with instruments to monitor these aspects through the four seasons.

When the information obtained in both studies was combined, in order to estimate ventilated façade system performance on a real scale, it was found that its energy-saving possibilities were considerably higher than those obtained when estimates were made using the recognised computer tools for certifying building energy efficiency.

1. INTRODUCTION

At present, ventilated façade systems with large format ceramic tiles are taking up a position on the market of external envelope applications as a singular alternative because of both their aesthetic possibilities and optimum functional performance, in particular with regard to their resistance to external agents, lack of maintenance, and acoustic and thermal performance.

Although the extensive available literature on architectural systems applicable to sustainable construction qualitatively suggests the advantages of ventilated façades as energy-efficiency enhancing features, there are no specific studies that offer information on their thermal performance under real conditions, on the influence of the different thermal transfer mechanisms that co-exist (conduction, convection, and radiation), and on the role of accumulation.

In this work, an experimental study has been carried out under real conditions of exposure throughout a full year-long cycle. For this purpose, a prototype fitted with instruments, which simulates a ventilated façade with a real height equivalent to the distance between building decks, has been used with a view to analysing the contribution of the different thermal transfer mechanisms and verifying the influence of the envelope's design parameters. Similarly, two real buildings were fitted with instruments to establish the range of variation of other non-scalable variables with the prototype, such as the continuity of the ventilated chamber on the vertical of the building and the types of access openings that determine the circulating flow through the ventilated envelope.

The resulting information has been used to develop and validate a mathematical model that allows the changes in the envelope's energy performance to be estimated in different climate zones and with different façade orientations.

2. VENTILATED FAÇADES WITH CERAMIC TILES

The ventilated façade is a multi-layer envelope mainly characterised by including an air chamber separated by two leaves: an internal leaf for resolving thermal insulation and air tightness, and an external leaf whose main mission is to form the air chamber, assuring continuous ventilation across the entire façade surface [1]. Figure 1 presents a typical scheme of a ventilated façade envelope.

In most cases, the backing wall (1) consists of ceramic brickwork of variable thickness, ranging from 12 to 29 cm, depending on the geographic zones and insulation requirements. The layer of thermal insulation (2) can be of various types and thickness, although the most usual material is a layer of closed cell polyurethane sprayed *in situ*, with a minimum recommended thickness of 0.035 W/mK. For the metal sub-structure (3) on to which the ceramic tiles are fastened (4), vertical and/or horizontal aluminium frames and profiles are normally used due to their lightness and their wide range of design possibilities. The ceramic tiles may be of very different formats (from 40x60cm to 100x300cm) with a wide range of surface finishes. With the insulation installed on the backing wall, the depth of the ventilated chamber tends to be between 5 and 10 cm. Although a wide variety of visible and hidden anchorage systems are available on the market, in principle they are not expected to have a significant influence on façade energy performance.



a) Construction detail.

b) Thermal performance.

Figure 1.

Ventilated façade energy performance depends on the magnitude of the solar radiation received on the surface of the ceramic tile. The energy coming from solar radiation is partly absorbed by the ceramic tile, which heats up and transmits energy by convection to the air inside the chamber and by radiation to the surface of the insulating layer. The heating of the air causes its density to decrease, making it rise inside the chamber and evacuate through the top. The energy received by the insulation, through convection from the air and radiation from the tile, is transmitted by conduction through the backing wall, penetrating into the interior enclosure.

As a whole, the ventilated envelope limits the energy that reaches the surface of the insulating layer and, therefore, it reduces the energy transferred by conduction through the backing wall to the inside of the enclosure. As a result, it is especially appropriate in climate conditions with a high atmospheric temperature and solar radiation for reducing the building's cooling demand.

3. EXPERIMENTAL STUDY

3.1. A scale ventilated envelope module.

In order to study the contribution of the different energy transfer mechanisms in ventilated envelopes, an experimental scale module that simulates the standard ventilated façade construction system [2] was built on the roof of ITC. This module has a geometry resembling that of a cube, with a square base and height equivalent to the typical distance between building decks (2.40 m); it has three walls and a ceiling of 60-mm thermal insulating panels with a low-emissivity cladding to minimize heat transfer.

The ventilated envelope was installed on the fourth wall, facing south, using the frame profile and fastening systems typical of an anchorage system with visible clips on a backing wall built of lightened clay blocks with a thickness of 14 cm. In order to have a wall with a thermal conductivity that was as homogeneous as possible, instead of mortar joints, some adhesive ribbons were arranged on the upper edges to join the blocks. On the other hand, a sheet of paper was placed between each row of blocks to prevent a "chimney effect" from developing inside the wall and, thereby, prevent excessive heat accumulation on the inside at the top.

Black porcelain tiles, size 60x120 cm, were used as a solar radiation collectors. The distance between the external part of the backing wall and the porcelain tiles was 10.5 cm, and this space constituted the heat transfer channel (CTC). Initially, the usual insulating layer was not installed on the outside of the backing wall in order to encourage the heat flow and to be able more precisely to determine the energy transfer through it.



a) Experimental module.

b) External sensors.

Figure 2.

The module had two independent ventilated channels with four porcelain tiles installed on the framework in a horizontal position, and respective top and bottom screens for adjusting air circulation through each channel. This allowed comparative tests to be carried out with one channel set up as a ventilated façade, and the other simulating an airtight double-leaf envelope.

Each channel was fitted with sensors to record the evolution of the characteristic variables of the ventilated façade system and the environmental conditions:

- a) Collector: Temperature on the inside of each tile (TPza).
- b) Heat transfer channel: temperature (TACTC) and speed of the circulating air were measured at the bottom and at the top.
- c) Backing wall: Temperature on the external face (TMurEx) and internal face (TMurIn) at different heights. Heat flow sensors were installed on the inner face for measuring the gains and losses through the backing wall (qMurIn).
- d) Interior enclosure: Temperature of the interior air (TAIn) at three heights. Respective heating and cooling devices for keeping the temperature constant. There was also a data acquisition system that stored the values of each variable with a 1-minute frequency.
- e) Outside atmosphere: Ambient temperature (TAEx), two pyranometers for measuring the total solar radiation (G_s) and the diffuse solar radiation ($G_{s,dif}$), an anemometer for determining wind speed (vAEx) and direction (dirAEx), and a pyrometer for measuring the sky temperature (Tsky).

Once the installation had been finished at the end of July 2008, monitoring began of all the variables throughout a full year-long period, which lasted until the beginning of September, 2009, keeping the average temperature of the interior air constant at $20\pm 1^\circ\text{C}$.

3.2. Ventilated envelopes on buildings.

Although it was possible to validate the suitability of the mathematical model developed for the simulation of the different energy transfer mechanisms using the information obtained from the scale ventilated envelope, with a reduced height, the influence of other non-scalable variables such as the continuity of the ventilated chamber on the vertical of the building, the influence of the wind at different heights and of the types of access openings to the convection channel on real envelope performance needed to be verified.

To do so, two buildings with different ventilated façade systems were selected with a view obtaining experimental information on the performance of construction system designs in their extreme configurations (figure 3).



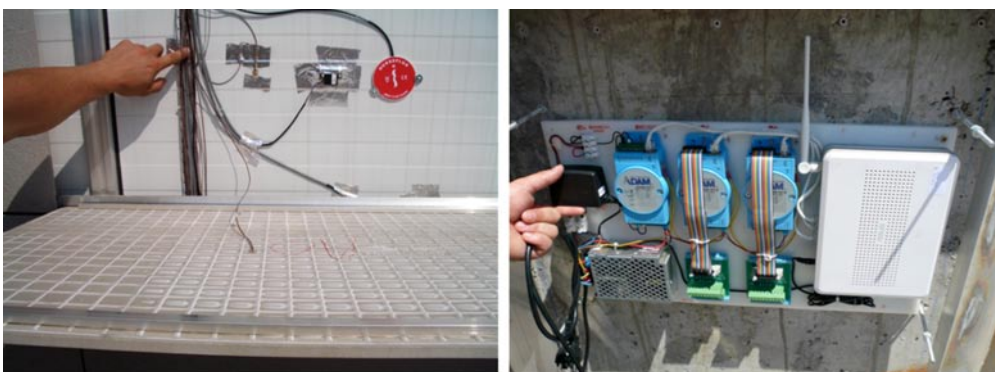
a) Building 1.

b) Building 2.

Figure 3.

The first one corresponded to an envelope with less ventilation capacity, with grey tiles, a ventilated chamber with a variable depth of between 1.5 and 5 cm in height, and closed horizontal joint with an insulating slab on the inside of the chamber. The second one corresponded to an envelope with a high capacity for collecting and evacuating heat, with black-coloured tiles, a ventilated chamber with a constant depth of 9 cm, an open horizontal joint of 7 mm and a high-density wall (reinforced concrete) with no insulation on the outside. Both buildings had the same total height (15 m) and orientation of the façade (south west, 205°), which was fitted with instruments.

As in the case of the prototype, temperature, heat flow density and air speed sensors were installed at approximately equal distances on four positions of the vertical of the building. Also, a system for acquiring and transmitting data for recording the values of the variables minute by minute was installed in each building (figure 4).



a) Installed sensors.

b) Data acquisition and transmission system.

Figure 4.

The evolution of the variables during a full year-long period was monitored with a view to obtaining the necessary information for completing the validation

of the mathematical simulation model. In the case of building 2, which was under construction during the study, it was possible to study the functioning of the envelope under different effective surface conditions of air access to the ventilation channel, from the initial situation with the channel completely open, through a period when it was opened to a minimum, until the final situation when it was half open, after the façade had been crowned.

4. MODELLING OF THE VENTILATED ENVELOPE

In order to be able to assess the energy performance of buildings with a ventilated façade under different climate conditions and for different design configurations of the envelope, a mathematical simulation model was developed. For this, the energy balance equations corresponding to each envelope section (collector, heat transfer channel, and backing wall) [3] were considered and resolved. The mathematical model is capable of simulating in a precise manner the evolution of the variables that are characteristic of each section throughout a full day, allowing the net energy transfer through the envelope to be estimated.

The coefficients of the model were adjusted, first, using the experimental data obtained from the scale envelope module with an interior temperature that was kept constant, which allowed the heat transfer factors by convection and radiation to be more precisely defined. Then, using the results obtained in the monitoring of the real-scale buildings, the parameters associated with air circulation through the heat transfer channel were confirmed in the model, especially with respect to the load loss resulting from the continuity of the channel and the effective area of the top and bottom openings, which condition the air mass flow that circulates inside the ventilated chamber and, hence, the energy evacuated to the outside.

As can be seen in figure 5, the mathematical model is capable of simulating the evolution of the different variables that define the envelope energy performance both in the case of the scale module (2.4 m in height) and in the real buildings (15 m) in the course of a daily cycle with sufficient precision.

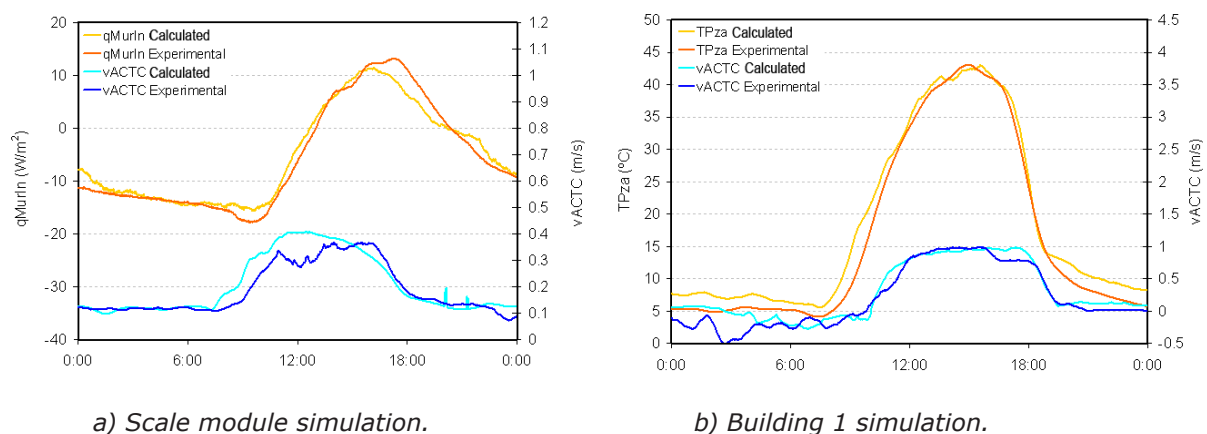


Figure 5.

5. ANALYSIS OF RESULTS

5.1. Comparison between ventilated and airtight envelopes.

Throughout the year-long monitoring period, different tests were carried out with the scale prototype, comparing the performance of a channel with a ventilated envelope configuration with the other channel simulating an airtight envelope (closed screens). Since both channels had identical design characteristics, it was thus possible to isolate the energy contribution of the ventilated channel. Figure 6 presents the evolution of the variables in both channels throughout one sunny winter's day.

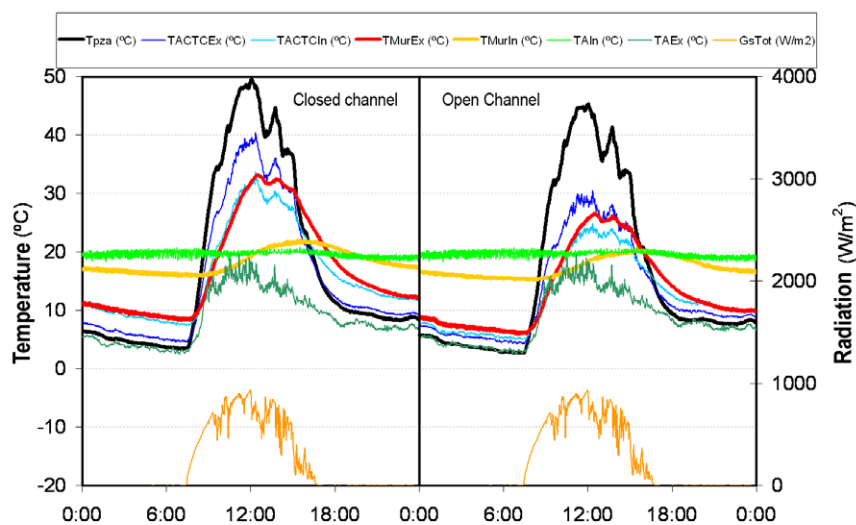


Figure 6. Comparison between the ventilated channel and the airtight channel in winter.

As can be seen in the central hours of the day, both the maximum temperature that the tile (TPza) reaches and the air temperatures inside the heat transfer channel (TACTC) are higher in the case of the closed channel with respect to the open one in which part of the energy is evacuated outside due to air circulation through the channel. This is why the amount of energy that the backing wall surface receives by radiation from the tile and by convection from the air is greater in the airtight envelope, in which the temperature gradient on the wall and the heat flow density that goes through it are also higher.

The ventilated envelope system acts in a way that favours energy evacuation (the chimney effect is enhanced) to the outside, and becomes more effective as the incident solar radiation increases and the outside air temperature decreases. Figure 7 shows the heat flow density per m^2 façade reached in the interior of the enclosure on a typical day of each month. As can be seen, the difference with respect to the airtight channel peaks during the winter period and minimises in the summer period. This is because, with a southern orientation, the incident solar radiation in December almost doubles that of June, while the ambient temperature is also higher in the summer months.

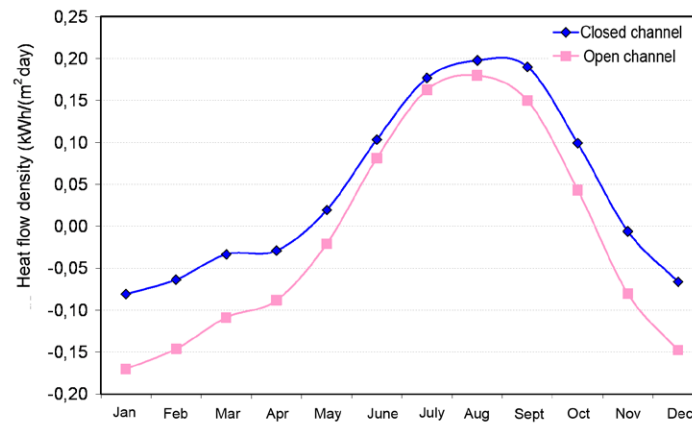


Figure 7. Daily energy input per m² envelope in the experimental module.

It may also be observed that the ventilated envelope system displays a contradictory effect since, though it reduces the heat accumulation in summer (less cooling demand), it also limits heat penetration in winter (higher heating demand). Therefore, it will be more suitable in warm climates with a high cooling demand.

5.2. Influence of ventilation channel design.

When the experimental results obtained of the air circulation speed inside the channel in the experimental module were compared with those observed on buildings fitted with instruments, it was found that, though the maximum speeds in the latter actually doubled those obtained in the experimental module, lower values than those expected were obtained, considering a load loss factor (K) similar to that obtained on an experimental basis with the 2.4 m module [3]. Since the load loss inside each channel depends on its design (depth, height, continuity, etc.) and on the type of ventilation openings, it was decided to determine the variation ranges of the load loss factor using the simulation model to define the value that allowed the circulation speed in each of the configurations to be reproduced. The following table details the values obtained for the different channels and effective ventilation surfaces.

CHANNEL	THICKNESS (cm)	HEIGHT (m)	OPENING (cm ² /m LENGTH)	LOAD LOSS FACTOR
Experimental module	10,5	2,4	600	4.9
Building 1	2.5/5	15	300	16
Building 2 Maximum opening	9	15	900	7.3
Building 2 Minimum opening	9	15	100	59.2
Building 2 Definitive opening	9	15	250	13.7

Table 1. Load loss factor values.

As can be seen, the load loss coefficients for the two buildings in their definitive construction configuration are of a similar nature, so that it may be assumed that this value is representative under actual conditions for usual types of ventilated building façades.

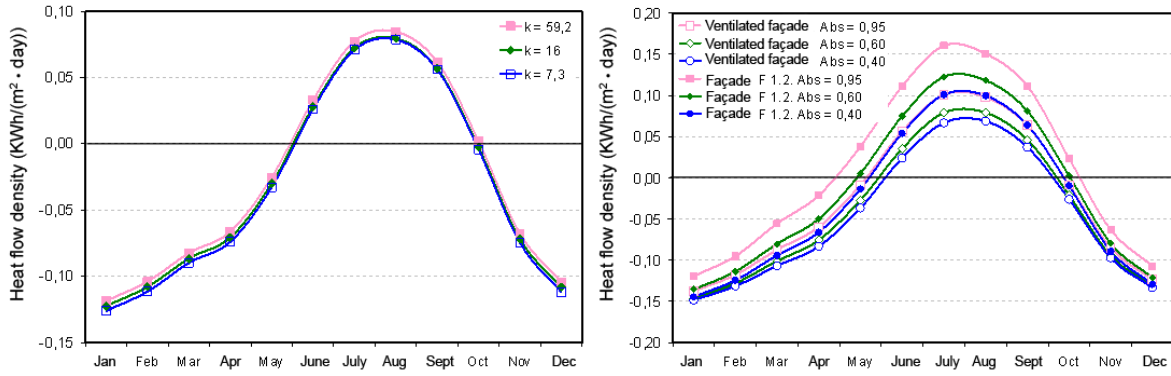
In order to verify the influence of the air speed with respect to the heat flow density through the envelope, the performance of a building with a standard ventilated façade was simulated (table 2) for the average monthly climate conditions in Castellon in the three opening configurations of building 2. Although it was experimentally verified that the load loss resulting from the reduction of the access openings to the ventilation channel produced significant variations in the air circulation speed, which could be significant in envelopes with little insulation, it was found that, for a building with a ventilated façade with the minimum recommended insulation, no significant changes were noted in the heat flow density under the different opening conditions (figure 8a).

BACKING WALL + INSULATION	VENTILATED CHANNEL	CERAMIC COLLECTOR
Design thermal resistance = 1,22 m ² K/W	Depth of 6 cm	h=9mm, λ=2,6 W/(mK) Absorptivity = 0,6

Table 2. Characteristics of the standard ventilated façade.

5.3. Influence of ceramic collector characteristics.

The amount of solar radiation absorbed by a body depends on its absorptivity, a property that is closely related to the colour. In order to analyse the influence of ceramic tile colour on the thermal performance of a standard ventilated façade and of a double-leaf façade ($R=1.22$ m²K/W), the heat flow density reached inside these two envelopes on a typical day of each month was calculated for the following three surface finishes: black colour (absorptivity = 0.95), grey/beige (0.60), and white (0.40). The results are shown in figure 8b, which confirm that, for both types of façades, the energy transmitted through the envelope to the inside increases with greater absorptivity. It is also seen that, with the same absorptivity value, the heat flow density is always higher in the double-leaf façade than in the ventilated façade, whose performance proves to be less dependent with respect to colour. This effect stems from the fact that high absorptivities increase the heat reception by the outer leaf while, at the same time, this enhances the chimney effect and the heat losses, making the thermal increase less than in a airtight chamber. It should be pointed out that the energy transmitted by a ventilated façade with maximum absorptivity (0.95) is of the same magnitude as that obtained for the double-leaf envelope with minimum absorptivity (0.40), which allows more flexibility in the exterior design of the façades with less heat accumulation, even when using black-coloured envelopes.



a) Influence of load loss.

b) Influence of façade colour.

Figure 8.

5.4. Influence of façade orientation.

Another aspect that influences the thermal performance of a façade is its orientation, since the solar radiation that affects a vertical element varies considerably, depending on the orientation and time of the year. Thus, figure 9 displays the incident solar radiation in Castellon during a sunny winter day (a) and a summer day (b) for each of the four orientations. It can be observed how in winter (December) the southern orientation is the one that receives most solar radiation, while in summer (June) the eastern-western orientations are those that receive a larger amount of energy. Between these two extreme situations, in the period from December to June, the southern orientation progressively receives less radiation, whereas the incident radiation on the eastern-western faces increases, whereas this tendency occurs in the opposite direction from June to December.

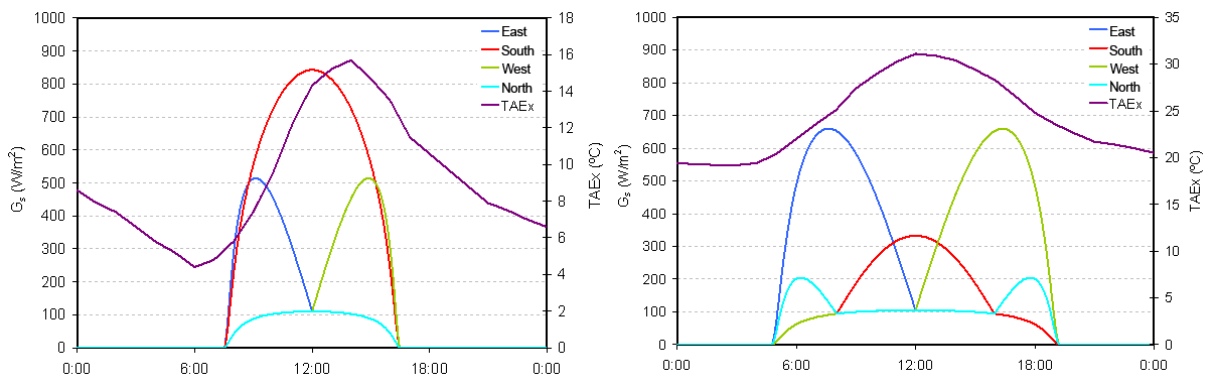


Figure 9. Incident solar radiation depending on the orientation in winter (a) and summer (b).

Taking into account the above considerations, figure 10 displays the evolution of the heat flow density inside the ventilated envelope in each of the orientations for a typical day of each month. It can be seen that for the winter period, the heat flow density is higher for the southern orientation, since this receives the highest amount of solar radiation.

As the year advances, the difference decreases with respect to the eastern-western orientation until in the months of May, June, and July, this is the orientation that exhibits a higher heat flow density. Then, the tendency reverses again and the differences between south and east-west increase until the winter period arrives. Obviously, in the northern orientation, the energy that crosses the envelope is less than in the other three orientations, since this building face is the one that receives less energy from the sun.

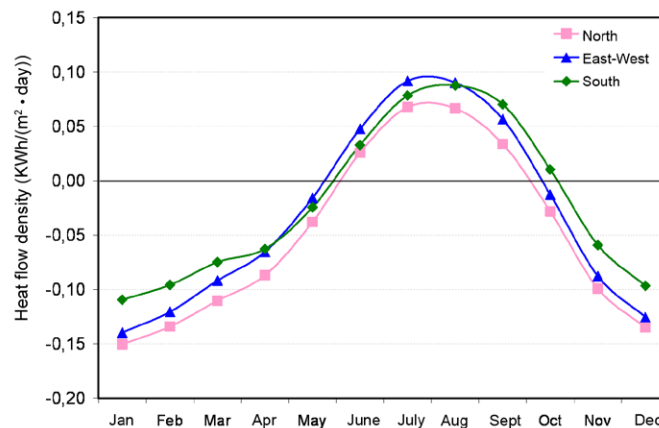


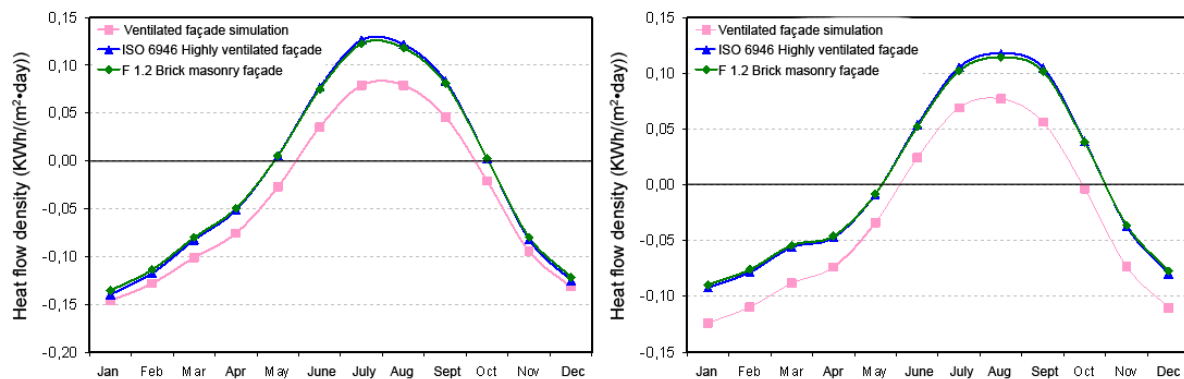
Figure 10. Daily energy input per m^2 envelope as a function of the orientation.

5.5. Contribution to building energy efficiency.

Although the simulation model allows the energy contributions through ventilated envelopes with different configurations to be estimated, in order to determine a building's energy efficiency, the gains and losses of the other building components (glazing units, internal contributions, ventilation, etc.) must be concurrently considered. However, the calculation tools currently available [4, 5, 6] do not allow the ventilated façade construction system to be included, unless the option established in the UNE-EN ISO 6946:1997 [7] standard for highly ventilated air chambers is used. According to this standard, for estimating the total thermal resistance in an envelope with a highly ventilated air chamber, the external layers (tile and air chamber) shall be disregarded and only the internal layers shall be considered, while the external surface resistance (R_{se}) shall be given the same value as the internal resistance.

For comparative purposes, the monthly calculation method (UNE-EN ISO 13790:2008 [8]) was used to estimate the heat flow density through $1 m^2$ of two types of envelopes with a design resistance that was equal to that of the standard ventilated façade (table 2). The first envelope corresponded to a masonry brick façade with a non-ventilated air chamber (code F 1.2 [9]) and the second one to the simulation of the façade with a highly ventilated chamber according to the modification of the above R_{se} . Both have an absorptivity surface of 0.6. The results obtained for two orientations in the monthly climate conditions of Castellón are shown in figure 11.

As can be seen, the change proposed in standard UNE-EN ISO 6946:1997 hardly modifies the heat flow density with respect to the masonry brick envelope F 1.2; nor does it reproduce the heat evacuation capacity of the real ventilated façade that shows a significant reduction in the heat flow density through the envelope, which is much more pronounced in the southern orientation. Therefore, the option proposed in that standard for simulating ventilated ceramic façades must be ruled out, since the highly ventilated chamber concept to which it refers cannot be applied to this construction system.



a) Eastern and western orientation

b) Southern orientation

Figure 11.

6. CONCLUSIONS

- With the experimental data obtained from the studies conducted with a scale module and two real buildings, a mathematical model has been developed and validated that allows the thermal performance of ventilated ceramic façades to be simulated.
- Using this model, it is possible to estimate the net energy transfer through the envelope in different construction system configurations, orientations, and climate conditions.
- It has been verified that the theories used for including the ventilated ceramic façade in the calculation tools for the assessment of energy efficiency do not allow its capacity for reducing the cooling demand to be correctly estimated.

ACKNOWLEDGEMENTS

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