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AIR CAVITY PERFORMANCE IN OPAQUE VENTILATED FAÇADES IN ACCORDANCE WITH THE SPANISH TECHNICAL BUILDING CODE

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Structured Abstract

Objective
The use and study of Opaque Ventilated Façades (OVF) has considerably expanded in recent years as an efficient envelope option when hoping to reduce cooling thermal loads for buildings. This is due to the solar protection provided by the outer layer and the ventilation from the air cavity. However, the actual situation in the air cavity of OVF buildings is usually very different from the theoretical studies, which do not consider the fixing systems of the outer layer regularly arranged inside the air cavity. This information is crucial to understand and validate predictions of the efficient behaviour of the system. Therefore, the objective of this work is to classify and analyse the performance of the air chamber in OVF existing buildings in Barcelona in accordance with current building regulations.

Methodology
Twenty-one buildings were surveyed and classified and the air movement and temperature inside the cavity was measured in ten buildings.

Conclusions
The findings show that although the Technical Building Code of Spain regulates the air cavity ventilation according opening minimums per linear meter, air inlet and outlet openings have the greatest influence on air cavity ventilation, even more so than open joint surface of the outer

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layer. For these reason, we recommend considering all OVF system variables within building regulations since there are significant variations of heat transfer regarding the physical and geometric characteristics of their elements.

Originality
The originality of the study lies in the survey and characterization of O in real buildings, and the results obtained by on-site measurements. This study is aimed at designers and construction professionals interested in the efficient performance of ventilated façade systems.

1. Introduction

The building envelope acts as the principal energy moderator and is a key component for guaranteeing interior comfort conditions. Heat gains and losses through building façades have a significant influence on annual heating and cooling consumption. In this context, Opaque Ventilated Façades (OVF) are seen as an efficient envelope option nowadays, when compared to a conventional façade, due to reductions mainly in energy demands on buildings for cooling thermal loads in locations with high solar radiation.

The OVF is a passive system formed by an opaque internal skin (heavy or light materials) and an outer layer. The inner skin acts as thermal and acoustic insulation and the outer layer consists of thin lightweight cladding panels. Between both layers, there is an air cavity that is drained and ventilated (Pardal March, 2009). In some cases, the joints of the panels are open and enable exterior air to enter and leave the cavity along the entire wall. In other cases, the external panel or the joints between tiles are closed and ventilation is only possible from openings at the top and bottom of the cavity. The growing industrialization and commercialization of these systems is based on improvements in thermal behavior from the natural ventilation of the air cavity. This results from continuous thermal insulation from the slab edges and from the protection provided by the external cladding from direct solar radiation. In order for this second point to be fully effective, it is necessary to insure ventilation of the cavity to avoid overheating.

Inside the ventilated chamber, air flow is induced by natural convection due to temperature differences between the inner surfaces of the cavity and the external air. Natural ventilation can be driven by two phenomena: buoyancy and the wind. Wind driven ventilation is a consequence of the pressure difference in the façade surfaces produced by wind forces. Buoyancy-driven ventilation occurs as a result of the height of the cavity (Ibañez-Puy *et al*., 2017). Because of this, a large number of studies have focused on the specific phenomena that occur inside the cavity.

The principal factors influencing the air moving inside the cavity are radiation and the outside wind. Regarding this, the results of an experimental study carried out in summer shows that a ventilated façade with higher ventilation channel and facing south has the best performance in terms of air velocity values and airflow rates (Stazi *et al.,* 2011). Furthermore, an OVF´s thermofluid-dynamic analysis affirms that energy savings increases if the solar radiation is higher: during the summer, the ventilated façade can create energy savings rates above 40% when compared to the same unventilated façade (Patania *et al*., 2010). Whit respect to the winter season, the study of the OVF in different climate zones in Spain shows that although the most influential weather variable is solar radiation, a combination of high temperatures and low wind speeds can also lead to important energy saving values (Peci Lopez *et al.,* 2015). However, a large number of studies (Lorente, 2002; Balocco, 2002; Manz, 2003; Xamán *et al.,* 2005; Sanjuan *et al*., 2011a; Sánchez *et al*., 2013) do not address the effects of the wind because they were developed for steady state conditions even though it is a fundamental aspect regarding the air moving inside the cavity.

Regardless, most of the journal papers relating to the success of the overall performance of a building with OVF agree that a previous detailed analysis of the context is important. (Ibañez-Puy *et al.,* 2017; Elarga *et al.,* 2015; Aparicio *et al.,* 2014; Sanjuan *et al.,* 2011b). The local climate, the specific design, the physical characteristics of the construction (inlet/outlet locations, cavity thickness, material properties, air source), the use and desired comfort of the building, as well as the cost of primary energy and CO2 emission should all be taken into account. In order to study the OVF, the studies vary according to the methodology adopted: thermofluid-dynamic analyses, (Patania *et al.,* 2010; Domínguez Delgado *et al.*, 2013; Suárez *et al.,* 2015) number simulations, (Balocco, 2002; 2004) and, in some cases, experimental models have been created (Sandberg & Moshfegh, 1996; Peci López *et al.,* 2012; Sánchez *et al.,* 2017). There are few analyses of real cases in actual operation (Stazi *et al.,* 2011; Aparicio *et al.,* 2014).

Nevertheless, a crucial point in understanding and validating how the OVF system behaves is by considering the actual dimensions of the air cavity. Often, theoretical studies do not consider the internal structures of the outer layer, which are horizontal or vertical elements that are regularly arranged inside the cavity and may interfere with air movement. In order to give a definitive criterion of the OVF energy performance, it is necessary to evaluate the specific façade geometry and materiality by taking into account building costs and the price of the energy used for heating and cooling.

Within the framework of a micro-sustainability level, the building envelope largely depends on the policies established in building codes: Yu *et al*. (2017) state that building energy codes can generate significant energy and economic savings by 2050. Some studies have advanced in the analysis of possible building and urban rehabilitations in relation to the Spanish Building Code (Daumal Domènech *et al.*, 2013; Cocco & Alonso, 2015). In this regard, building regulations should guide the specific conditions of a ventilated façade making it suitable to the urban context and the climate zone. The advancement and growth in the construction industry of these enclosure systems indicates the need for studying OVF behavior in relation to building regulations. The Technical Building Code of Spain (Código Técnico de la Edificación) classifies air cavities by the degree of ventilation. For this reason, the present paper focuses on the effectiveness of the ventilation from OVF cavities in real buildings in relation to the building regulations in Spain. The value of this study lies in the survey and characterization of the make-up of more than 20 ventilated façades as they are constructed in the Barcelona area, and the results obtained by on-site measurements: air velocity and temperature inside the air cavity.

1.1. Considerations for air cavity ventilation regulation

The first legal account referring to OVF cavity ventilation dates from 1979. Basic Building Regulations (NBE-CT-79) were oriented to achieve energy savings through the proper construction of buildings, addressing the problems arising from the increased energy cost, as well as the thermal aspects that affect buildings and their habitability conditions (Boletín Oficial del Estado, 1979). The NBE-CT-79 articulated the thermal conditions of buildings and established a classification for vertical enclosures with ventilated air cavities. This was done by relating the total section of the ventilation opening *S* (cm^2) and the length of the enclosure *L* (m). Three types were established:

- Weakly ventilated air chamber: S/L < $20cm^2/m$
- Moderately ventilated air chamber: 20 ≤ S/L < 500 cm^2/m
- Highly ventilated air chamber: S/L ≥ $500cm^2/m$

The NBE-CT-79 was repealed with the advent of the Technical Building Code (Código Técnico de la Edificación) in 2006, in which the criteria of energy saving in the building were maintained through specific sections. However, neither of them specifically included the OVF in the basic documents. Therefore the CTE requires the approval of certified documentation that guarantees the beneficial performance for any alternative solution proposed (brick, concrete or natural stone) for the façade. The European Technical Assessment (ETA) is a document that provides information about the performance of a construction product and a description of its essential characteristics. This assessment is located in the new Construction Products Regulation (EU) No.305/2011 which went into law in 2013 in all European Members States and in the European Economic Area (European Technical Assessment, 2013).

On the other hand, the Basic Health Document (Documento Básico de Salubridad) and the Energy Saving Document (Documento Básico de Ahorro de Energía) are documents of the CTE that refer to the classification of the air cavity by the degree of ventilation. However, each classifies in a different way:

The Basic Health Document (DB-HS) defines a ventilated chamber as "the separation space in the construction section of a façade or a roof that allows the diffusion of the water vapour through exterior openings arranged in such a way that ensures cross ventilation". The document defines minimum required degrees of impermeability against the penetration of rainfall in the façades, and it refers to medium, high and very high filtration resistance barriers to the air cavity. A ventilated air cavity is only required when a very high resistance barrier for filtration is required (Barcelona meets the medium and high filtration resistance barrier requirements). In these cases, the following considerations for the cavity have been established:

- The cavity must be arranged on the outer side of the inner wall insulation;
- A system for collecting and evacuating filtered water should be provided at the bottom of the chamber and for when it is interrupted;
- The thickness of the cavity must be between 3 and 10 cm;
- Ventilation openings must be provided with a minimum effective area of $120cm^2$ for each $10m^2$ of façade between floors distributed at 50% between the top and bottom. The openings may be accompanied by: gratings, open joints in discontinuous coatings having a width greater than 5mm or other another barrier that produces the same effect.

The Energy Saving Document (DB-HE-1) defines the characteristics of façade parameters concerning calculations of transmittance and resistance of the enclosures in relation to the outside air. According to the code, the air cavities are characterized through their thermal resistance. Therefore, there is a distinction between a slightly ventilated and a highly ventilated air cavity. The differences between one and the other is the joint surface value of 1,500mm² per ml counted horizontally for vertical cavities. The following typologies are defined:

a) Non-ventilated air cavity: without any specific air flow system; an air cavity without insulation from the outside environment. However, small openings to the outside may also be considered as "non-ventilated" if those openings do not allow air flow through the chamber and do not exceed 500mm^2 per m of length when counted horizontally for vertical air cavities.
b) Lightly ventilated air cavity: one without a device limiting air flow from the outside environment and with openings within the following range: 500mm^2 <S openings ≤ 1500mm^2 per m length
c) Highly ventilated air cavity: one in which aperture values exceed 1500mm^2 per m in length counted horizontally for vertical air cavities.

Regarding ventilation opening minimums, according to a study carried out at the Construction Technology Institute of Catalonia (ITeC), the European Technical Assessment (DITE 034) gives 5000mm^2 per linear meter as the most restrictive value for openings at the bottom and top of the façade, compared to the 1500mm^2/m indicated in the DB-HE (Bento Fernández, 2014).

Furthermore, the limit values and the thermal insulation verification method indicated in the DB-HE-1 are applicable to the inner skin; but, these results may be undesirable if the outer layer is not considered. Certain adaptations to calculation programs would be required to include their data because steady state calculations only take into account the temperatures of the coldest month of the year. Therefore, heat gains in the air chamber in hot periods are neglected (Ferrer Gispert *et al.,* 2014).

Additionally, thermal resistances of non-ventilated and lightly ventilated air cavities are defined according to thickness. In these cases, no layer of the enclosure is neglected and the transmittance of the cavity is considered from tabulated and simplified values. In order to perform the calculation of the temperature inside the chamber, the external convection coefficient is modified by simplifying the calculation and making it unrealistic (Aparicio Fernández, 2010). However, for highly ventilated air cavities, the total thermal resistance of the enclosure is obtained by disregarding the thermal resistance of the air cavity and those of the other layers between the air cavity and the outside environment. This includes an outer surface resistance (corresponding to the calm air) which equals to the inner surface resistance. In addition, the coefficient of external convection equals the interior and does not contemplate the heating produced by the solar gains inside the cavity.

Regarding transmittance, the CTE assigns average limit values to the enclosures of buildings which vary according to their location in Spain. These values depend on the coefficient of thermal conductivity of each material, the surface resistances and the resistance of the cavity of enclosures concerning sealed or unsealed cavities. However, when the cavity is ventilated the calculation of the transmittance thickness is more complex. In these cases, there is heat transfer due to different heat exchanges: by convection and radiation between the outside environment and the outer sheet, which includes solar radiation; by radiation between the two walls of the cavity; by convection between the walls of the cavity and the mass of air circulating; by conduction through the walls, etc. All these conditions vary greatly since they depend on the particularity of each project. Dissimilarities include the materials of the inner and outer sheets, the dimensions and geometry of the joints, the width of the cavity and the inside structure.

2. Material and methods

This study was done in two stages: first, twenty-one OVF buildings were identified and classified according to their actual building characteristics. Second, air movement and temperature were measured inside the air cavity in ten buildings.

2.1. Choice of the cases studies

Twenty-one buildings with Opaque Ventilated Façade were identified. Only buildings with more than 6 stories (18m) were considered in this study. One file per case was made. Each one includes location, orientation, use of the building, as well as the construction details of the enclosure system and the definition of the dimensional variables of the ventilated cavity. This information was obtained from in site surveys of the buildings, and from a request for construction details from the original sources: architects, designers, construction companies and companies that market the studied system.

2.2. Construction variables

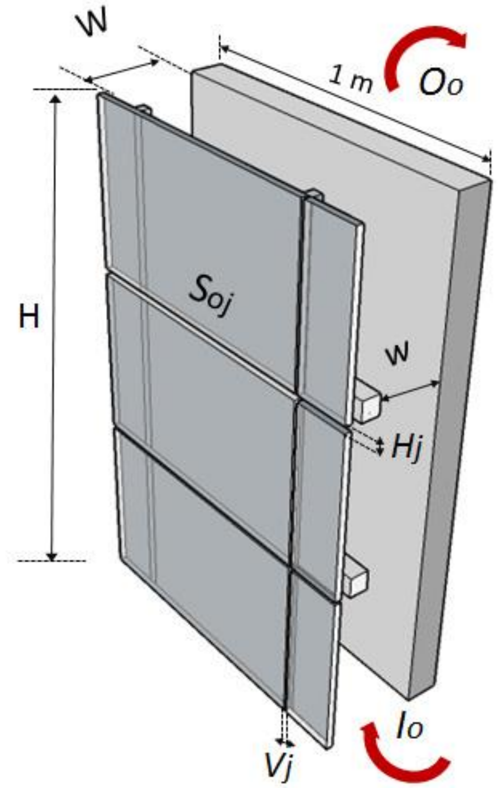
The main variables to be studied were defined: the opening inlet and outlet of the air cavity, open joint surface of the outer layer, and width and height of the cavity. Table 1 and Figure 1 show the description and nomenclatures used.

Table 1. **Characterization of the OVF system variables**

Ventilation variables (air circulation channels)	Description	Elements	Nomenclature
Top and bottom inlet and outlet	Openings at the bottom and top of the cavity (linear meters)	Inlet opening (bottom)	Io
		Outlet opening (top)	Oo
Joints between the panels of the outer layer	Vertical and/or horizontal open joints (linear metres) / Open joint surface of the outer layer ($1m^2$ façade)	Vertical joints opening	Vj
		Horizontal joints opening	Hj
		Open joint surface in $1m^2$ façade	Soj
Cavity between layers	Width and height of the cavity (linear metres)	Width between the inner face of the outer layer and the outer face of the inner layer (insulation)	W
		Width of the real cavity (Chimney stack)	w
		Height of the cavity	H

Source: Own elaboration

Figure 1. **Dimensional variables of the OVF system**



Source: Own elaboration

2.3. *Classification of the ventilated cavity*

This classification was made concerning the air inlet and outlet variables (Table 2).

Table 2. **Classification of the ventilated cavity types according to the top and bottom solution**

Closed Cavity	Façades with NO air inlet and outlet neither in the bottom nor in the top	CC
Semi-Open Cavity	Façades with only one opening: either the bottom or the top of the cavity is closed	SC
Open Cavity	Façades with open air inlet and outlet in the bottom and in the top of the cavity	OC

Source: Own elaboration

Figure 2 shows the buildings selected according to the cavity classification. As it can be seen, fifteen of the twenty-one study cases (70%) have both ends of the cavity (lower and upper) closed with watertight plates. Of the remaining six buildings, only two have open air inlet and outlet, and four cases have one open end.

Figure 2. **Case studies classified according to the type of ventilated cavity**

Source: Own elaboration

2.4. Diagnosis of existing cases under real conditions

Measurements were made in the summer -August and September- on clear sky days. The selection of the measured buildings was made according to the access possibilities and to the characteristics of the building. The cases without continuous thermal insulation ahead the slab edges (CC7 and OC1) were discarded. Table 3 shows the dimensions of the defined variables, and Table 4 shows the materiality of the inner and outer skin façade of each building studied.

Table 3. **Ventilation variables of each building under study**

	VENTILATION VARIABLES							
	Air Inlet and Outlet		Open Joints			Cavity *(m)*		
	ai (m)	*ao (m)*	*Vj (mm)*	*Hj (mm)*	Soj *(m^2)*	*W*	*w*	*H*
CC1*	-	-	-	8	0.018	0.07	0.07	12.5
CC2*	-	-	6	8	0.015	0.03	0.03	12
CC3*	-	-	-	10	0.012	0.07	0.07	22

CC4*	-	-	6	-	0.009	0.08	0.02	20
CC5*	-	-	6	6	0.009	0.12	0.07	2.7
CC6*	-	-	6	-	0.003	0.027	-	2.7
CC7	-	-	-	-	-	0.05	0.05	12
CC8	-	-	-	-	-	0.07	0.07	23
CC9	-	-	-	8	0.013	0.05	0.05	16.5
CC10	-	-	-	6	0.011	0.05	0.05	18
CC11	-	-	6	-	0.01	0.03	0.02	2.7
CC12	-	-	3	-	0.009	0.06	0.048	15
CC13	-	-	4	-	0.005	0.087	0.06	18
CC14	-	-	4	-	0.005	0.087	0.06	15
CC15	-	-	6	-	-	0.09	0.05	12
SC1*	-	0.02	10	-	0.006	0.1	0.1	2.9
SC2	-	0.02	-	8	0.014	0.085	0.058	2.7
SC3*	0.07	-	6	-	0.005	0.07	0.03	12
SC4*	0.05	-	-	-	-	0.09	0.06	12
OC1	0.02	0.02	-	8	0.013	0.02	0.02	18
OC2*	0.04	0.03	-	-	-	0.07	0.07	15

Source: Own elaboration

Table 4. **Materiality variables of each building under study**

	MATERIALITY VARIABLES		
	Outer skin	Thermal Insulation	Inner skin
CC1*	Gres (0.6 x 0.6m)	Projected polyurethane (0.06m)	Concret blocks
CC2*	Travertine (1.3 x 0.7m)	Extruded polystyrene (0.03m)	Brick
CC3*	Ceramic (0.25 x 0.75m)	Projected polyurethane (0.06m)	Brick
CC4*	Ceramic (0.6 x 0.3m)	Rockwool (0.03m)	Brick
CC5*	Phenolic resin (2.3 x 0.8 m)	Rockwool (0.04m)	Gypsum board and rockwool sandwich
CC6*	Asbestos Cement (1.2 x 2.7m)	Rockwool (0.06m)	Brick
CC7	Travertine (0.75 x 0.5m)	-	Brick
CC8	Solid aluminium (0.9 x 0.90m)	Rigid insulation on impermeable membrane	Ceramic brick
CC9	Asbestos Cement (1.2 x 0.5m)	Rockwool (0.04m)	Reinforced concrete panels and rockwool sandwich
CC10	Natural Stone (0.45 x 0.7m)	Rockwool (0.03m)	Fiberglass panel and rockwool sandwich
CC11	Natural Stone (1 x 0.5m)	Rockwool (0.05m)	Brick
CC12	Concrete polymer (0.3 x 0.2m)	Fiberglass wool (0.1m)	Concret and bricks
CC13	Natural Stone (0.7 x 0.45m)	Rockwool (0.06m)	Brick
CC14	Natural Stone (0.7 x 0.45m)	Rockwool (0.06m)	Brick

CC15	Asbestos Cement (0.3 x 1.4m)	Rockwool (0.04m)	Brick
SC1*	Phenolic resin (1.8 x 1m)	Rockwool (0.04m)	Gypsum board and rockwool sandwich
SC2	Ceramic (0.9 x 0.25m)	Rockwool (0.10m)	Cement board (Knauf)
SC3*	Phenolic resin (1 x 0.7m)	Projected polyurethane (0.03m)	Brick
SC4*	Phenolic resin (0.6 x 1.1m)	Projected polyurethane (0.03m)	Brick
OC1	Travertine (0.8 x 0.6m)	-	Brick
OC2*	Phenolic resin (0.9 x 1.6m)	Projected polyurethane (0.03m)	Brick

Source: Own elaboration

A *Testo 405i* thermal anemometer was used with a 400mm extendible telescope, operated through a smart phone. The equipment registers the air speed (hot wire sensor with a measuring range 0 to 30m/s and resolution 0.01m/s) and air temperature every two seconds (NTC temperature sensor with a measuring range -20 to 60°C and resolution 0.1°C). In some cases, the extendible telescope was introduced through the open joints of the outer layer.

In other cases, one plate was removed and replaced to install the anemometer inside the air cavity (see Figure 3). In all cases, the provision was made for the hot wire sensor to be perpendicular to the vertical airflow inside the cavity. The methodology consisted in monitoring the cases in periods of 30 minutes in the morning and 30 minutes in the afternoon. The data were recorded in the following sequence: 5 minutes outside, 20 minutes inside the cavity and 5 minutes outside.

Figure 3. **Images of the measurements made in case studies**

Source: Own elaboration

Different façade orientations were evaluated: four buildings façades with North-West orientation (CC2, CC4, CC6 and OC2), three building façades with North-East orientation (SC1, SC3 and SC4) and four building façades with South-West orientation (CC1, CC3, CC5 and SC3). The measurements were performed at heights of 0.8 to 2.1m in all cases.

Additionally, in cases SC3 and OC2 it was possible to monitor the highest point of the cavity, at 12 and 15m respectively. Table 5 shows the triple entry box of measured cases according to orientation and height monitored: low (L) and high (H) height.

Table 5. **Measured cases according to orientation and height monitored**

	CC1		CC2		CC3		CC4		CC5		CC6		SC1		SC3		SC4		OC2	
North-West																				
North-East																				
South-West																				
Height	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*	*L*	*H*

Source: Own elaboration

3. Results and Discussion

3.1. Air movement and temperature in the wall cavity

The measurements of ten of the characterized buildings (marked with an asterisk in Figure 2 and Tables 3 and 4) are shown in Figures 4 to 7. The thermal and air velocity results are presented in all cases during the measured time of highest solar radiation: during the evening, for cases facing westward and during the morning in cases facing eastward. The measurements that were performed at Close Cavity (height 0.8 to 2.1m) are represented in Figure 4; at Semi Open Cavity at a height of 0.8 to 2.1m in Figure 5; at Semi Open Cavity at a height of 12m in Figure 6 and the measurements performed at Open Cavity at 1m and 15m are represented in Figure 7.

The results showed that temperatures increased and the air velocity decreased significantly inside the cavity when compared to exterior conditions. Relative to the air velocity at the lowest heights, for the close cavity cases (Figure 4) the interior air flow reduced when compared to the exterior in ranges of percentage from 62% (CC5) to 100% (CC6). Cases CC1, CC2, CC3 and CC4 reduced 85%, 82%, 94% and 92% respectively.

The smallest reduction was for case CC5 because it is the only one that has the outer layer with both -vertical and horizontal- open joints. For the semi-open cavity (Figure 5), the reductions were 62% in case SC1, and ranged from 14% to 26% in SC3 (South and North face respectively). The largest reduction was for case SC1. That is because it is the only measured case with a closed air inlet (the height of the measurements was at 0.8m). Finally, in the open cavity case (Figure 7), the air velocity inside the cavity fell 19%.

In the highest point of the cavity, the interior air velocities showed significant reductions with respect to the exterior. In the open cavity (Figure 7), the decrease was 53%. This is due to the northern orientation and that during the measurement the façade did not receive solar radiation. In the semi-closed cavity, (Figure 6) air velocity decreases were 72% and 86% for the southern and northern orientations respectively. These high values are explained because the air outlet of the cavity is closed.

The higher air velocities in the wall cavities evaluated are explained in two ways. First, the air inlet and outlet openings have a significant influence on the movement of air in the cavity: the mean air velocity in the CC cases was 0.13m/s, while in the cases SC and OC the average velocity was 0.35m/s. On the other hand, the orientations with greater solar incidence on their façades also influence air movement. The air velocity was higher in the buildings facing south-west than those to the north-east and north-west with mean differences of 0.04m/s in the case of closed cavities and 0.45m/s in semi-closed cavities. In conclusion, the two key factors influencing the proper behaviour of the ventilated cavity are: the area of the inlet and outlet openings and the solar incidence of the façade.

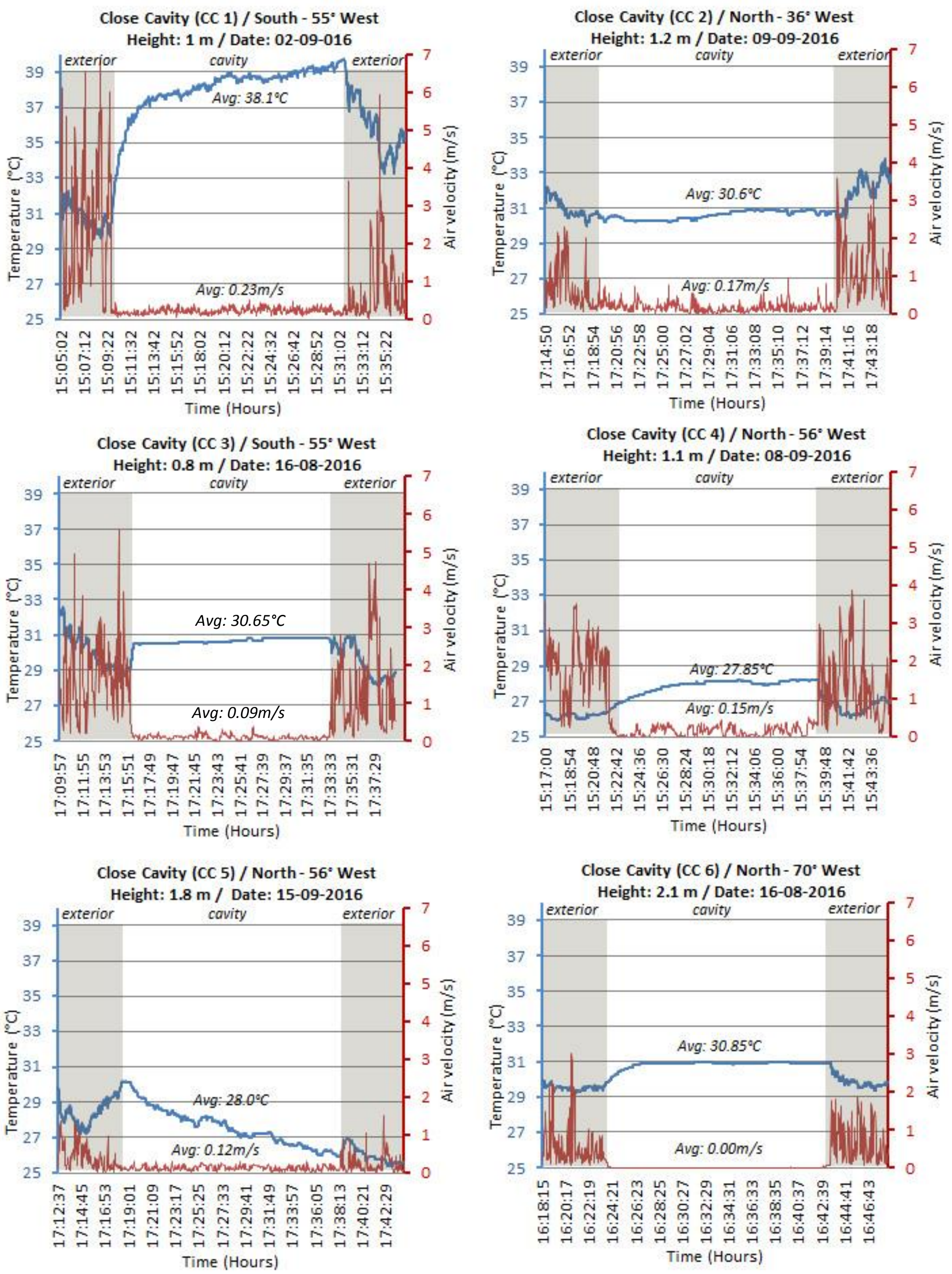
These results are in agreement with those obtained by thermofluid-dynamic analyses from computer simulations of the ventilated façade (Patania e*t al.,* 2010). These indicate that energy savings increase when solar radiation increases. The increase of inlet air velocity causes a reduction of air temperature inside the duct which also increases the energy savings rate. For this reason, the OVF is recommended for high radiation zones.

There are always heat gains inside the air cavity: air temperatures tended to be higher than outside. Mean increments of 5.4°C were registered in the SC3-Southwest orientation case. This result is coincident with reported measurements of existing buildings where the average indoor-outdoor temperature differences in summer were 7°C for the southern orientation (Aparicio Fernández, 2010).

However, only one case (CC2 of travertine stone) showed temperatures inside the cavity lower than in the exterior of the total of cases monitored in this study: this case has the lowest coefficient of conductivity in its outer layer. This indicates that temperature increase in the chamber is associated with the thermo-physical characteristics of the outer façade. This is in agreement with the results of the work of Patania *et al.* (2010) where it is concluded that the energy performance of the OVF improves when the external layer has low thermal conductivity values, high density values, high specific heat values, and low thermal diffusivity values.

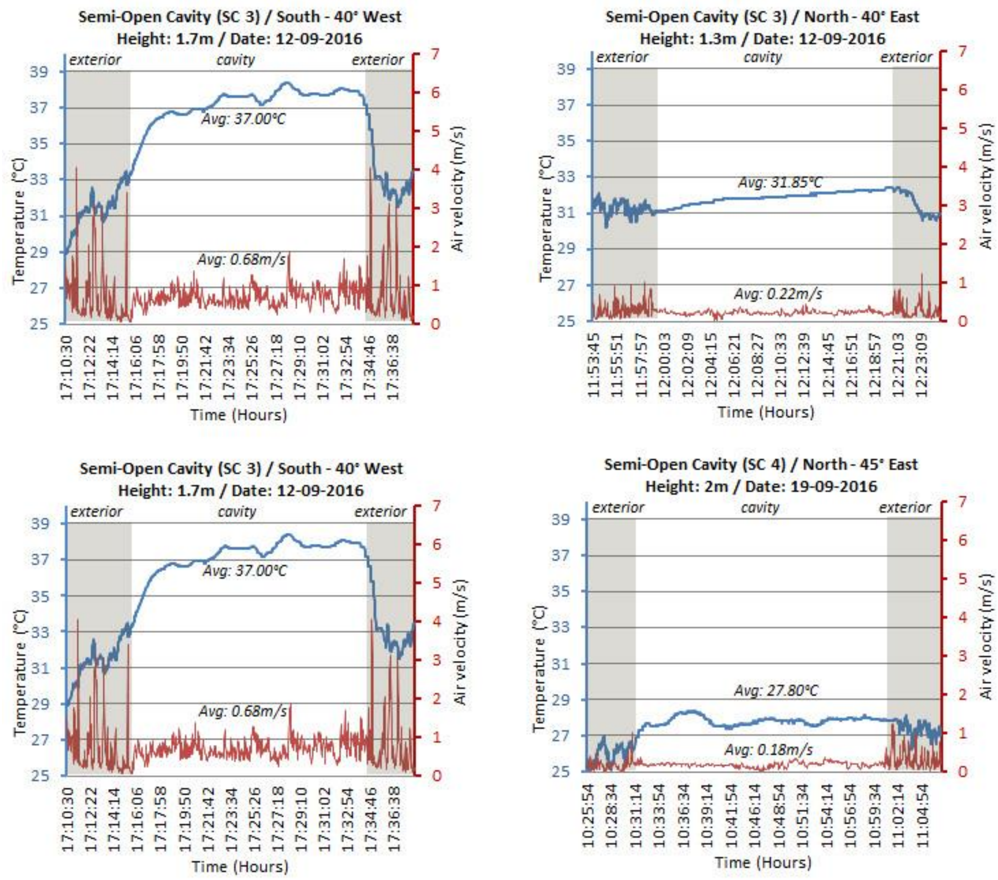
Air velocities inside the cavity are related to increases in temperature inside the cavity for the closed and semi closed cavity cases: average air velocity of 0.23m/s with mean differences of 4.6°C in CC1 and average air velocity of 0.68m/s with mean differences of 5°C in SC3. In other words, more air movement does not necessarily contribute to a decrease in temperature inside the cavity.

Figure 4. **Thermal and air velocity results in Closed Cavity cases (0.8 to 1.2m height) during the measured time at highest solar radiation**



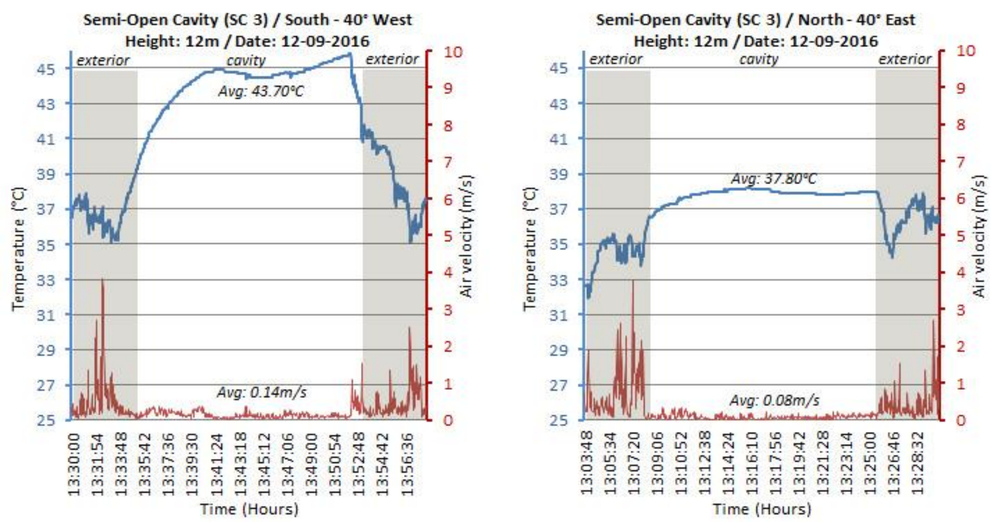
Source: Own elaboration

Figure 5. **Thermal and air velocity results for Semi-Open Cavity cases (0.8 to 1.2m height) during the measured time of highest solar radiation**



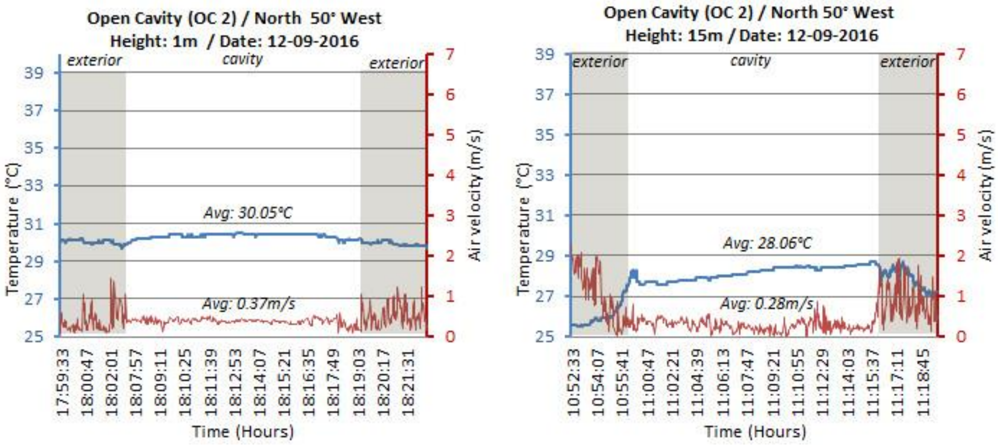
Source: Own elaboration

Figure 6. **Thermal and air velocity results in Semi-Closed cases at the top of the cavity (12m) during the measured time of highest solar radiation**



Source: Own elaboration

Figure 7. **Thermal and air velocity results for Open Cavity cases during the measured time of highest solar radiation**



Source: Own elaboration

3.2. Air movement inside the cavity with regard to the open area regulated in the Spanish Technical Building Code

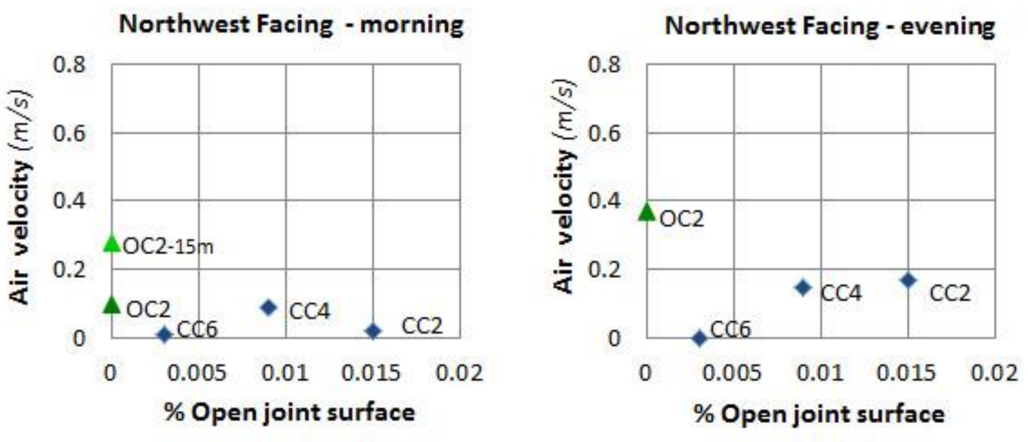
The results of the mean velocities inside the cavities in relation to the percentage of open joint surface of all the study cases are presented. As is seen in Section 2, the Spanish Technical Building Code refers to the classification of air cavities according to the degree of ventilation. According to the Basic Health Document for a ventilating cavity, openings must be at least 0.0012m²/m². However, this surface must be at least 0.0015m²/m² for the cavity to be highly ventilated according to the Energy Saving Document.

In Table 3, it can be seen that the joint surface of the outer layer exceeds the regulated minimum value considerably for both health and energy purposes in all the cases under study. However, the greatest ventilation of the cavity occurs in cases with open ends (SC3 and OC2) and not in the case with the highest open joint surface (CC1).

For buildings with an orientation facing North-West (Figure 8), the highest average air velocity was 0.37m/s in the open cavity case (OC2), which has an air inlet opening of 4cm and an outlet opening of 3cm. In this case, one can deduce that the air movement would be higher if the outer layer had open joints. There was no air movement (air velocity average of 0m/s) inside the gap for closed cavity cases (case CC6).

This is because it is the only case in which the horizontal internal structure causes a null with the width (*w*) of the cavity. In addition, the Width (W) is only 3cm and has a discontinuous height (*H*=2.7m) due to strangulations in slabs (see Table 3). In cases CC2 and CC4, the mean air velocities in the evening were 0.17m/s and 0.15m/s. These are cases in which the widths (*w*) of the cavities are 3cm and 2cm, respectively, and the height of the cavity is continuous along the total height of the building.

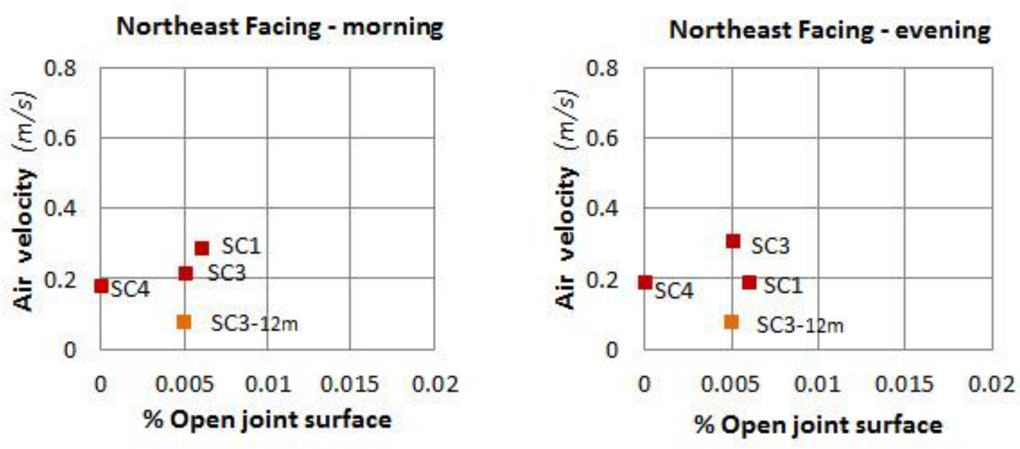
Figure 8. **Relation between Open joint Surface (%) and Air velocity (m/s) in North-West Facing OVF**



Source: Own elaboration

For the buildings facing North-East (Figure 9), all the evaluated cases correspond to the semi-closed cavity characterization. The highest average air velocity was 0.31m/s for the SC3 case. This is due to the largest air inlet opening dimension (7cm) of the buildings. Also, the width of the cavity is 3cm and the height of the cavity is continuous along the building (*H*=12m). As for the SC1 case, the average air velocity was 0.29m/s. This building has the largest open joint area (0.006m^2) of the North-East cases, a 10cm wide cavity, but with closed air entrance and the smallest air outlet opening (2cm). Also, it is a discontinuous cavity due to strangulation in slabs (*H*=2.9m). Finally, in the case of SC4, the average air velocity was 0.19m/s without open joints in the outer layer but with an air inlet opening of 5cm and a 6cm cavity width (*w*) and a continuous cavity height (*H*=12m).

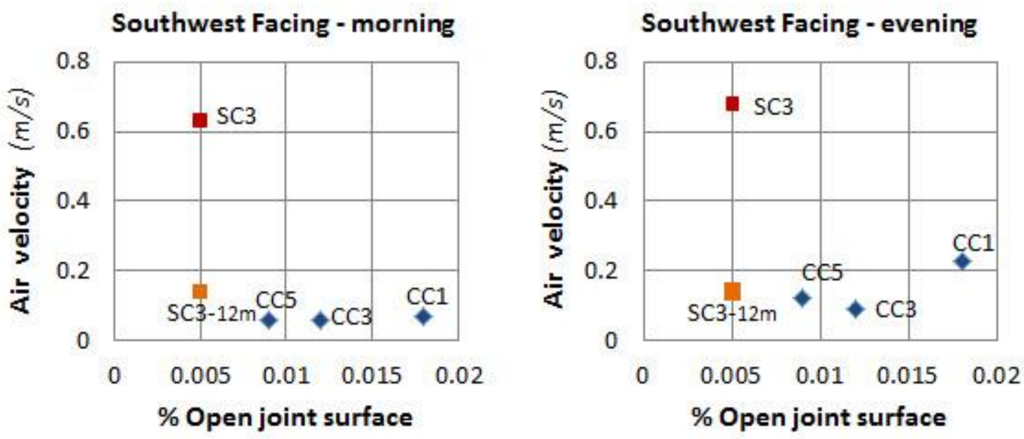
Figure 9. **Relation between Open joint Surface (%) and Air velocity (m/s) in North-East Facing OVF**



Source: Own elaboration

For buildings facing South-West (Figure 10), three closed cavity cases and one semi-open cavity case were monitored. The last one in the list, (SC3), had the highest air velocities at an average of 0.68m/s despite being the one with the lowest open joint surface. This is due to features already mentioned about air inlet openings and a continuous height of the cavity. As for the three closed cavity cases, they have a cavity width (*w*) of 7cm. CC1 presented the highest velocities, an average of 0.23m/s, because it has the largest open joint surface and a continuous height of the cavity (*H*=12m). The CC3 and CC5 cases presented similar mean velocities of 0.16m/s.

Figure 10. **Relation between Open joint Surface (%) and Air velocity (m/s) in South-West Facing OVF**



Source: Own elaboration

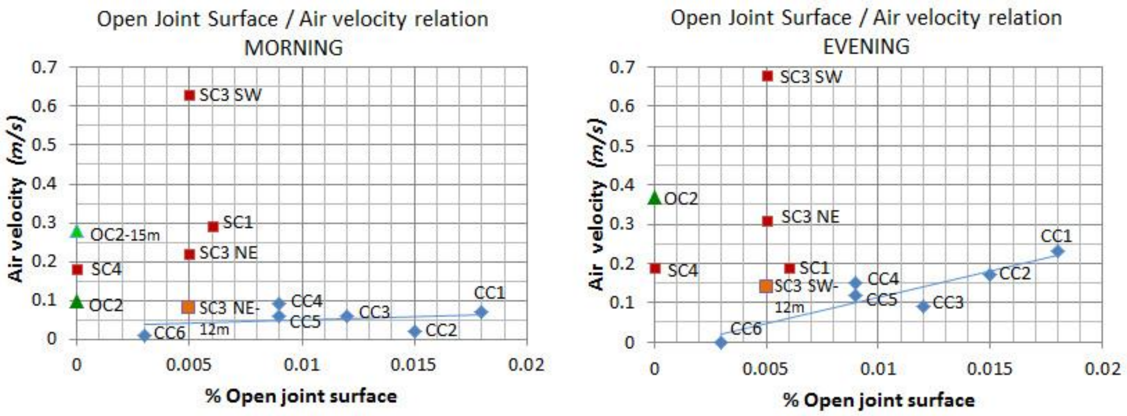
On the other hand, it can be observed that the average velocities of the total cases evaluated were higher during greater incidence of solar radiation on the façades according to the orientation and the time period (morning and afternoon).

The North-West and South-West cases recorded higher velocities in the afternoon (0.7m/s and 1.12m/s respectively) and the North-East cases recorded higher velocities in the morning (1.1m/s). This indicates that solar radiation is an important variable for increasing air movement in the OVF cavity.

Figure 11 shows the linear relationships of open joint surface increases in relation to air velocity in all the cases under study. This relationship is more evident in cases with a closed cavity in the afternoon and in cases with a semi-open cavity in the morning because of the higher incidence of solar radiation on the façades: CC cases that are oriented to the West (South-West and North-West) and SC cases that are oriented to the East (North-East).

Likewise, buildings with apertures at each end of the cavity are those with the highest velocities inside. For this reason, it is possible to demonstrate how influential the apertures of the cavity are for the desired performance of the VF.

Figure 11. **Relation between Open joint Surface (%) and Air velocity (m/s) in all cases**



Source: Own elaboration

4. Conclusions

The present paper focuses on the study of the effectiveness of OVF air cavity ventilation regarding the considerations laid out by the Technical Building Code of Spain (CTE). Following these guidelines, environmental field measurements and geometric and materiality analyses were made for real buildings.

The findings show that air inlet and outlet openings have a major influence on air cavity ventilation, even more so than the open joint surface of the outer layer. Most academic thermofluid-dynamic computer studies of air cavity performance consider these openings but can differ from real on-site measurements. The CTE supports air cavity ventilation through cladding panel open joints and all the buildings under study achieve more than enough this minimum surface. The results show that as the percentage of open joint area increases, the air velocity in the wall cavity also increases (mean of 0.09m/s). However, this velocity increase is not significant in relation to the cases with inlet and/or outlet openings (mean of 0.23m/s).

Regarding the values given by the CTE´s Basic Health and the Energy Saving Document, ventilation openings must be provided with a minimum effective area of 0.0012m^2/m^2 and 0.0015m^2/m^2, respectively. The buildings surveyed showed that the outer layer´s open joint surface exceed these values by between 50% and 90%.

The thermal results of the cases under study indicate that the air inside the wall cavity overheats considerably, especially during the hours of greater solar incidence. This overheating is necessary for the convection effect. However, the CTE does not contemplate temperature calculations inside the air cavity. This is an important factor to consider given the significant solar gains in hot and temperate climates. The excessive temperature rise in the air cavity may lead to a bad performance of the façade resulting in unforeseen condensation or heat gains on the inner layer.

Related to the OVF construction materials and envelope components, the present study shows that although the companies that commercialize the system recommend the existence of openings at the bottom and top of the cavity, it seems that it is more laborious and costly to truly take advantage of this solution in actual buildings.

The approach outlined in this study delves into two guidelines: on the one hand, measurements should be planned at different heights of the air cavity; and, on the other hand, it is necessary to advance the study of the thermo-dynamic phenomena that happen within the air cavity in order to generate application proposals for building regulations that want to incorporate the OVF envelope system in different geographic and climatic contexts. If building regulations include the OVF system, all system variables should be considered since there are big variations in heat transfer according the physical and geometric characteristics of the elements.

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