

Thermal Behavior of a Ventilated Façade Using Perforated Ceramic Bricks

H. López-Moreno, A. Rodríguez-Sánchez, C. Viñas-Arrebola, C. Porras-Amores

Abstract—The ventilated façade has great advantages when compared to traditional façades as it reduces the air conditioning thermal loads due to the stack effect induced by solar radiation in the air chamber. Optimizing energy consumption by using a ventilated façade can be used not only in newly built buildings but also it can be implemented in existing buildings, opening the field of implementation to energy building retrofitting works.

In this sense, the following three prototypes of façade were designed, built and further analyzed in this research: non-ventilated façade (NVF); slightly ventilated façade (SLVF) and strongly ventilated façade (STVF). The construction characteristics of the three façades are based on the Spanish regulation of building construction “Technical Building Code”. The façades have been monitored by type-k thermocouples in a representative day of the summer season in Madrid (Spain). Moreover, an analysis of variance (ANOVA) with repeated measures, studying the thermal lag in the ventilated and no-ventilated façades has been designed.

Results show that STVF façade presents higher levels of thermal inertia as the thermal lag reduces up to 17% (daily mean) compared to the non-ventilated façade. In addition, the statistical analysis proves that an increase of the ventilation holes size in STVF façades can improve the thermal lag significantly ($p > 0.05$) when compared to the SLVF façade.

Keywords—Energy efficiency, experimental study, statistical analysis, thermal behavior, ventilated façade.

I. INTRODUCTION

THE building sector, before the transport and industry sectors, is the most energy wasteful sector in Europe. Specifically, this amount represents 28% of the global energy consumption in Spain, of which more than half is generated by the use of air-conditioning systems, with an amount of 25,880 ktoe in 2010 and with an upward and sustained growth over the past 15 years [1]. This fact combined with the Spanish’s energy dependence, with values reaching the 80% [2], is changing the consumer habits, opting for buildings in which sustainability, habitability and environmental quality are requirements.

This situation has led to the development of the European Directive 2002/91 / CE (and subsequently upgraded 2010/91 / CE and 2012/91 /CE) which set specific measures to ensure building energy efficiency improvement [3]. These European regulations are transposed to the Spanish regulation by: (1) the Technical Building Code (TBC), (2) the Action Plan Strategy for Energy Saving and Efficiency (PAE4+) for the period 2011-2020 and (3) the Basic process for certifying the energy

efficiency of new buildings [4]. For these reasons, nowadays, the main objective of engineers and architects are focused on finding new and innovative construction systems committed to energy efficiency, as for example the ventilated façade (VF) reducing approximately 40% of economic costs due to the reduction of the thermal load of the building [5]. Ventilated façade has been the subject of numerous research studies in the last years [6]-[10].

The VF is composed by an independent panel (outer sheet) to the supporting wall (inner sheet) fixed through a series of anchors, with ventilation gaps allowing entry and exit of air creating a ventilated chamber due to chimney effect induced by solar radiation in the chamber. Because of this fact, the VF system is able to reduce the negative effects of external agents and moisture, allowing to minimize the overheating during summer season and avoiding condensations. Thermal and acoustic improvement is achieved by fixing the insulation to the outer face of the supporting wall, avoiding thermal bridges. In addition, this solution is applicable not only for the construction of new buildings, but also it can be applied in existing buildings, which may have thermal deficiencies, due to the lack of insulation, high thermal bridges, etc. So, the VF may be a good solution for building retrofitting. However, there is a lack of knowledge and experience regarding the behavior of VF as their speed of innovation is very quick. Due to the heterogeneity of the VF system and the use of new materials that are demanding high performance, presents great difficulties to predict their behavior. On the other hand, the complex physical equations for estimating energy demand of VF make it necessary to use computational fluid dynamics (CFD). Therefore, dimensioning tools that have been established in the different regulations are poorly detailed and incomplete. For this reason, the aim of this research is to develop a full and detailed experimental study of the behavior of a ventilated façade, for which the design, implementation and monitoring of prototypes will be necessary in order to get real measurements, taken and recorded on site. Two types of ventilated facades --as considered by the current Spanish regulation (TBC)-- have been studied: Slightly Ventilated Façade (SLVF) and Strongly Ventilated Façade (STVL). Finally, both systems have been compared with a Non Ventilated Façade (NVF) reference.

II. EXPERIMENTAL PROTOTYPES

The experimental prototypes have been made in the Escuela Técnica Superior de Edificación (ETSEM) of the Universidad Politécnica de Madrid. It is situated in the following geographical coordinates: latitude 40.44 North, longitude 3.73

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West and altitude over sea level 655 m. Specifically, the model is facing south and located on the northwest roof of the building.

A. Design of Experimental Prototypes

The experimental prototypes are mainly composed by two elements (Fig. 1): 1) the façade -- ventilation gaps will change in each façade according to the TBC regulation-- and 2) surrounding insulation in order to simulate the interior of a room.

1. Sheets of XPS 1250x600x50 mm.
2. Timber sheets placed as the base of prototypes
3. Outer sheet: perforated hollow brick of 240x115x70 mm.
4. Cement mortar
5. Joints cement mortars 1 cm of thickness
6. Air chamber 4 cm of thickness.
7. Sheets of XPS 1250x600x60 mm.
8. Inner sheet: perforated hollow brick of 240x115x70 mm.
9. Thick plaster (TP) and fine plaster (FP)

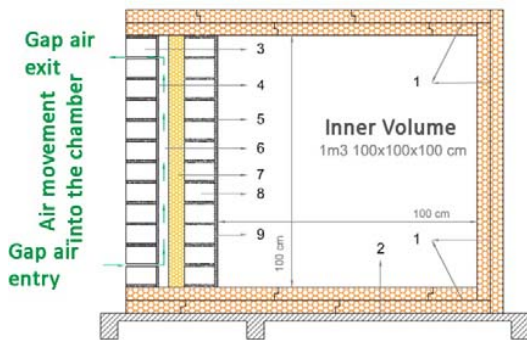


Fig. 1 Prototype and description of the materials used

B. Characteristics of Ventilated Façade

All three prototypes have a façade dimension of 1.00 m² in order to make comparisons between them. All of them are formed by an outer perforated sheet made of 12.50 cm of perforated plastered brick, standing with cement mortar, an air chamber of 40 mm, thermal insulation of extruded polystyrene with a thickness of 60 mm and an inner sheet made of 12.50 cm of perforated plastered brick.

Ventilation gaps and voids were designed following the conditions stated in the TBC regulation (document DB-HS; "Section HS-1: Protection against moisture" and the document DB-AH in Appendix E "Calculation of characteristic parameters of demand").

Non-ventilated Façade (NVF): It is a kind of façade where there are no gaps in the air chamber, so the effective area (A_{ef}) is zero (Fig. 2).

Slightly Ventilated Façade (SLVF): According to requirements of TBC, the prototype of 1.00 m² for the SLVF, total effective area SLVF is 1000 mm² (comprised between 500 mm² and 1500 mm² specified in the normative). This area will be divided into 2 upper and 2 lower surfaces of 25 mm wide by 10 mm high, coinciding with the height of the cement joint between bricks (Fig. 3).

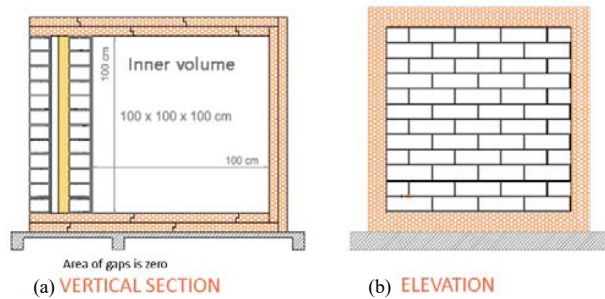


Fig. 2 Scheme of Non-Ventilated Façade (NVF). $A_{ef} = 0 \text{ mm}^2$. (a) Vertical section and (b) elevation

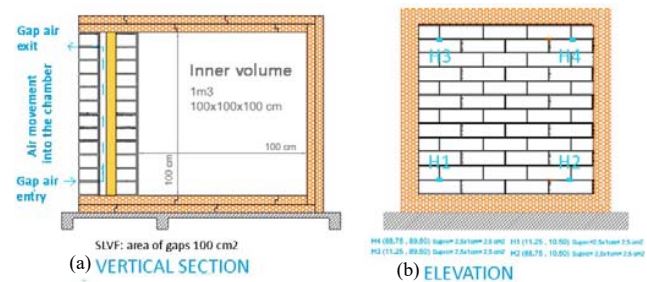


Fig. 3 Scheme of Slightly Ventilated Façade. $A_{ef} = 1000 \text{ mm}^2$. (a) vertical section and (b) elevation

Strongly Ventilated Façade (STVF): According to requirements of TBC, the prototype of 1.00 m² for the STVF, the total effective area for slightly ventilated façade is 3000 mm². This area, as it is for SLVF, is divided into 2 upper and 2 lower surfaces 75 mm wide by 10 mm high, coinciding with the height of the cement joint between bricks (Fig. 4).

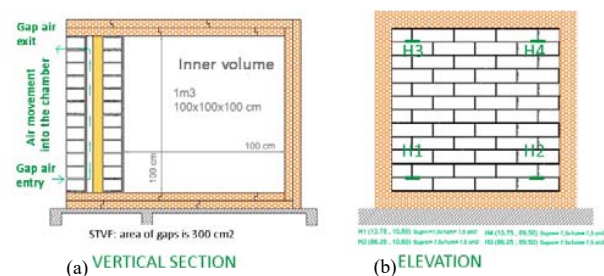


Fig. 4 Scheme of Strongly Ventilated Façade. $A_{ef} = 1000 \text{ mm}^2$. (a) vertical section and (b) elevation

The construction of the insulation cubes aims to simulate the interior space of the room. In this way, the exterior side of the façade will be exposed to varying climatic conditions of temperature, air velocity and radiation, while these variables in for the interior side of the façade remain more constant.

Hence, three independent prototypes are designed cubes about 1.00 m³ (1.00 m x 1.00 m x 1.00 m) formed by extruded polystyrene (XPS), except one of the lateral faces, which will be façade of study. The thickness of the cubes is 100 mm, thus ensuring a more constant indoor temperature. Panel sheets were performed in 1250.00 x 600.00 x 5.00 mm, so it was necessary to design a cutting appropriate to achieve the

desired dimensions.

The materials used for the execution of prototypes are described in Table I.

TABLE I
THE MATERIALS USED FOR THE EXECUTION OF PROTOTYPES

Materials	
1.	Sheets of XPS 1250x600x50 mm.
2.	Wood sheets placed as the base of prototypes
3.	Cement mortar 1:6: CEM I 42,5 N and river sand.
4.	Perforated hollow brick of 240 x 115 x 70 mm.
5.	Cement mortar 1:3 con CEM I 42,5 N and river sand.
6.	Pieces of 40 mm thickness of XPS.
7.	Sheet of XPS of 60 mm thickness.
8.	Cement mortar 1:6: CEM I 42,5 N and river sand.
9.	Perforated hollow brick of 240 x 115 x 70 mm.
10.	Thick plaster (TP) and fine plaster (FP).
11.	Sheets of XPS 1250x600x50 mm.
12.	Polyurethane foam.

C. Monitoring and Recording of Experimental Models

In order to register and monitor the variables of the prototype the following equipment has been used:

Temperature Sensors (Continuously Record): k-type thermocouples responsible for measuring the temperature of the different surfaces of the models, which have been used data-logger (OPUS 200 two-channel and 8-channel OPUS 208), whose results have been compiled by Smart software V-15.

Temperature Sensors (Punctual Record): k-type thermocouples in which the results were obtained manually in-situ and whose values are reflected in a data-logger the PHYW home.

Table II represents the nomenclature and symbols used to designate each of the thermocouples used.

TABLE II
NOMENCLATURE AND SYMBOLS USED TO DESIGNATE THE MEASURING EQUIPMENT

○	TA	Outside area of the outer sheet in contact with brick
△	TB	Area of the air chamber in contact with the plaster
◇	TC	Area of the air chamber in contact with the insulation
□	TD	Inner area of the inner sheet in contact with the plaster
L: Low area M: Middle area T: Top area		
Non-Ventilated (NVF)	Slighted Ventilated (SLVF)	Strongly Ventilated (STVF)

Because it was impossible to obtain sufficient channels for recording surface temperature in all desired points, the following distribution was chosen: NVF temperature values TA, TB, TC and TD were recorded at the middle level of the façade, SHVF thermocouples were placed in the lower section (TB and TC), middle (TB, TC and TD) and upper (TB and TC), while the STVF data were collected in the lower section (TB and TC), media (TA, TB, TC and TD) and upper (TB and TC) (Fig. 5).

The recordings were made in summer conditions, from 18th until 20th of September 2012 between 8:00 am and 8:00 p.m. Air temperatures were measured every 10 seconds and were

recorded each 15 minutes, except the manual records, that were measured hourly.

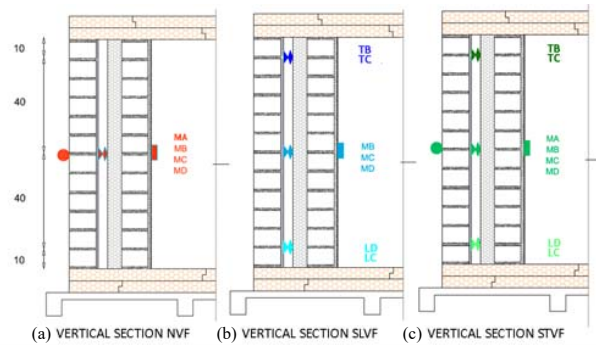


Fig. 5 Location of measuring devices in different facades: (a) NVF, (b) SLVF and (c) STVF

D. Statistical Analysis

The proposed statistical analysis aims to compare the thermal lags obtained in the three prototypes of facades studied. These analyzes were performed using SPSS statistical commercial software. Specifically, an analysis of variance (ANOVA) with repeated measures was designed by studying the existing thermal lag (Text-Td) between the ventilated facades (SHVF and STVF) and non-ventilated (NVF). The Huynh-Feldt statistic was used to adjust the sphericity. The ANOVA analysis proposed is possible considering all experimental measurements taken at three prototypes façade were performed simultaneously. The significance level was set at 0.05 ($p < 0.05$). The repeated measures ANOVA analysis has proven to be robust even in cases where data is not fully distributed as normal. In addition to establishing statistically significant differences, the effect size was also analyzed for relevance. The effect size is a measure of interaction between two variables and is used as a technique for comparison of means. The effect size is also known as partial eta-squared, η_p^2 , which estimates the degree of association to the sample (1):

$$\eta_p^2 = SS \text{ effect} / SS \text{ effect} + SS \text{ error} \quad (1)$$

Effect size is given by the variance of the sums of the squares of a particular effect (effect SS), from the sum of the squares of this effect, the more the error sum of squares (SS error). The effect size can be classified as small ($0.01 \leq \eta_p^2 \leq 0.06$), middle ($0.06 \leq \eta_p^2 \leq 0.14$), or large ($\eta_p^2 \geq 0.14$) [11].

III. RESULTS

A. Evolution of Temperature

The evolution of the temperature recorded during the period of the cycle in the middle section, is shown in Fig. 6 and Table III.

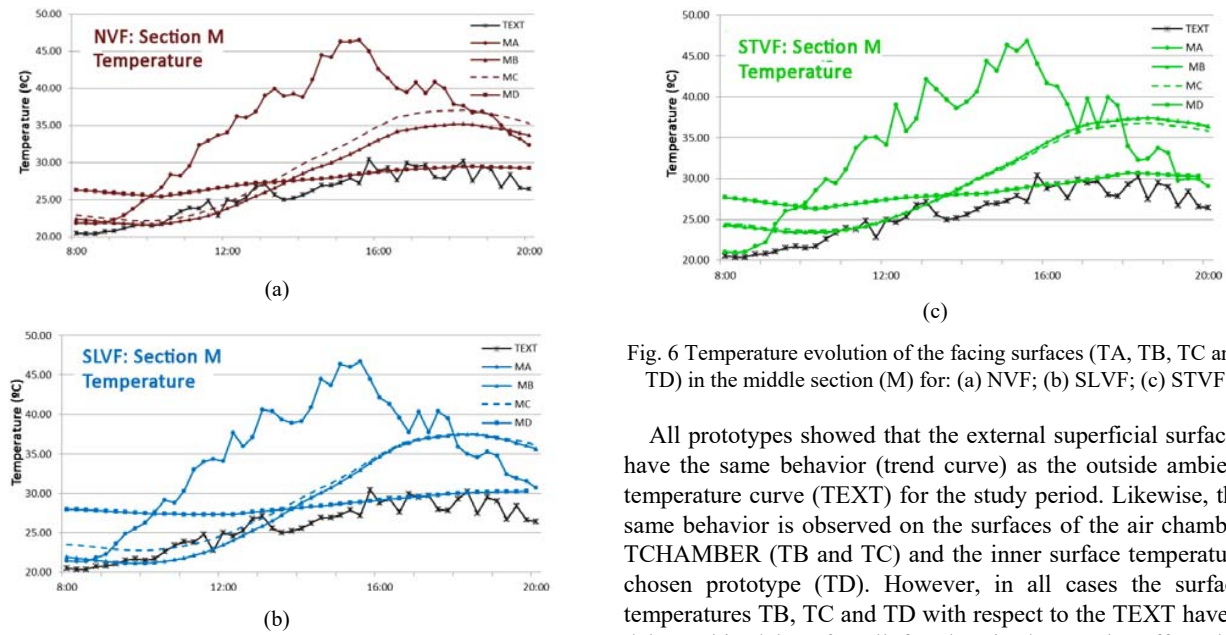


Fig. 6 Temperature evolution of the facing surfaces (TA, TB, TC and TD) in the middle section (M) for: (a) NVF; (b) SLVF; (c) STVF

All prototypes showed that the external superficial surfaces have the same behavior (trend curve) as the outside ambient temperature curve (TEXT) for the study period. Likewise, the same behavior is observed on the surfaces of the air chamber TCHAMBER (TB and TC) and the inner surface temperature chosen prototype (TD). However, in all cases the surface temperatures TB, TC and TD with respect to the TEXT have a delay. This delay, for all facades, is due to the effect that origins the air chamber, and allows analyzing the influence of the air chamber in behavior and improving the thermal inertia of the three building systems under study.

TABLE III
THERMAL VALUES IN LOWER, MIDDLE AND UPPER SECTION FOR SLVF AND STVF AT 8:00 AM AND 20:00 PM

	TC and TA			T _{chamber} (T _C) relation with T _{EXT} (T _A)		Fluctuation	Delay
	T _{C MAX}	T _{C MIN}	T _{A MAX *}	ΔT_{TA-TC} when T _{C MAX}	ΔT_{TA-TC} When T _{C MIN}	ΔT_C (T _{C MAX} - T _{C MIN})	Δ_{Hour} (T _{A MAX} - T _{C MAX})
MIDDLE SECTION							
NVF	37.07 18:15	22.14 10:00	46.52 15:30	0.85 18:15	3.41 10:00	14.94	2:45
SLVF	37.60 18:15	22.79 10:00	46.69 15:30	-2.08 18:15	0.40 10:00	14.81	2:45
STVF	36.82 18:30	23.64 10:15	46.85 15:30	-4.41 18:30	3.36 10:15	13.81	3:00

Improving the thermal inertia is determined, first, for the evaluation of temperature fluctuations in the air chamber, obtained from the maximum and minimum temperature values in the chamber ($\Delta T = T_{MAX \text{ CHAM}} - T_{MIN \text{ CHAM}}$) and secondly, by fluctuations of delay between records obtained for the maximum temperature of the outer face of the façade and the records registered in the air chamber ($\Delta_{hour} = T_{A \text{ MAX}} - T_{C \text{ MAX}}$). On the one hand, it is observed that the maximum T_c in STVF (36.82°C) is smaller than those for the NVF (37.07°C) and SLVF (37.70°C) respectively, measured in the three cases warmest hours of the day (6:15 p.m., 6:30 p.m. and 6:15 p.m.); on the other hand, in relation to the low temperature, the lowest minimum temperature TC is obtained in the NVF (22.14°C) compared to the SLVF (22.79°C) and STVF (23.64°C) respectively for the coolest hours of the day (10:00 am, 10:00 am, and 10:15 am).

Temperature variations outside (T_A) for the surface temperature of the chamber (T_C), for maximum TC values are lower in the STVF respect the SLVF and NVF (-4.41°C < -2.08 C < 0.85°C) while for the minimum values of TC are

higher for STVF, followed by the NVF and SLVF (3.36 °C > 3.41 °C > 0.40 °C).

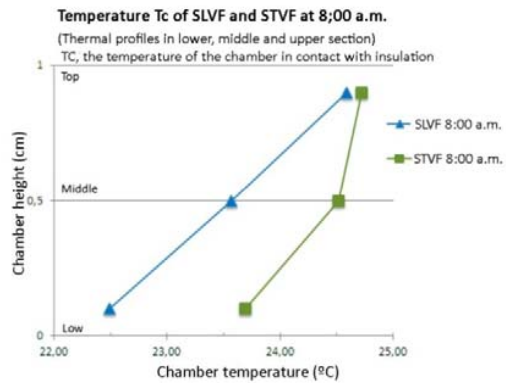
Temperature fluctuations in the TC surface for maximum and minimum values are lower in the STVF compared to SLVF and NVF (13.18°C < 14.81°C < 14.94°C). On the other hand the delays caused by the time difference between the maximum outside temperature (T_A) and maximum temperature of the chamber (T_C) are higher in the STVF compared to SLVF and NVF (3:00 pm > 2:45 pm).

B. Thermal Profiles in Lower, Middle and Upper Section for SLVF and STVF

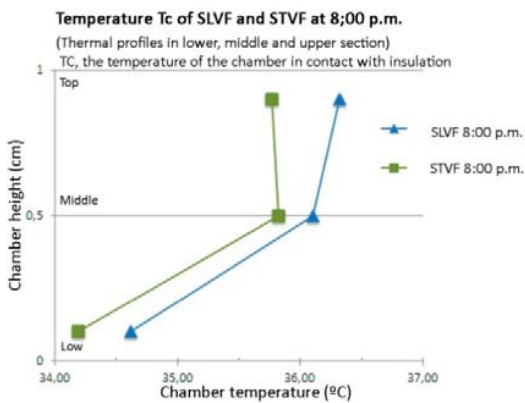
Fig. 7 represents the thermal profiles in lower, middle and upper section for SLVF and STVF at 8:00 am and 20:00 pm for the surface TC, the temperature of the chamber in contact with the insulation are represented in Table IV.

TABLE IV
THERMAL VALUES IN LOWER, MIDDLE AND UPPER SECTION FOR SLVF AND STVF AT 8:00 AM AND 20:00 PM

SECTION		Temperature, T _c (°C)			
		SLVF 8:00 a.m.	STVF 8:00 a.m.	SLVF 8:00 p.m.	STVF 8:00 p.m.
LOW	0.1 m	22.49	23.69	34.62	34.19
MIDDLE	0.5 m	23.57	24.52	36.10	35.82
UPPER	0.9 m	24.59	24.72	36.32	35.77



(a)



(b)

Fig. 7 Thermal profiles in lower, middle and upper section for SLVF and STVF at (a) 8:00 am and (b) 20:00 pm

In the STVF, the TC values depending on the internal temperature (TD) have smaller fluctuations at the start and end of the study. This represents more homogeneous temperatures throughout the study cycle. The highest values are been recorded for early hours in the morning, coinciding with the record of colder ambient temperatures, and lower for late hours in the afternoon, when the environmental temperatures are hotter. It is significant to note, that temperatures increase when increasing the level section, verifying the physical foundation of the VF of air circulation in the chamber due to temperature differences. These results show the vital need for the design of ventilation gaps in the lowest and highest possible area of the chamber, to prevent obstruction of airflow with the formation of hot and cold air-stratified bags in these areas.

C. Statistical Analysis

This statistical analysis aims to quantify the differences in the thermal lag (damping) inside-outside when we replace a front non-ventilated by a ventilated façade (SLVF or STVF). Based on the study executed is verified that both ventilated facades (SLVF and STVF) thermal lag obtained show statistically significant differences ($p < 0.05$) compared with non-ventilated façade.

The effect size reaches the following values using (1): $\eta_p^2 = 0.15$ (FLV) and $\eta_p^2 = 0.16$ (FMV). The statistical values corroborate that both ventilated facades improved significantly, "large effect ($\eta_p^2 \geq 0.14$)", the global thermal inertia of the façade. Furthermore, it is shown that the increasing ventilation gaps in strongly ventilated façade means an increase, "large effect ($\eta_p^2 \geq 0.14$)" of the thermal lag with respect to the slightly ventilated façade.

The correct size of the gaps is an important consideration in the design of the ventilated façade because it will influence radically in the passive properties of the construction system. This potential, as it has been demonstrated in this research and may entail a reduction in the thermal lag (damping) inside-outside, when we replace a non-ventilated façade by a ventilated façade, of 7% (SLVF = 1000m²) and 12% (STVF = 3000m²).

IV. CONCLUSIONS

The STVF, with the largest area of ventilation gaps (3000 mm²), presents higher energy and comfort levels than SLVF and NVF. The longer thermal delays and lower thermal fluctuations observed in STVF show the thermal inertia improvement of the façade that can be archive in warm Spanish seasons (starting at 8:00 am to 8:00 pm).

Location of the ventilation gaps are the key for optimal performance. They should be placed near the floor and ceiling of the chamber to avoid creating hot-cold air bags. The principle operation in which is based the ventilated is demonstrated because of the circulation of the air inside the ventilated chamber.

This research justifies the use of the STVF as an important building system to achieve a social, an environmental and an economic balance, in new and existing building. Correct sizing of the gaps is an important issue to have into consideration for designing ventilated facades due to it will influence radically in the passive properties of the construction system.

Using ventilated façade instead a non-ventilated could means a reduction in the thermal lag between inside-outside up to 7% (SLVF = 1000m²) and 12% (STVF = 3000m²).

ACKNOWLEDGMENT

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