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Thermodynamic Analysis of Ventilated Façades under Operating Conditions in Southern Spain

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Abstract**—**In this work we study the thermodynamic behavior of some ventilated facades under summer operating conditions in Southern Spain. Under these climatic conditions, indoor comfort implies a high energetic demand due to high temperatures that usually are reached in this season in the considered geographical area.

The aim of this work is to determine if during summer operating conditions in Southern Spain, ventilated façades provide some energy saving compared to the non-ventilated façades and to deduce their behavior patterns in terms of energy efficiency.

The modelization of the air flow in the channel has been performed by using Navier-Stokes equations for thermodynamic flows. Numerical simulations have been carried out with a 2D Finite Element approach.

This way, we analyze the behavior of ventilated façades under different weather conditions as variable wind, variable temperature and different levels of solar irradiation.

CFD computations show the combined effect of the shading of the external wall and the ventilation by the natural convection into the air gap achieve a reduction of the heat load during the summer period. This reduction has been evaluated by comparing the thermodynamic performances of two ventilated and two unventilated façades with the same geometry and thermophysical characteristics.

Keywords**—**Passive cooling, ventilated façades, energy-efficient building, CFD, FEM.

I. INTRODUCTION

OVER the last years, interest in the development of passive systems for heating and cooling has experienced a remarkable rise because of the need to decrease the energetic costs in the thermal conditioning of buildings

The aim of this paper is to analyze the heat transfer through a system consisting of ventilated façades in the operating conditions of summer weather in southern Spain, and to determine if under such climatic conditions the studies ventilated façades provide some energy saving compared to the non-ventilated façades, and to deduce their behavior patterns in terms of energy efficiency.

Specifically, we consider various values of temperature, solar radiation and wind velocity which are typical of the seasonal and geographical setting.

The most common configuration for ventilated façades consists of an outer layer that is mechanically connected by using special structures to an inner layer, a wall made of brick, or any other material that can provide support to the outer layer. Usually, the thermal insulation is in contact with the external surface of the inner layer. The external slab can be made of a wide variety of materials and is the visible face of the building and define the exterior aesthetic of the building.

This layout generates an air cavity between the two layers which is naturally ventilated trough openings in the bottom and top of the façade.

Furthermore, it is noteworthy that ventilated façades allow multiple configurations and geometries that shape their thermodynamic features. In this paper we focus on façades which have opened ventilation channels in its front and two different sizes for the ventilation openings are studied.

In hot climates, the main advantage attributed to ventilated façades is the reduction of cooling load for the building climatization. This reduction is achieved by the combination of two factors: ventilation induced by natural convection in the ventilated chamber and the protection from solar radiation provided by the external layer of the façade.

Specifically, a stack effect is produced in the ventilated chamber because of the warming caused by solar radiation on the outer surface of the façade.

Then, heat is transferred by conduction through the outer slab to its internal surface facing the ventilated chamber and the opposite inner wall surface face is heated by radiation.

This way, natural convection causes an air flow in the ventilated chamber, which extracts the heat accumulated in the walls. This should result in a reduction of the temperature of the walls and therefore a decrease in the heat gain into the building should take place.

However, while it is possible to guarantee the performances of a mechanical ventilation system, this is not necessarily the case for natural ventilation because, essentially, the performances of natural ventilation are subject to the influence of meteorological conditions (wind, temperature difference and solar irradiation).

In this work, we obtain some conclusions about thermodynamic behavior patterns of the ventilated façades considered under the action of different environmental factors.

II. MODELIZATION OF THE VENTILATED FAÇADES

A. Physical Model

The ventilated façades of our study were modeled as a two-dimensional system Fig. 1, with a composite inner wall and an outer layer, creating between both surfaces an air gap.

This air gap is delimited at the top and at the bottom by the roof and the floor of the building respectively. Their communication with the external environment takes place,

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according to the considered geometry, through openings located at the base and at the upper part of the outer wall.

Dimensions and physical characteristics of the different layers which make up the studied façade are described in Table I.

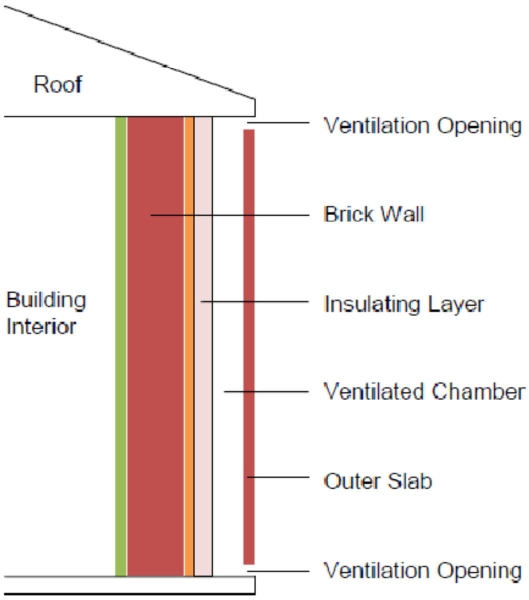

Fig. 1 Schematic Section of the Ventilated Façade

In the system made up by the ventilated façade, the three basic mechanisms of heat transfer are present: radiation, convection and conduction. Specifically, the heat transfer in the façade is determined by:

- Heat gain on the outer slab due to solar irradiation.
- Heat exchange by convection and radiation between the outer surface of the façade and the environment.
- Heat transfer by conduction through the outer slab.
- Radiative heat exchange between the two surfaces which delimit the ventilated chamber.
- Convective heat exchange between the surfaces of the ventilated chamber and the air flowing inside it.
- Heat transfer by conduction through the inner wall.
- Heat exchange by convection and radiation between the internal surface of the inner wall and the interior of the building.

In order to establish the physical model, it is necessary to bear in mind that air flowing in the interior channel removes or adds heat to the walls of the channel at a rate fundamentally determined by the air flow speed through the chamber and by the difference of temperatures between the channel walls and the air.

The air flow speed through the ventilated chamber is conditioned by the natural convection phenomenon which takes place inside the chamber and by the air flow through the openings of the façade, which in turn is influenced by the speed of the exterior air and even by this air temperature.

Therefore the Navier-Stokes that describe the air flow, the equation for energy transport in the air, and heat transfer equations through the different façade walls must be resolved coupled.

B. Equations that Govern the Fluid

Changes expected for the relative temperature $T - T_{amb}/T_{amb}$, are not too important and therefore Boussinesq simplification can be used to model buoyancy effects due to natural convection.

Thus, we assume that thermophysical properties of air are constant except the density, which is supposed variable in the equation for conservation of the vertical momentum.

Therefore, the equations which determine the fluid behavior are the conservation of mass, momentum and energy equations:

$$\begin{cases} \nabla \cdot \vec{U} = 0 \\ \dfrac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \nabla \vec{U} - \nabla \cdot (\nu \nabla \vec{U}) + \nabla p = \vec{b} \\ \dfrac{\partial T}{\partial t} + \vec{U} \cdot \nabla T - \nabla \cdot (\alpha \nabla T) = 0 \end{cases}$$

where $\vec{U}$ is the velocity; p the pressure; T the temperature; ν and α the cinematic viscosity and the thermal diffusivity of the air.

In these equations $\vec{b} = \begin{pmatrix} 0 \\ -g\,\beta(T - T_{amb}) \end{pmatrix}$ represents the force of buoyancy due to natural convection, being g the gravitational acceleration, T_{amb} the ambiance temperature and β the coefficient of thermal expansion that we can approximate by $\beta = 1/T_{amb}$ under the hypothesis of ideal gases.

For the fluid the condition of non-slip is imposed on all the surfaces of the ventilated façade and exterior soil.

In the air inlet to the computational domain the speed and the temperature of the air is fixed. In the remaining borders, the values of speed and temperature of the air are the result of the calculation made.

The temperature of external soil border is taken equal to the ambiance temperature.

C. Thermal Conduction trough the Solid Walls

Heat conduction through the outer slab and the inner wall is modeled by the equation

$$\frac{\partial T}{\partial t} - \nabla \cdot (\alpha \nabla T) = 0$$

where the diffusivity coefficient α is variable taking now the value corresponding to each material of the various layers which constitute the inner wall and the outer slab.

This equation is closed with the boundary conditions we get when writing the energy balance equation corresponding to each surface.

On the external face of the outer slab, the energy balance must consider:

- The solar radiation incident on the surface. The effective value considered for this radiation is the absorbed perpendicular component of the solar irradiation incident on the surface.
- The exchange of radiative thermal energy between the outer surface of the external slab and the environment. For this exchange, the value of the sky temperature is calculated according to the ambiance temperature by using a common correlation from ASHRAE [1]:

$$T_{sky} = 0.0552\, T_{amb}^{1.5}$$

where both temperatures are absolute.

- The convective heat exchange with the environment. For this exchange, it has been used an average coefficient of convective heat transfer through the surface area. In order to determine this coefficient we use the correlation given by Liu and Harris in [2]:

$$h_c = 6.31\, U_S + 3.32 \quad W/m^2K$$

where U_S is the wind velocity in m/s measured near the surface of the façade. This correlation provides U_S with a more accurate calculation of h_c, since we use the wind velocity near the front and not the velocity of the atmospheric wind entering the computational domain.

For the surfaces of the outer slab and of the inner wall delimiting the ventilated chamber, the energy balance equation must consider:

- The exchange of radiative thermal energy between both surfaces.
- The convective heat exchange with the air flowing through the chamber. This transfer is directly calculated during the computation using the thermophysical properties of the materials and the computed variables in each cell of the finite element grid.

Finally, for the inner wall surface facing the interior of the building, the energy balance equation is obtained by considering a constant internal temperature $T_{room} = 24°C$ and a heat exchange by convection and radiation with a mixed heat transfer coefficient $h_i = 8\ W/m^2K$, which is recommended in the Spanish technical specifications for this type of indoor heat exchange [3].

III. NUMERICAL SIMULATION

A. Computational Domain

For the numerical solution of the set of equations describing the problem, we have started from a two-dimensional domain that includes both the ventilated façade and a wide region outside it, in order to adequately simulate air flows in the front of the façade.

This domain has been meshed using triangular elements to perform a discretization of the problem by the Finite Element Method (FEM). The considered mesh has a total of 13415 triangles allowing a reasonable precision in the numerical results obtained Fig. 2.

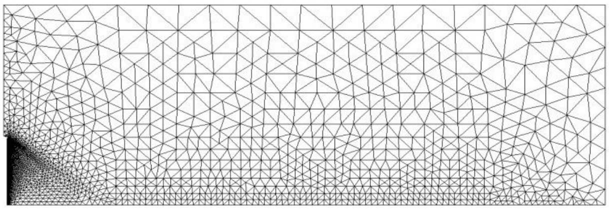

Fig. 2 Mesh of the computational domain

In the figure above, the building containing the ventilated façade is in the lower left corner, while the right boundary of the domain is the air inlet boundary, for cases of non-zero air velocity.

B. Numerical Computation

The numerical solution of the problem has been carried out by a finite element discretization of the Navier-Stokes thermodynamic equations.

For the computational resolution the open source logical FreeFem from French INRIA has been used.

The equations of heat transfer through the inner wall and the outer layer have been solved by finite difference discretization.

C. Environmental Conditions

It has been considered a set of environmental conditions that tries to reproduce the most relevant features of summer in southern Spain.

These conditions are characterized by high temperatures as well as by relatively high levels of radiation during daytime hours.

Winds usually are not strong but can range from absolute calm to a relatively moderate wind, which may significantly increase the heat sensation.

This way the values studied in this paper are 300 and 400 W/m^2 for the incident solar radiation normal to the outer surface of the façade [4], ambient air temperatures of 30º and 40ºC, and inlet wind velocities of $0, 2, 4$ and $6\ m/s$. These values allow us to establish patterns of behavior for the ventilated façades under the required climatic conditions.

D. Studied Façades Features

The geometry of the studied façades is similar to that shown schematically in Fig. 1. The height of the cavity is 6 m. The Spanish Technical Building Code [3] points for ventilated façades than the width of the chamber should be between 30 and 100 mm, and ventilation openings must have a total effective area at least equal to a 120 cm^2 for each 10 m^2 of facade between slabs, 50% distributed between the upper and lower opening. Although some authors [5] point out that the optimum energy efficiency ventilated façade is achieved for a width camera about 15 cm , in this paper we stick to the values set by the Technical Code [3], and we focus on two ventilated façades with a chamber width of 10 cm, two different widths for the air vents, namely 10 cm and 15 cm, so that they meet the requirements specified in the Technical

Code. Both facades will be designated from here as FVP1 and FVP2, respectively.

Dimensions and thermophysical characteristics of the studied façades are listed in Table I of Appendix A.

For the external surface of the outer layer, an absorptivity value of solar radiation equal to 0.63 is considered.

The emissivity coefficient of the two surfaces of the external layer has been taken as 0.93 and for the inner wall surface facing the ventilated chamber, the emissivity coefficient has been taken equal to 0.75.

These values are taken according to the technical specifications for the materials considered.

IV. RESULTS AND DISCUSSION

To study the façades considered, we have carried out a set of simulations that collect the different environmental conditions of temperature, solar intensity and wind speed described below.

The values obtained were compared with those presented in [6] for the case of inlet air velocity zero, ambient air temperature equal to $28℃$ and solar intensity equal to $400\ W/m^2$. Our simulation results for the average velocity of air inside the ventilated chamber and the heat flow into the building show a good analogy with those presented in such a work.

A. Heat Flow in the Ventilated Façades for Different Environmental Conditions

The simulation results show the qualitative behavior expected for ventilated façades Fig. 3. Thus, higher levels of solar radiation and outside temperature correspond to a higher heat flow inside the dwelling.

Regarding the influence of the outside air velocity, it is worth pointing out how heat flow is greater when air is at rest in all the cases and decreases with increasing wind speed. This can be motivated by the increasing ventilation within the ventilation chamber and by increasing energy exchange in the outer side of the facade for larger values of wind speed.

It is observed that for air at rest or with low velocities there is some difference between the two facades, although when the air velocity is increasing, the heat flow tends to be similar.

B. Heat Flows with Respect to the Temperature

In all the studied cases, the heat flow in the ventilated façades is clearly lower compared to non-ventilated façade.

For ambient air temperature equal to $30ºC$ and ventilated façade Fig. 4, the greatest values of heat transfer to the interior corresponds to inlet air velocity equal to zero. It is observed a gradual decrease in the heat flow to the interior as the air velocity increases.

However, for the non-ventilated façade there is an opposite phenomenon. This may correspond to the fact that the movement of air affects only the outer surface without extracting heat from the interior.

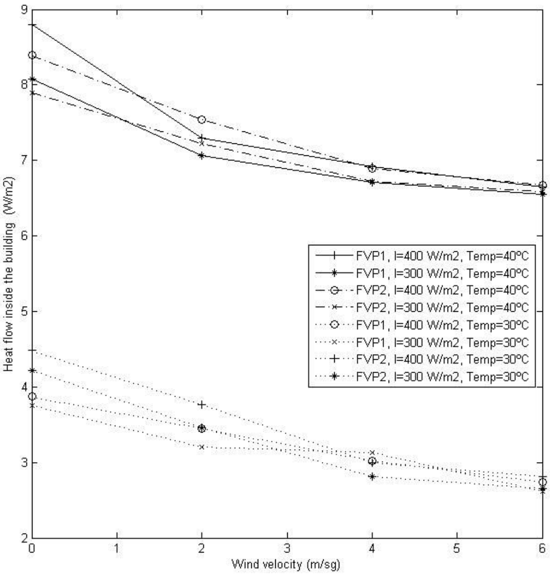

Fig. 3 Heat flow inside the building for the ventilated façades (FVP1, FVP2) under different environmental conditions

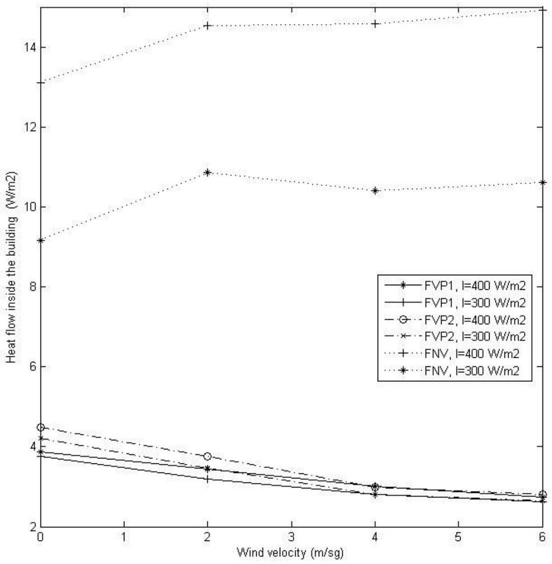

Fig. 4 Heat flows for an ambient air temperature of 30ºC for ventilated façades (FVP1, FVP2) and for unventilated façade (FNV)

For ambient air temperature equal to $40ºC$, the behavior of the ventilated and unventilated façades is similar to the previous case as is shown in Fig. 5.

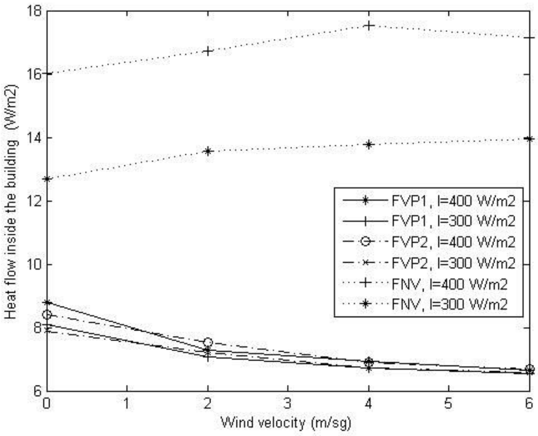

Fig. 5 Heat flows for an ambient air temperature of $40ºC,$ for ventilated façades (FVP1, FVP2) and for unventilated façade (FNV)

C. Heat Flows with Respect to the Solar Radiation Intensity

In Figs. 6 and 7, it is observed that natural convection when inlet air velocity is zero produces the worst results. It is noteworthy that for the intensities of solar radiation considered, the presence of moving wind causes a decrease of the heat flow to the interior, in accordance with the previously observed.

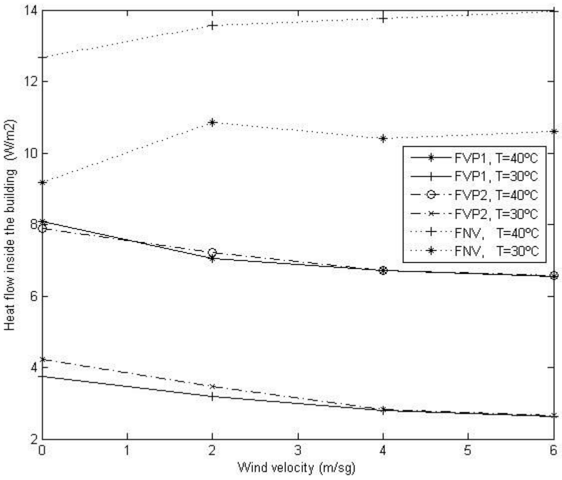

Fig. 6 Heat fluxes for solar radiation intensity equal to $300\ W/m^2$

This effect may be caused by the fact that the heat removal is higher when the speed of the air flow in the chamber increases when the wind speed increases, with a very similar behavior of the two facades considered for radiation intensities studied as can be concluded from the two graphs.

D. Heat Flow Difference between the Unventilated and the Ventilated Façade

In all the studied cases, the minimum differences in the heat flow are produced when inlet air velocity is equal to zero. It should be highlighted again the role of solar radiation in producing good results in the ventilated façade Fig. 8.

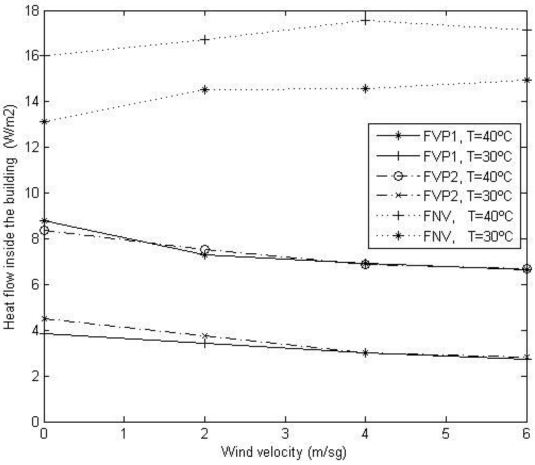

Fig. 7 Heat fluxes for solar radiation intensity equal to $400\ W/m^2$

Indeed, we see that for the highest temperature, the difference in heat flow is greater for higher radiation levels, which we have already discussed above. Presumably this is due to the effect of increasing natural convection that higher radiation levels produce in the ventilated chamber.

As we can seen, the worst result is obtained for the case of a temperature of $40℃$ and a radiation of $300\ W/m^2,$ which strengthens the observed fact that the heat removal levels produced by such radiation compensate to a lesser degree warmer air entry from outside.

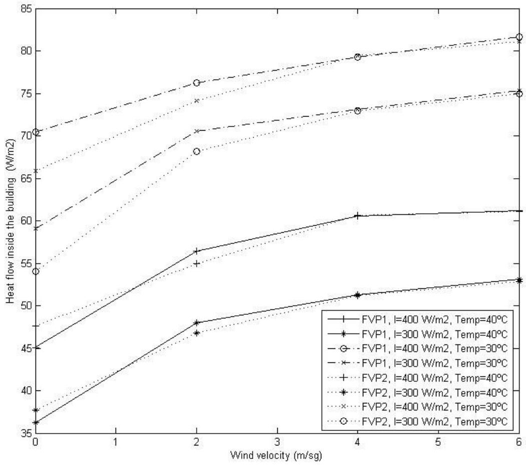

Fig. 8 Heat flow difference between the unventilated and the ventilated façades

E. Energy Saving Rates

In Fig. 9, energy saving rates for the different environmental studied conditions is shown.

In a general way it is worth noting that the lowest savings rate of the ventilated façades in relation to non ventilated façade takes place when the velocity inlet air is zero. In this case, heat removal through the ventilation openings happens only by natural convection, without external air movement backing.

For the different inlet air velocities considered it is observed that the saving rate increases in relation to inlet velocity equal to zero.

If anything should be noted is a higher savings rate for higher air speeds, according to the above stated role that external air in movement increases the ventilation of the ventilated chamber.

The worst result is obtained for a high air ambient temperature, $40ºC$, and for more moderate levels of radiation, $300\ W/m^2$. This behavior is presented by both ventilated facades FVP1 and FVP2.

This may be because the air entering the ventilated chamber is not evacuated quickly enough from it, since the lower solar radiation received by the outer layer results in less heating of the chamber surfaces and therefore in a lower velocity air flow due to natural convection.

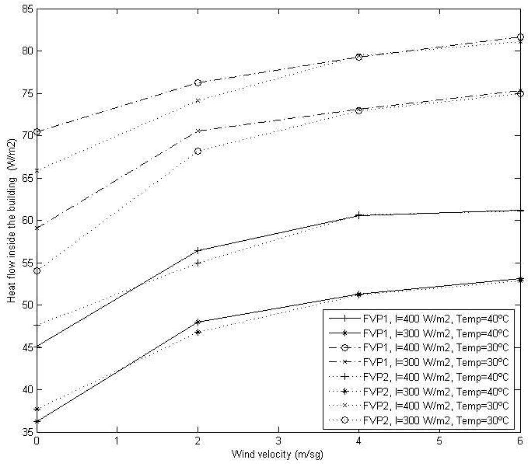

Fig. 9 Energy saving rates for different environmental conditions

For example, it is worth noting that for the same temperature of $40ºC$, the energy saving rate is much better for an intensity of solar absorbed radiation of $400\ W/m^2$ due precisely to the increased stack effect that this intensity produces with increasing air flow velocities within the chamber. This effect is common to all exterior air speeds considered.

Another fact that can be deduced from the graphs is that the performance of ventilated facades is lower for high temperatures, as shown in Fig. 9. This fact already noted by some authors for the case of air at rest [5], [6], here it is also observed and shown for nonzero air velocities.

V. CONCLUSIONS

- We have developed a numerical code for simulating the behavior of a ventilated façade under atmospheric typical conditions of the summer season in the South of Spain. The code has been validated by using the results presented in [6].
- We have studied the thermodynamic behavior of two specific ventilated façades, comparing its efficiency with another non-ventilated façade with the same thermophysical properties. We have focused on the analysis of how the ambience temperature, solar radiation and wind speed determine heat flow into the building.
- From the results it can be concluded that the overall studied ventilated façade has a better behavior in terms of passive cooling of the building compared to non-ventilated façade. The considered ventilated façade can provide energy savings rate in a range from 35% to 85% in relation to the non-ventilated in the climate context considered. This is because in the warm season, the air flowing through the ventilated chamber removes some of the heat accumulated in the ventilated façade surfaces, reducing this way heat gain into the building.
- It is noted that although high levels of radiation and air ambient temperature increase heat gain, the energy saving rate remains significant. However, when high air ambient temperature is associated with low levels of irradiation, this rate significantly decreases.
- We conclude that in the environmental conditions of the summer season in southern Spain, the use of ventilated façades allows a significant reduction of the heat load of the building in relation to the non-ventilated façades, although the rate of energy savings achieved is relatively sensitive to the combination of such environmental conditions.
- In future work it would be interesting to extend the study to facades with different configurations, in order to study how different colors of the outer slab, the thickness of the ventilated chamber, the size of the vent openings, and the dimensions of the facade, work in the operating conditions of summer weather in southern Spain.

APPENDIX

TABLE I
THERMOPHYSICAL CHARACTERISTICS OF THE VENTILATED FAÇADES FVP1 AND FVP2

Nº of layer	Description	Thickness (m)	Density (kg/m^3)	Specif. heat $(J/kg\ K)$	Conductivity $(W/m\ K)$
1(Ext.)	Ceramic slabs	.013	2000	800	1
2	Air (ventilation duct)	0.1	1.184	1005	0.0255
3	PUR aislant	0.035	40	1674	0.028
4	Perforated bricks, lime mortar and cement	0.115	1600	1000	0.59
5 (Int.)	Plastering	0.015	1800	1000	0.90

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