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Additional Information

Energy performance of a ventilated façade by simulation with experimental validation

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Abstract

A model for a building with ventilated façade was created using the software tool TRNSYS, version 17, and air flow parameters were simulated using TRNFlow. The results obtained with the model are compared and validated with experimental data. The temperature distribution along the air cavity was analyzed and a chimney effect was observed, which produced the highest temperature gradient on the first floor. The heat flux of the external wall was analyzed, and greater temperatures were observed on the external layer and inside the cavity. The model allows to calculate the energy demand of the building façade proposing and evaluating passive strategies.

The corresponding office building for computer laboratories located in Valencia (Spain), was monitored for a year. The thermal behaviour of the floating external sheet was analyzed using an electronic panel designed for the reading and storage of data. A feasibility study of the recovery of hot air inside the façade into the building was performed. The results obtained showed a lower heating demand when hot air is introduced inside the building, increasing the efficiency of heat recovery equipment.

Introduction

Losses and heat gains through building façades have a significant influence on the annual consumption of heating and cooling of buildings. Moreover there is a recent trend among some architects to consider façades as being sophisticated membranes

worthy of careful design.

Although the origins of Double-Skin Façades (DSF) date back to the early twentieth century there is a growing tendency among architects and engineers to use them [1] and they must be taken into account to ensure rigorous calculations of the energy demands in new and existing buildings.

Many other terms exist that are synonymous with DSF, such as active façade, double envelope, rainscreen or ventilated façade. The European standard EN 13119:2007 "Curtain walling. Terminology", associates the term DSF to the existence of glass skins separated by a cavity but not to the need for a ventilated cavity [2]. In this sense the term "ventilated façade" would be more appropriate for the façade analyzed in this work. It consists of an opaque external layer composed of lightweight and thin cladding panels with open joint between them and an opaque internal skin which acts as thermal and acoustic insulation. Between both layers there is an air cavity drained and ventilated (see Figure 1). The air cavity of opaque DSF has received less attention than the other configurations with glass [3] and there are still very few studies that focus on their energy performance [4].

Several recent studies have focused on the use of natural ventilation in buildings as an alternative system to reduce energy demand. The heated internal air that is generated inside the air cavity can be introduced inside the building if it is convenient, thus reducing the heating energy demand and the heating energy consumption of the building. This internal warm air can be introduced using an inlet opening through which the ambient air comes in, and one or two exhaust openings for returning the air to the outside or introducing it into the building. Air flow can be produced naturally through the façade due to the wind effect or thermal buoyancy. Additionally, on sunny days part of the solar radiation absorbed by the façade is transferred to the air in the gap.

The use of DSF in the construction sector and their thermal benefits have been widely studied quantitatively over the last 30 years [5][6][7].

In this paper a façade which uses this system was modelled with a Transient Systems Simulation Program (TRNSYS) [8] and its add-on for airflow simulation in buildings, and monitored. Haase et al. [9] provided a similar research developed for hot and humid climates (Hong Kong) and glass façades. More recently López et al. [10] employed the same simulation software for modelling an experimental module of an opaque ventilated façade.

Once the building is modelled and validated with experimental data, this model is used to reduce the energy demand of the building with ventilated façade.

In the present work, it has been studied a lightweight cladding, specifically a sandwich panel comprising two aluminium sheets bonded to a polyethylene core with a thickness of 4 mm. To develop this study, a full year of data was collected from the four sides of an office building located in Valencia (Spain). Once the model was validated, it was used to carry out simulations, by varying different parameters such as the degree of air ventilation inside the cavity, allowing to reduce the building energy demand.

Experimental monitoring

Features of the building under study

An existing office building for computer laboratories was monitored for a year. The building is located in Valencia, Spain (latitude 39.28ºN, longitude 0.22ºE). All the enclosures in the building have a floating external sheet which acts as a rainscreen. The building has a rectangular base measuring 92 m long and 17.50 m wide, with three storeys, measuring a total internal height of 16 m. The building is free-standing, orientated about 20º East. For the purpose of clarity, the orientations have been named North, South, East and West, although they are in fact orientated North-northeast, South-Southwest, East-Southeast and West-northwest, respectively. In order to study the behaviour of the rainscreen wall components in different seasons and their thermal performance, measurements were taken during the period from January 1st to December 31st 2009.

The façade of the analyzed building is composed with an external cladding layer. The cladding layer is made of panels surfaced with natural aluminium and a mineral-filled core with a total thickness of 0.004 m; plate rigidity is ensured by folds and rivets at the edges. The panels are all 0.59 m wide by 3.5 m long (length varies at the corners and window jambs). An inner sheet gives the panels water and air tightness and also allows for the rainscreen to be fixed to it (to the internal layer). This sheet is made of a prefabricated mortar panel, rock wool insulation and an inner plaster panel with a total thickness of 0.14 m. Between the internal and external leaves there is a ventilated cavity with 0.10 m of thickness (see Figure 1). This façade system is used in all the orientations that were analyzed. All the properties of the materials of the external wall

of the building under study are given in Table 1.

The reflectance values were obtained using a LAMBDA 35 UV/Vis Systems Spectrometer (Perkin-Elmer). From the results obtained in the measurements, an average value was calculated from the integration of the area below the curve of the specular reflection of the material vs. the wavelength. This entire procedure was carried out using Excel and UVPC Software, which allowed the authors to export data in text format. Figure 2 shows the curve for the tile.

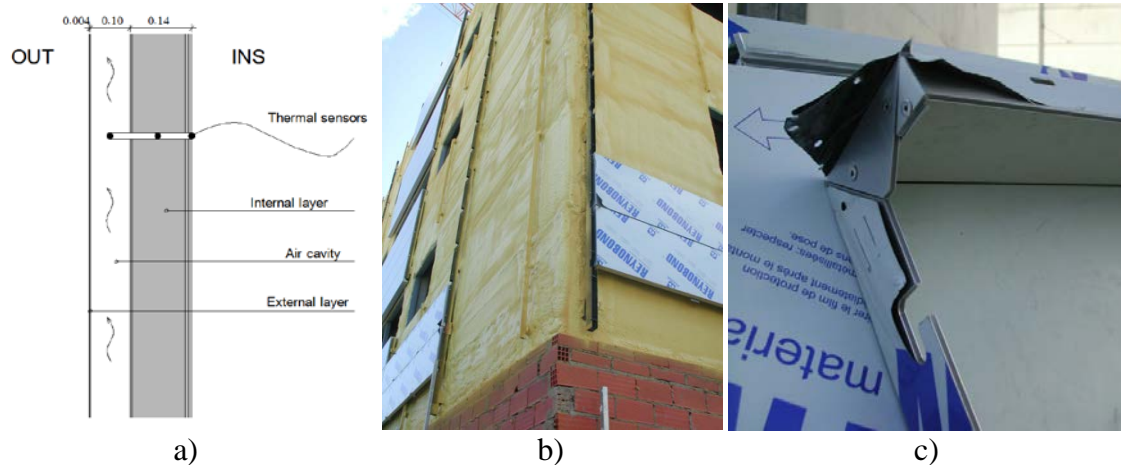| a) | b) | c) |

Figure 1.   a) Components of the ventilated enclosure with weight-reduced screen. Black dots represent points where temperatures were measured (thermal sensors), b) Image of the corner, c) External layer

The data from the building with the ventilated façade was analyzed in order to validate the model developed with TRNSYS. This façade could be used to reduce the energy demand of the building and to maintain conditions of thermal comfort inside, without requiring large amounts of energy.

Layer	Thickness (m)	Thermal conductivity (W/m K)	Density (kg/m^3)	Specific heat (J/kg K)
Composite panel. Alucobond$^®$	0.004	5.65	980	1350
Ventilated air cavity	0.10			
Rigid polyurethane foam (PUR/PIR)	0.04	0.031	12	1500
Mortar panel	0.01	0.23	1200	1500
Mineral Wool	0.08	0.036	50	1000
Plasterboard of natural gypsum. Pladur$^®$	0.016	0.25	900	1000

Table 1.   Thermal properties of the external wall layers. Tabulated values provided in ISO 10456:2007 [11].
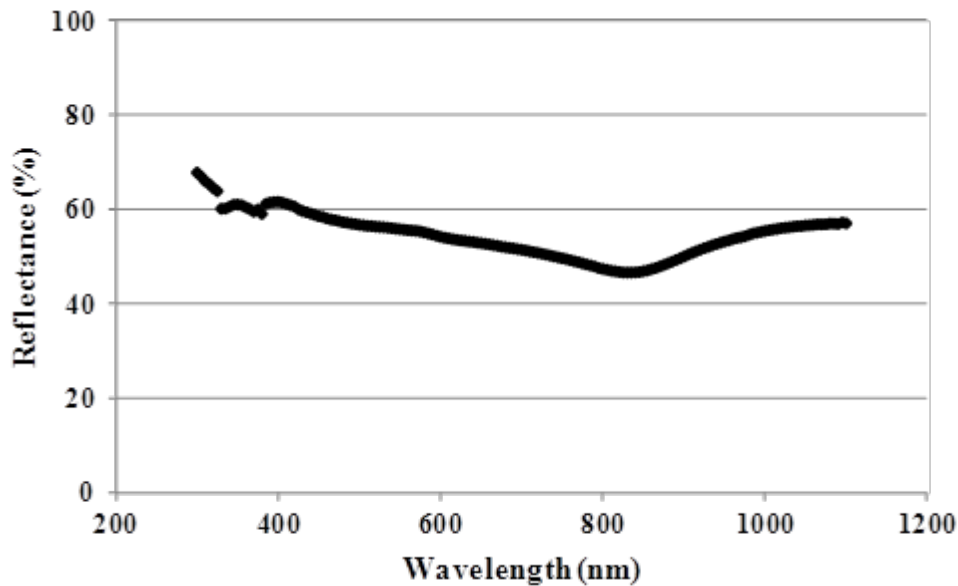
Figure 2.   Diffuse reflectance at a spectral range of 300 nm to 1100 nm.

Measurement set-up

An electronic board, based on a microcontroller, was designed for the reading and storage of data. This equipment enabled the reading and storing of data as well as its transmission to the computer via a USB. The system was composed of 6 temperature sensors, situated in two blocks (3 sensors each one), so that the differences of temperatures can be monitored through the wall. Resistance thermometers were used with a declared accuracy of ±0.15 C (Class A according to EN 60751, range: −50÷300 ºC) using standard calibration. They were introduced inside the wall as shown in Figures 1 and 3. A wooden cylinder was used as the sensor support in order to ensure better wall insertion and avoid air drafts as much as possible. In order to insert the sensors, the cylinder was drilled, forming a cavity for the sensor as well as for the electrical wiring. In this way distances between sensors could be adjusted depending on the type of wall.

The thermal sensors were installed on the 2nd floor at the corners so that all the data could be collected from the same level at all orientations. The sensors were installed at the corners (see Figure 3) where the ventilated air cavity is continuous all along the building and at about 8 m from the ground. There were no other elements in this area that could cast a shadow over the analyzed enclosure. In addition, there were no vertical obstructions from the first floor to the roof at the corners of the building, thereby allowing for vertical air circulation. The rest of the façade contains windows which

interrupt the chimney effect in the air cavity. Inside the cavity there appeared to be air exchange between the different orientations. Sensors were installed in all offices in approximately the same manner, although their location was modified in some offices owing to the layout of certain pieces of furniture. All offices have the same comfort conditions and exterior windows.
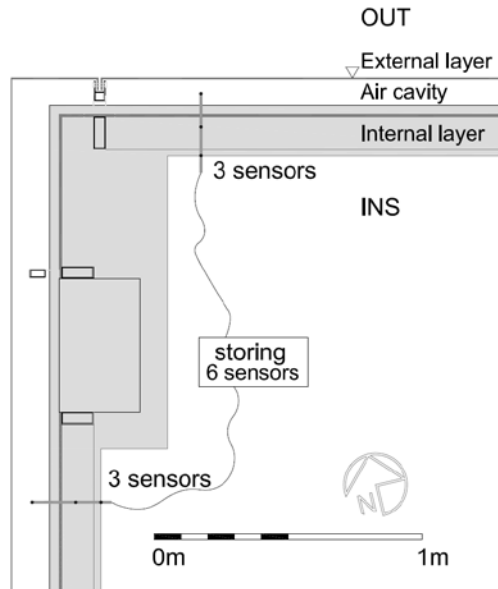

Figure 3.   Placement of sensors installed in each corner of the 2nd floor.

Data was recorded at intervals of 5 min. Wind direction, wind speed, ambient temperature and relative humidity was monitored every 5 min by a weather station installed close to the studied building. The building under study was heated continuously to a room temperature of 20º C by means of a heat pump system.

Developed transient model

In order to estimate the natural ventilation of the external air cavity depending on the thermal properties of the natural rainscreen façade and evaluate the decreasing impact of incident radiation on the indoor environment, Computational Fluid Dynamics (CFD) software was used. Computer modelling and simulation are currently some of the most powerful techniques available to engineers and designers. Experimental and numerical models allow to predict and analyze parameters of a building, permitting its control.

A model for the test building was created by using TRNSYS-17 simulation software, and SketchUp was used to model the building in 3D. The effect of the air cavity was modelled by adding a small space between the inlet and the outside. A CFD tool was used for the analysis of the air flow parameters through the ventilated air cavity which

were calculated using the multizone airflow model TRNFLOW. The software works by calculating solar gains (solar radiation) and conduction and convection processes of the airflow through the air cavity. Several possible calculation models have been developed to simulate the thermal behaviour of air cavity [6]. A major challenge is that airflow affects the heat transfer but is also influenced by external conditions of wind and the pressure it creates on the building envelope [9]. For this study a combined thermal and airflow simulation was chosen. TRNSYS and TRNFLOW were used to model an office building with ventilated façade. A simulation model has been developed and the geometries have been adopted as illustrated in Fig 4a.

<table>
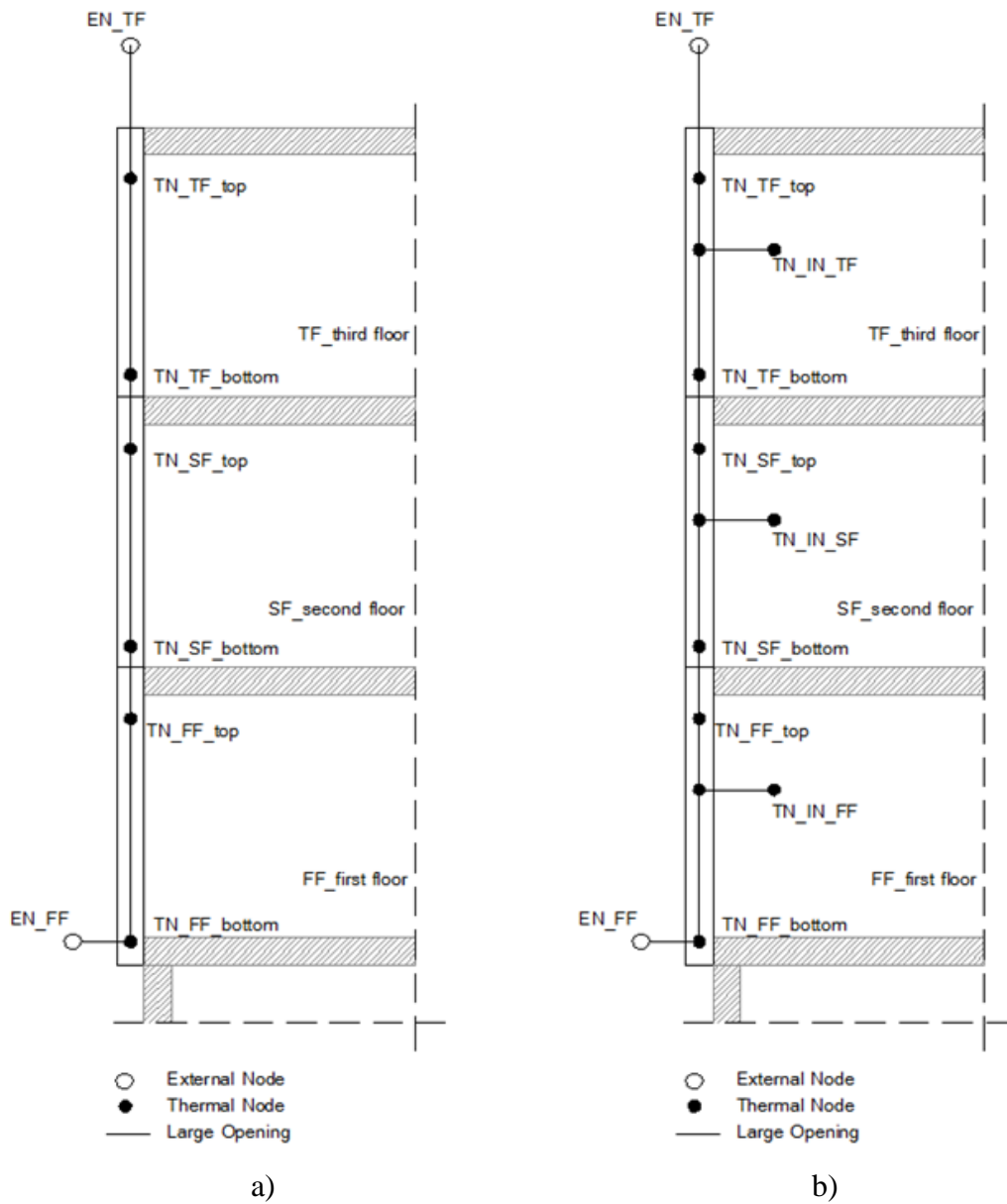<tr><td>a)</td><td>b)</td></tr>
</table>

Figure 4.   CFD model: a) external air curtain (current solution), b) supplied air

The building details were defined in a previous section. The external layer contains a composite lightweight panel consisting of two coil-coated aluminium sheets that are fusion bonded to both sides of a polyethylene core. Joints between panels are horizontal, with 10 mm-thick. The air cavity is connected to the outside through the open joints. The building was modelled using four floors. In order to carry out a TRNFlow simulation, the air cavity is introduced as a continuous space whose thickness is 90 mm, as in the actual building. The air cavity is connected along the entire façade, vertically between floors and horizontally along the different orientations. The open joints are considered in the external sheet, connecting the air cavity to the outside.

The CFD creates a 3D model which takes into account different factors of the building and its immediate environment. In table 2 the parameters of the building used in the TRNSYS and TRNFlow simulation are shown.

Type No.	Work	
Type-99	Weather data	Weather data collected during the analysis
Type-56	Building + CFD simulation	Parameters of the building considered in the simulation and multizone airflow model.
Type-65a	Output data	Data obtained to compare with the data collected.

Table 2.   Parameters used in the simulation of TRNSYS.

In order to validate the results, the following weather data was entered into the model: wind speed and direction, solar radiation on the horizontal plane, temperature and humidity.

Model validation

The measured values for the air cavity temperature and the ones predicted by TRNSYS were compared using the weather data recorded during the test period as input for TRNSYS. A total of 1,261,440 data (8760 hour/year x 24 thermal sensors x 6 data/hour) were collected during a year but in this article we have considered data for four representative months (March, June, September and December 2009) and for the four orientations (420,480 data). Table 3 shows the maximum, minimum, mean and root mean square for the difference between simulated and measured values for all orientations. The coefficient of determination (R^2) was also obtained.

Month	March				June				September				December			
Orientation	N	S	E	W	N	S	E	W	N	S	E	W	N	S	E	W
Maximum	4.85	13.62	6.00	8.49	9.34	8.10	8.43	9.04	9.91	7.70	11.38	5.76	3.06	11.24	10.33	4.27
Minimum	-8.01	-15.30	-7.83	-3.98	-7.06	-10.74	-8.47	-7.33	-6.27	-13.18	-6.17	-9.42	-4.29	-9.38	-7.55	-6.38
Mean	-0.25	-0.39	0.36	0.52	0.66	-0.67	1.32	0.92	0.79	-0.27	0.45	0.09	-0.33	0.22	0.22	0.13
Root mean square (RSQ)	2.31	3.39	1.88	1.59	1.93	2.66	2.47	2.06	2.52	2.22	1.90	1.66	1.28	2.07	2.08	1.56
R^2	0.90	0.84	0.89	0.91	0.80	0.82	0.82	0.89	0.79	0.93	0.88	0.91	0.94	0.91	0.88	0.91

Table 3.   Maximum, minimum, mean, root mean square and R^2 for the difference between simulated and measured values

The results for the measured and simulated cavity temperature for December, as it is the month with the highest thermal gradient between the temperature of the cavity and the outside, are compared in Figure 5. Interesting results were obtained from the South façade, achieving the highest difference in temperature between air cavity and outside air. In Figure 5 the results over eight days (192 hours) are shown when horizontal irradiation was higher than 400 W/m^2; those days could be classified as clear days in Valencia. Substantial differences were found between different orientations. The results from the North façade (Figure 5a) are quite similar (lower than 2ºC) to the maximum outside air due to the absence of radiation on this façade in December. Figure 5b shows the measured and simulated temperatures at the air cavity on South façade. The measured and simulated temperatures of the air cavity are shown with maximum values around 35ºC. Figure 5c shows the results for the East façade; the temperature of the air cavity behaves in a manner that is characteristic for this orientation. West façade results, which are shown in Figure 5d, present a thermal behaviour similar to the North façade because this façade presents a typical West-northwest orientation. The comparison for December demonstrated the good fit of the model, in addition similar results have been obtained for the other months (March, June and September) and the four orientations.
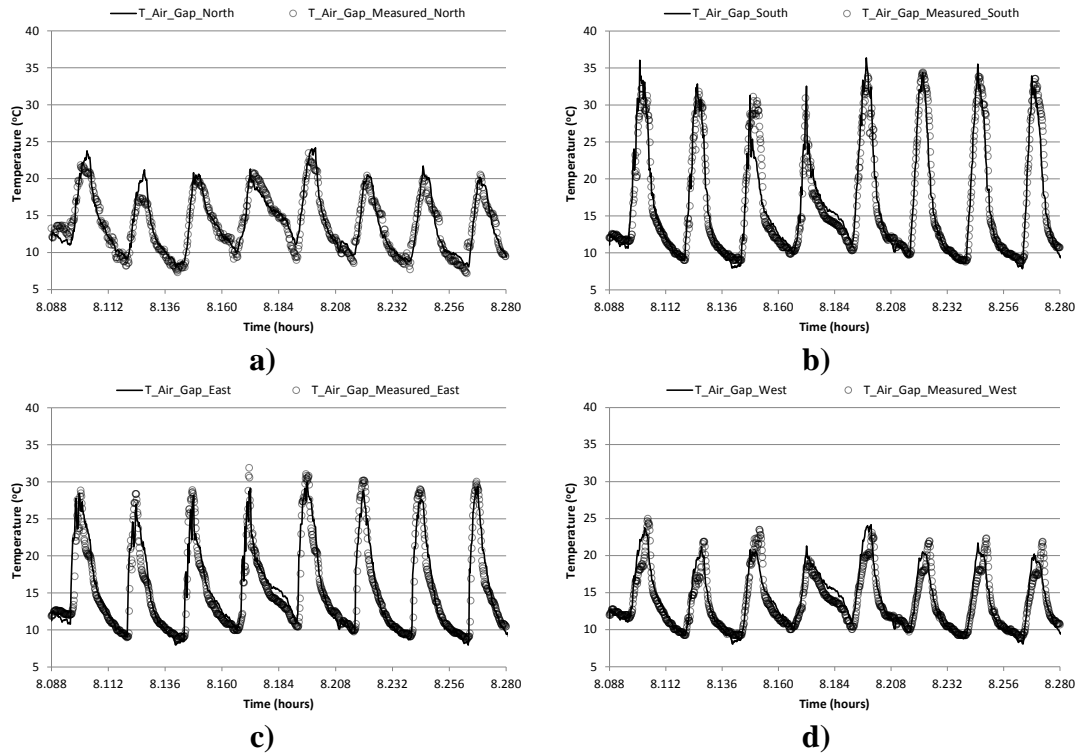
Figure 5.　　　Measured and simulated cavity temperatures in December: a) North façade, b) South façade, c) East façade and d) West façade.

For all the façades, the cavity temperature monitored for the 4 months (March, June, September, December) was compared with the values generated by the model. The difference in the predictive capability of the model for each façade can be observed in the Figure 6. In the Figure 6 is shown that the deviation from the bisector (perfect solution) is near to 15% while for the South façade is near to 20%. These data confirm the values of the R^2 parameter given in Table 3. As Figure 6 clearly shows, the developed model provides temperatures slightly above the measured values, with fairly good adjustment. The South façade shows a slightly higher dispersion than the others but the values of the R^2 (Table 3) are acceptable and comparable to the other façades.
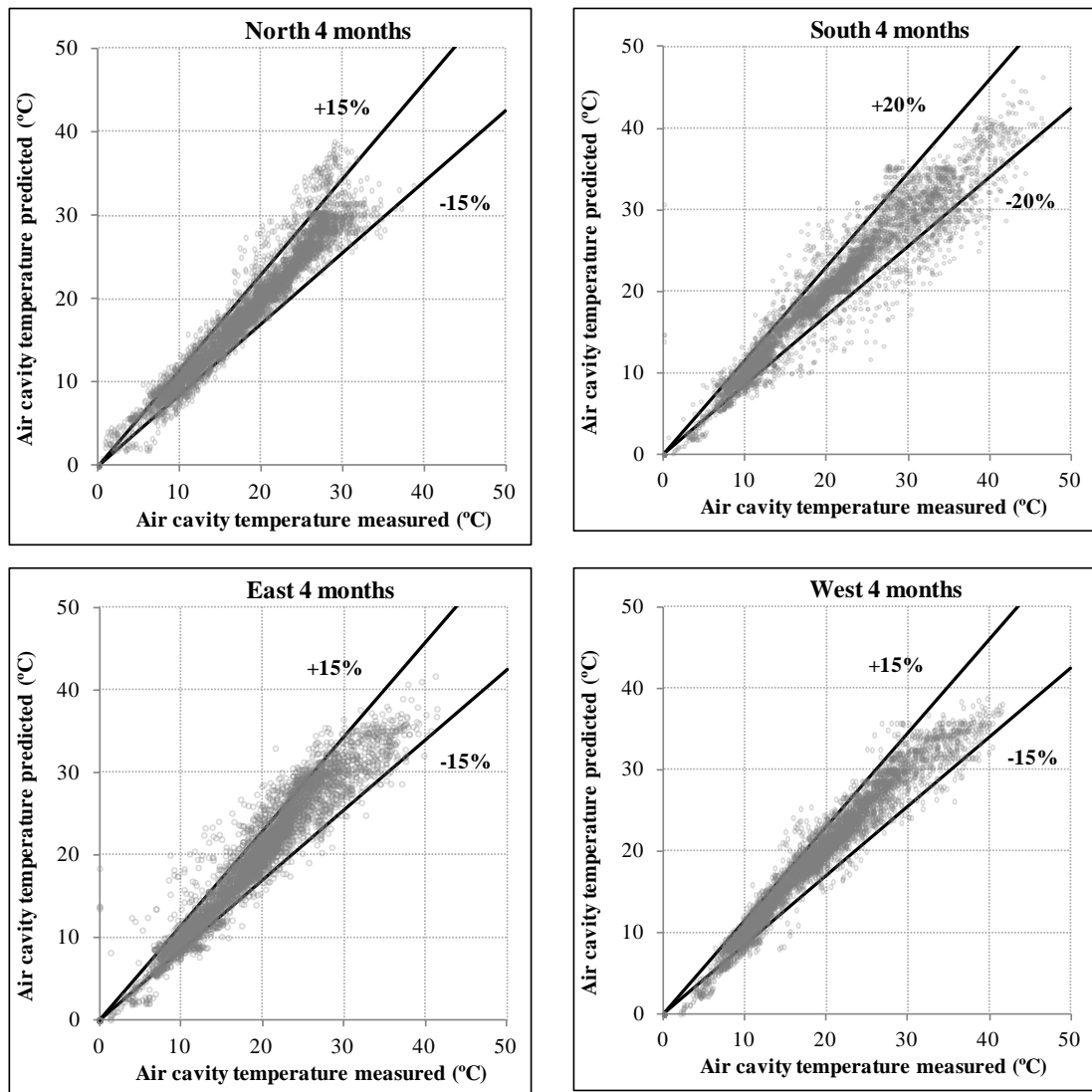
Figure 6.   Correlation between measured and predicted air cavity temperatures. a) North façade, b) South façade, c) East façade, and d) West façade.

It was deemed important to determine whether the heated air could be used inside the building. To this end, the validated model was used to determine the degree of ventilation in the air cavity. Two different scenarios were used:

- In the first scenario, all openings which connect with the outside air were closed, and the temperature of the closed air chamber was determined.

- In the second scenario, large openings which connect with the outside air were added. In this case, the opening sizes were set at five times larger than those of the current openings.

With these simulations it was possible to compare the results obtained inside the air cavity, allowing the authors to determine how these systems work. Figure 7 shows the results obtained with the different scenarios on the South façade, in December, as this

façade features a higher temperature rise due to solar gains throughout the year. It was found that the air temperatures fell between the two intervals analyzed, so it was possible to confirm that this system represents a medium ventilated cavity. This same effect was confirmed in the rest of the air cavities, regardless of orientation and time of year.
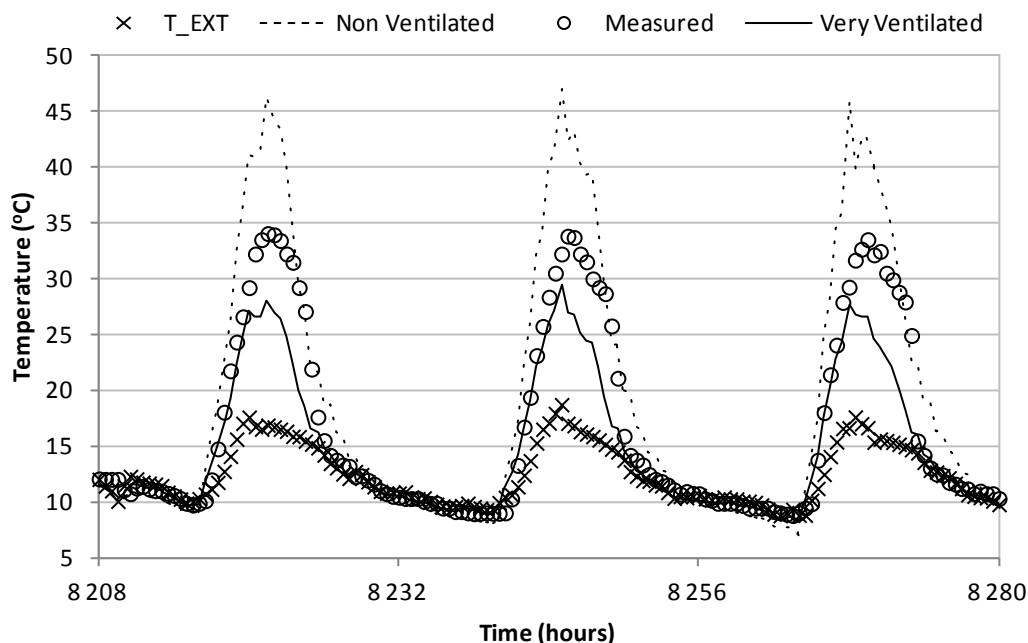

Figure 7.   Ventilation in the air cavity on the South façade obtained by TRNFLOW.

Simulation results

The most interesting results obtained by the model were those for superficial temperature and average temperature in the enclosures, which helped the authors ascertain the temperature distribution across the entire envelope of the building. The heat fluxes were obtained on an hourly basis to calculate the thermal balance of the building for each orientation.

Figures 8b and 8d show the correlation between the overall solar radiation on the South façade and the air cavity temperature in the different layers of the envelope. It shows that the temperature inside the air cavity is affected by solar radiation and the maximum temperature inside the air cavity is obtained two hours after the maximum radiation.

Figures 8a and 8c show the vertical temperature distribution inside the air cavity on different floors of the building over a one-day period. It was found that the highest temperature gradient occurs on the first floor. The temperature distribution reaches a

maximum at the top of the air cavity, due to a chimney effect which drives additional convection of warm air heated by the absorption of solar radiation by the system [8]. The temperature difference is always lower on the second floor, a height which corresponds to the middle of the chimney. It was also observed that when the solar radiation increases on the South façade, temperature increases quickly due to the thin external layer. Of course this effect is reversed when solar radiation decreases.

This effect was analyzed for different orientations and it was repeated on East and West façades; however the effect is higher on the South façade as it receives more hours of radiation in winter for northern latitudes. The heat flux through the different layers of the wall was analyzed. This parameter depends on the radiation values, for greater radiation increases the temperature inside the air cavity which in turn brings about an increase in heat flux. The heat flux also depends on the external temperature outside the wall, as greater temperatures on the external layer mean greater temperatures inside the cavity. And the temperature on the external layer, in turn, depends on the external temperature and the solar gains of this layer. Moreover the heat losses through the internal wall are reduced when the temperature inside the air cavity is higher than the external temperature; this is possible when the temperature inside the air cavity is higher than the temperature inside the building. So when the external temperature is lower than the internal temperature the gradient inside the wall is reduced with the solar gains. For this reason, during the winter season a high cavity air flow rate is not desirable, because the convective heat transfer between the air and the internal layer reduces the temperature on the inside wall of the cavity and increases heat flux through the inside wall.

On the other hand, this effect is reversed when the external temperature is higher than the internal temperature. In this case the heat flow is not always incoming, and outgoing heat is preferred as this promotes heat removal from the interior spaces. Therefore, to avoid this effect the hot air should be removed. It is interesting to compare the profile for a typical winter day and summer day where this effect is clear. The most important difference between these two situations is related to the direction of the heat flux through the inside wall of the ventilated façade.
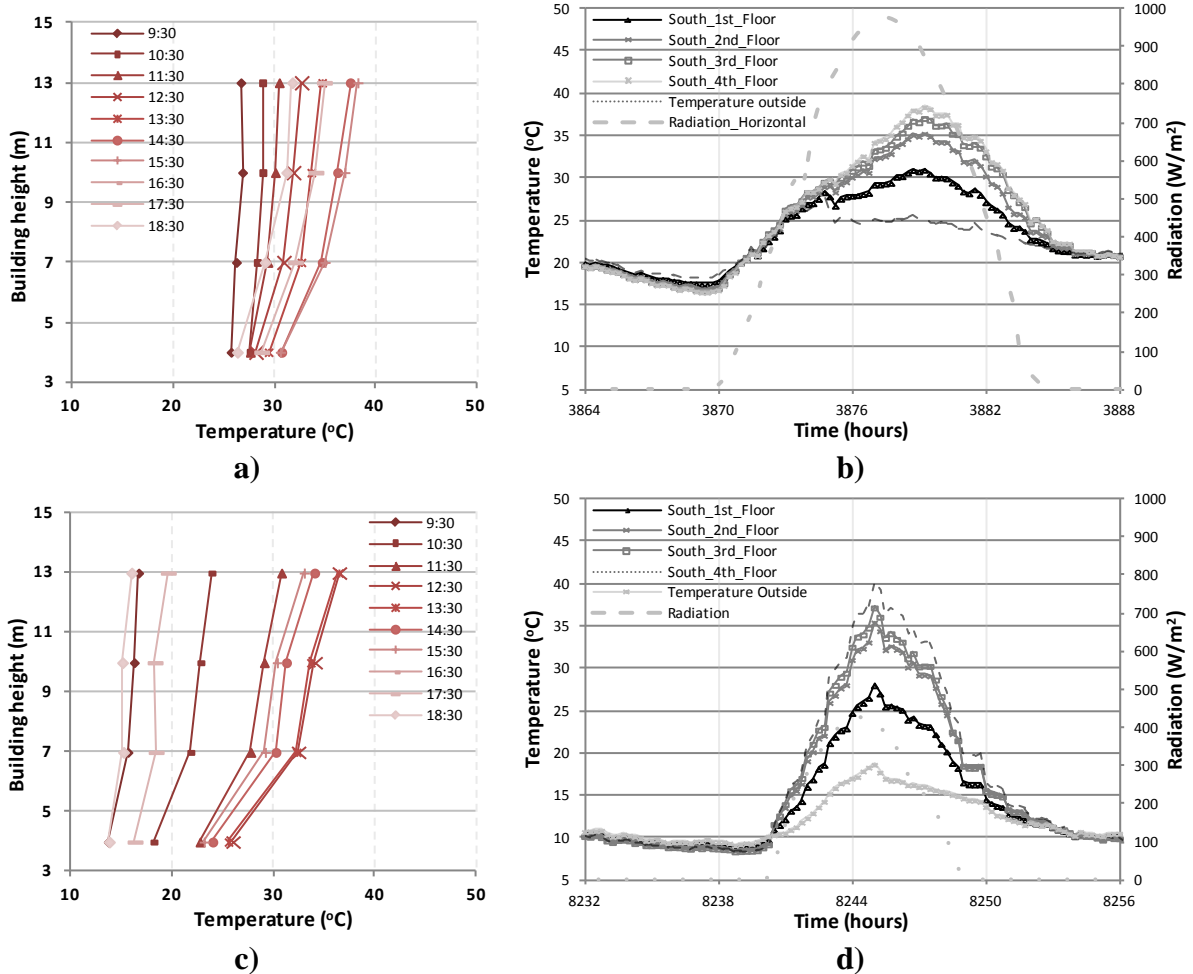
Figure 8. a) Vertical air temperatures on South façade in June, b) thermal profile in June over a 24-hour period on different floors, c) vertical air temperatures on South façade in December, d) thermal profile in December over a 24–hour period on different floors.

Improvements of energy performance

Giancola et al [4] demonstrated that, during the hot seasons in warm climates, if there is sufficient air flow inside the air cavity a portion of the heat loads is removed. But if both the outdoor temperature and radiation are very high, the heat gains can be increased.

During the cold season the ventilated façade can improve thermal insulation when solar radiation values are high. On the other hand, when both solar radiation and the outdoor air temperature are low, the energy balance in the façade can be negative.

It follows that DSF do not necessarily improve the energy efficiency of their designs [12]. Although for a Continental Mediterranean climate (Madrid), Suárez et al. give an energy saving estimation around 9% for a South open joint ventilated façade in comparison with a sealed cavity one [13]. Recently Carlos et al. [14] have also demonstrated the advantages or heat recovery for a ventilated double window and

Gracia et al. have studied a new type of ventilated façade with macro-encapsulated phase change material [15]. That is why in this section we have evaluated the effect of introducing the hot air generated in the interior of the façade into the interior of the building. As can be seen, this process involves a significant increase in heat gain through the wall and, in most cases, a decrease in the air temperature of the exhaust at the inlet of the heat recovery equipment.

Currently, the ventilated façade works as an external air curtain (Figure 4b) without using the hot air generated inside the air cavity. Some openings that connect the air cavity with the interior space have been simulated (Figure 4a). These openings are only considered on the South façade because, as seen in the data analysis, it is this orientation which receives more hours of sunlight and where temperature is more likely to increase in winter. The openings allow the warm air to enter the building and distributed to all areas through the HVAC system.

The setpoint data for activating the system and allowing warm air to enter the building, in winter, are an indoor temperature that is lower than 25.5ºC and an air gap temperature that is higher than 25ºC. The building is only used during the day so night air is not considered.

The results show a decrease in annual heat demand from 39.80 kWh/(m^2 year) to 10.32 kWh/(m^2 year), which represents a reduction of 74.06%.

Finally we have studied the behavior of the façade with other orientations other than South (west and east), obtaining heat demands of 12.52 and 12.98 kWh/(m^2 year) respectively (Figure 9). It is verified that, although South is the preferred orientation for the use of heat in winter, orientations other than north are also viable.

This means that the installation of this system in warm and sunny climates with few cloudy days during the winter months is economically feasible. To harness this heat, it is important to pay attention to the materials used in the design of the façade and its outer surface which is exposed to the sun.
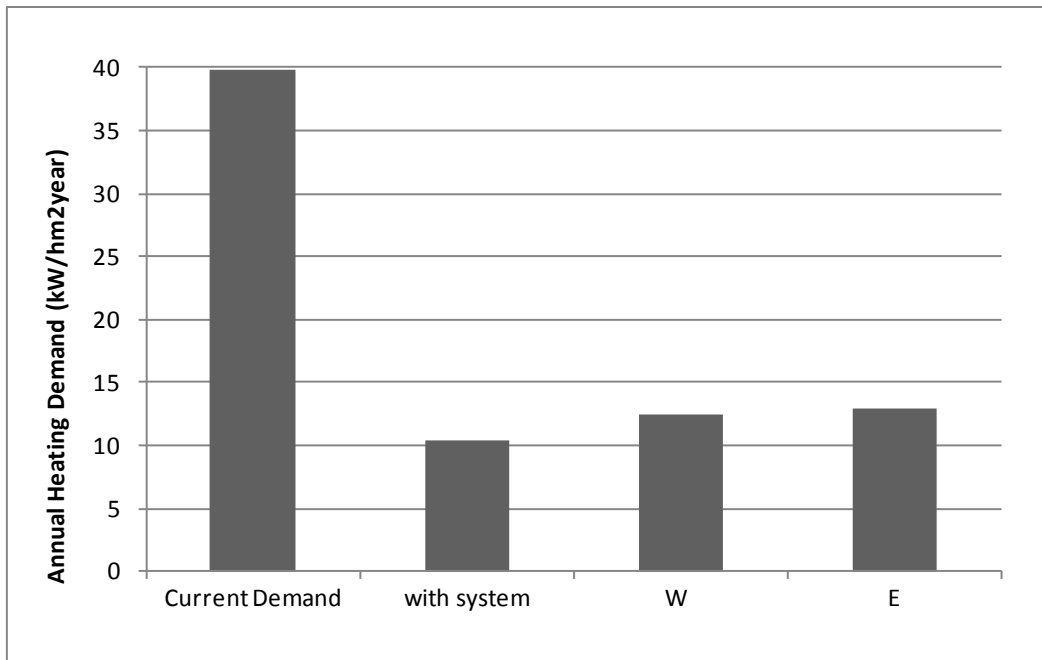
Figure 9. Heat demand in the current situation, with the external supplied air, and with recirculated internal air in orientations south, west and east.

Conclusions

A model for a building with ventilated façade was created by using the energy software tool TRNSYS, version 17; air flow parameters of the ventilated air cavity were simulated using TRNFlow, a CFD tool. The model took into account meteorological variables, wind speed and direction and solar radiation of the considered location. The corresponding building, an office for computer laboratories located in Valencia, Spain, was monitored for a year. In order to analyze the thermal behaviour of the floating external sheet, an electronic board was designed for the reading and storage of data.

The results obtained by the model agree with the experimental results and the fit was found to be fairly good. The temperature distribution along the air cavity was analyzed and the chimney effect produced the highest temperature gradient at the first floor. The heat flux was analyzed on the external wall, and greater temperatures were observed on the external layer and inside the cavity.

A feasibility study of the recovery of hot air from inside the façade for use in the building was performed. The heating demand analysis showed that there is a lower heating demand when hot air is introduced in the building, which increases the efficiency of the heat recovery equipment. This result could be applied in Mediterranean climates which have relatively mild winters and few cloudy days.

The performance of the façade using CFD and <mark>transient simulation</mark> software allowed for real results to be obtained to calculate the energy demand. It is important to use these tools to design and optimize ventilated façades taking into account different materials in different locations.

Acknowledgements

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