Development and Experimental Validation of a Multi-Functional Façade Model within an Object Oriented Platform

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Abstract

The present work is on the experimental validation of a multi-functional façade model developed within an object-oriented simulation platform. An existing building façade is retrofitted by means of PV and vacuum insulation panels, which form a ventilation channel. For the optimum performance of the PV panel element, the channel thickness is chosen by means of the numerical tool so as to maximize the heat evacuated from the ventilation channel throughout the year, thus enhancing the efficiency of the whole system. The multi-functional façade is properly instrumentalized and is exposed to real meteorological conditions in order to assess its long term reliability, durability, and energy performance. Moreover, with the gathered experimental data, the developed numerical model will be validated.

Keywords: PV panel, ventilated façade, numerical simulation, object-oriented numerical platform, experimental validation.

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1. Introduction

Energy efficient buildings have a large potential due to the necessity of reducing energy consumption and carbon emissions in line with European climate and energy targets for the year 2020. In order to improve the overall impact of the buildings, different strategies and architectonic solutions are being implemented, stimulating the development of accurate tools and methodologies in order to analyze their performance properly (Clarke and Hensen (2015)). The employment of multi-functional façades with double skins seems attractive due to their high potential to provide structural and energetic advantages, as well as aesthetic and comfort perception. Moreover, they can provide space for integrated PV panels (Agathokleous and Kalogirou, 2016). The channel formed within two skins can generate a microclimate around the building. The temperature gradients can facilitate natural and hybrid ventilation (Gratia and De Herde, 2007) and it can be used for heat recovery purposes, reducing the heating and cooling loads of the building (Ioannidis et al., 2017).

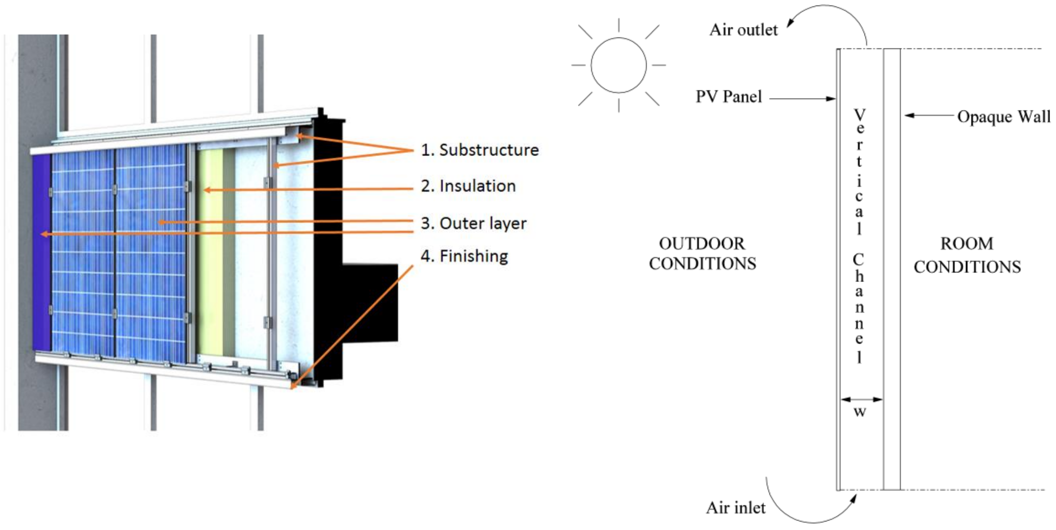

Fig. 1 Schematic view of the PV Ventilated Façade design (left), sketch of the functioning PV Ventilated Façade (right).

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The present work aims at taking to a further step a previous investigation on the implementation of a numerical model capable of predicting the thermal and fluid dynamic behavior of a multi-functional ventilated façade (Kizildag et al., 2015) within the existing parallel and object-oriented platform NEST (Damle et al., 2011). This methodology was recently employed within the framework of an innovative project (Retrofitting Solutions and Services for the enhancement of Energy Efficiency in Public Edification, RESSEEPE Project) in the task of envelope retrofitting. In the framework of this task, numerical simulations taking into account different configurations formed by a PV panel, a natural convection ventilation channel, and vacuum insulation panels were performed. The numerical study yielded a design which optimizes the PV panel efficiency under the weather conditions of Coventry, where one of the demo sites of the mentioned research project is located. In Figure 1, the schematic view of the final design for the retrofitting of the existing building is depicted. Note that this final design is the outcome of the synthesis of both thermal and structural analyses carried out in the design stage.

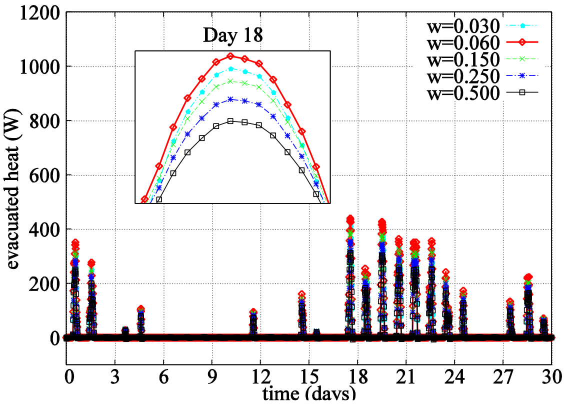

Fig. 2 Numerical analysis of the evacuated heat for different channel widths in the pre-design stage.

In Figure 2, an example of the influence of the possible ventilation channel widths on the evacuated heat is depicted for a typical month, based on the meteorological data obtained from Meteonorm ® software for the closest location to the John Laing Building in Coventry. Note, however, that the chosen channel thickness (see Figure 1) considers the overall effect of the results obtained for the whole year, which does not necessarily correspond to the optimum solution for a given period.

2. Mathematical and numerical modeling

In the NEST numerical platform, the system is a collection of some basic elements that can individually be solved for given boundary conditions, which are obtained from neighbor elements. By means of efficient coupling strategies, different levels of modelling can be put together in problems of complex heat transfer and fluid flow phenomena, for which multi-functional façades represent a good example. For instance, the critical elements of the façade or the building can be simulated by means of CFD models based on large-eddy or direct numerical simulations (Lehmkuhl et al., 2007), providing high precision results where necessary. The coupling of these results with lower order of modelling is powerful in allowing for carrying out simulations corresponding to extended domains in space and time.

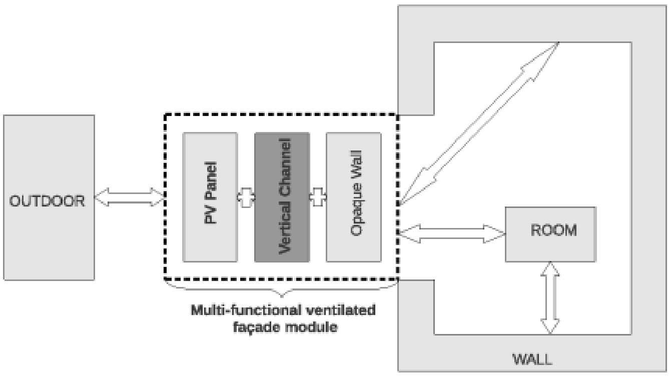

Fig. 3 Scheme of the NEST system as a collection of elements to model the Coventry demo site ventilated PV façade.

The NEST numerical platform is especially powerful in that it also allows parallel computation, which can redistribute the available computational resources according to the demands of the employed elements. The implemented module of the numerical tool aims at modelling an existing building envelope retrofitted by means of PV panel that is installed in the façade to form a vertical channel. The scheme of the resulting multi-functional ventilated façade module is shown in Figure 3.

Details of the mathematical and numerical model for the employed elements to form the PV Ventilated Façade is given by Kizildag et al. (2015). Note that *PV Panel* is modelled as an opaque one-dimensional conduction element with internal heat generation, assuming that the portion of the incident solar energy which is not used in the electricity generation is absorbed by the panel. This study basically addresses the thermal performance of the element.

Regarding the *Vertical Channel* element, it is worth noting that Bernoulli equation is applied in the inlet of the channel, assuming acceleration from an unperturbed point at the bottom of the channel. As for the thermal boundary conditions, improving the mathematical model employed in the previous work (Kizildag et al., 2015), the inlet temperature is no longer set constant at the mean outdoor temperature value of the simulated period, but it is dynamically adapted from the available meteorological data. The governing continuity, momentum, and energy equations regarding the *Vertical Channel* element are discretized by means of appropriate numerical schemes as explained in (Patankar, 1980) and using SIMPLEC algorithm.

Opaque Wall element is modeled in the same fashion as the PV Panel element, except for the existence of the inner heat generation terms. This element, which models the insulation layer, uses the thermophysical properties corresponding to the aerogel-based superinsulating mortar or vacuum insulation panels (VIP) provided by the manufacturers of these architectonic solutions, applied in the retrofitting of the demo building.

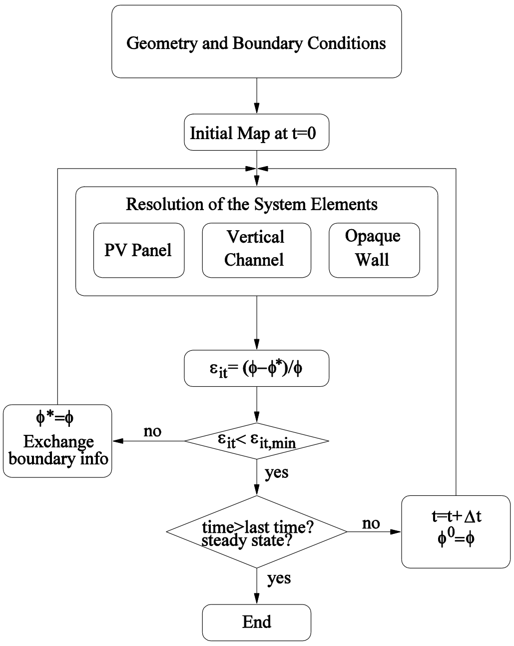

Fig. 4 Global resolution algorithm of the numerical tool.

The global resolution algorithm of the numerical model is shown in Figure 4. At each iteration, once the inputs (e.g. temperature, heat flux etc.) are obtained from the neighbors, the governing equations for each element are solved and the final outputs are supplied again to the neighboring elements as boundary conditions. Iterations continue until convergence is reached at a given time step and next time step calculation starts as the variables are updated. Details of the numerical platform are provided in (Damle et al., 2011).

3. Experimental validation of the numerical model in demo site

The validation of the numerical model was performed separately for each element constituting the PV façade using subsystems for which an analytical solution exists (see Kizildag et al., 2015 for details). As for the PV Panel and Opaque Wall, an analytical solution exists. Regarding the Vertical Channel, the analytical solution presented in (Bar-Cohen and Rohsenow, 1984) was used. Detailed results of the code validation were given in (Kizildag et al., 2014).

The present work, however, is aimed at completing this initial analytical validation by a proper experimental validation. Thus, in order to validate the implemented numerical model, the whole PV façade module of the retrofitted façade of the John Laing building (see Figure 5), composed of a PV panel, a ventilation channel, VIP panels and brick layers, was instrumentalized.

Fig. 5 Retrofitted façade of the John Laing Building in Coventry University.

The façade is equipped with a pyranometer measuring the global solar radiation in the plane of the façade, and a temperature sensor registering the outdoor ambient temperature in the vicinity of the prototype. Within the ventilation channel, two anemometers are placed, one in the midheight, the other in the 90% of the PV panel height locations. Two temperature sensors are also located in these locations. Another temperature sensor is also placed in the inner surface of the VIP panel which confines the ventilation channel. See Figure 6 for the images corresponding the instrumentalization of the PV façade.

Fig. 6 Pyranometer and outdoor temperature sensor (left), anemometer and inner tempearure sensors (right).

The experimental data from the sensors installed in this facility is gathered by a data acquisition system during prolonged periods of time. In Figure 7, the measured meteorological data for the PV façade for the winter and spring periods are depicted. Note that, during the winter period, the available solar energy on the plane of the façade is significantly lower with respect to spring conditions, which makes the months of March and April periods more suitable for the analysis of the façade. For the validation of the numerical model, the gathered meteorological data is feeded in the numerical model as the boundary conditions of the studied case, and the numerical outcomes of the model is than compared with the experimental data obtained from the temperature and air velocity sensors located within the cavity of the ventilation channel. To that end, three representative variables are selected:

- average air velocity within the ventilation channel
- temperature at the outlet of the channel

- temperature at the VIP surface, adjacent to the ventilation channel

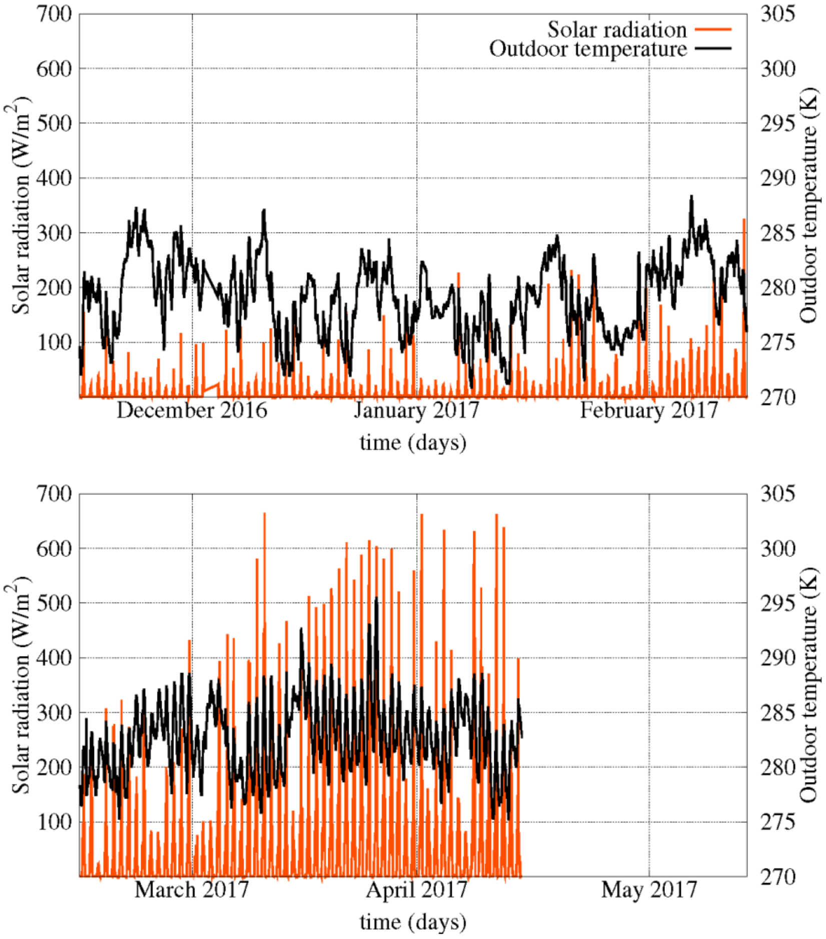

Fig. 7 Solar radiation and ambient temperature in demo site during winter (top) and spring (bottom).

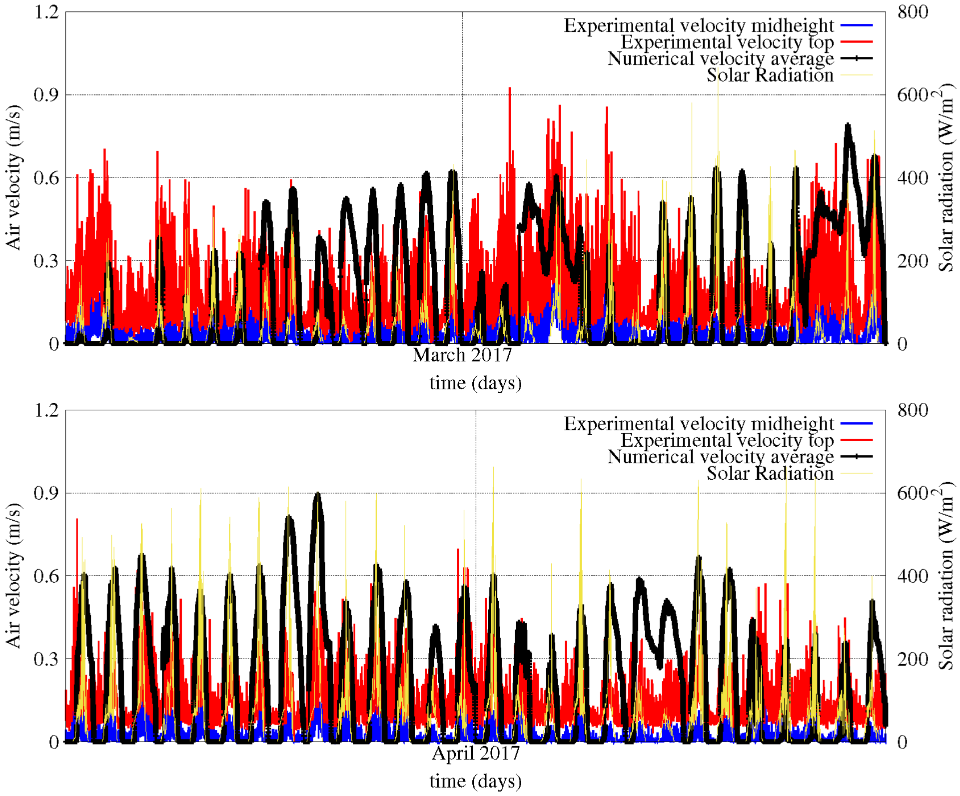

Fig. 8 Comparison of the numerical model's average velocity field with the experimental readings for March 2017 (top) and April 2017.

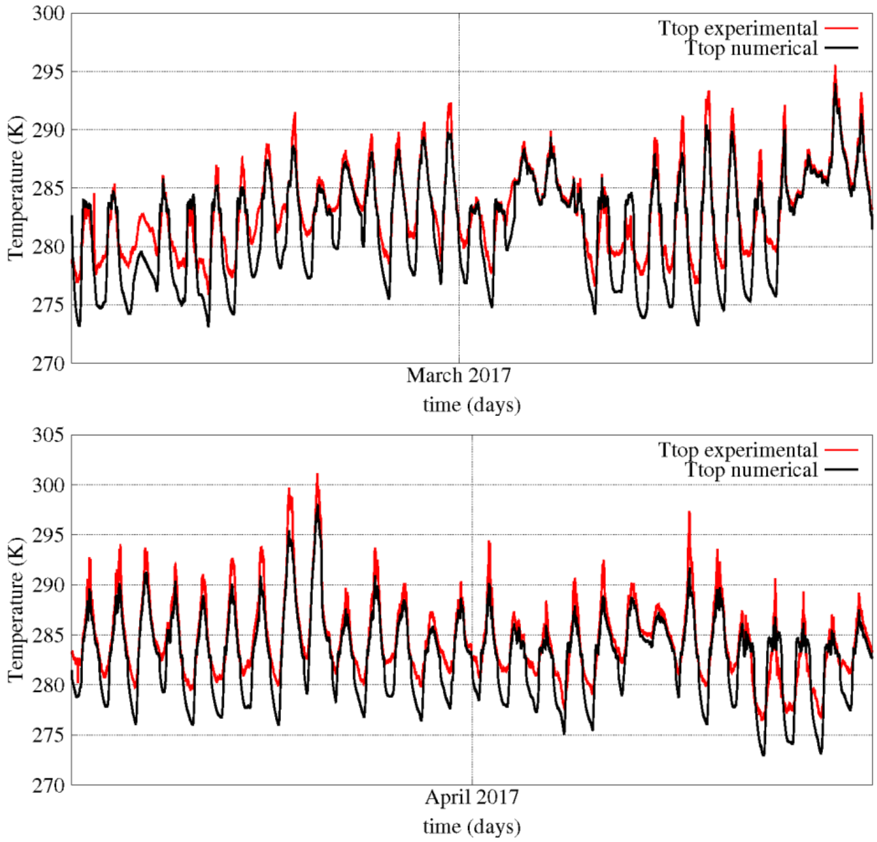

Fig. 9 Comparison of PV Façade air outlet temperatures obtained numerically and experimentally for March 2017 (top) and April 2017 (bottom).

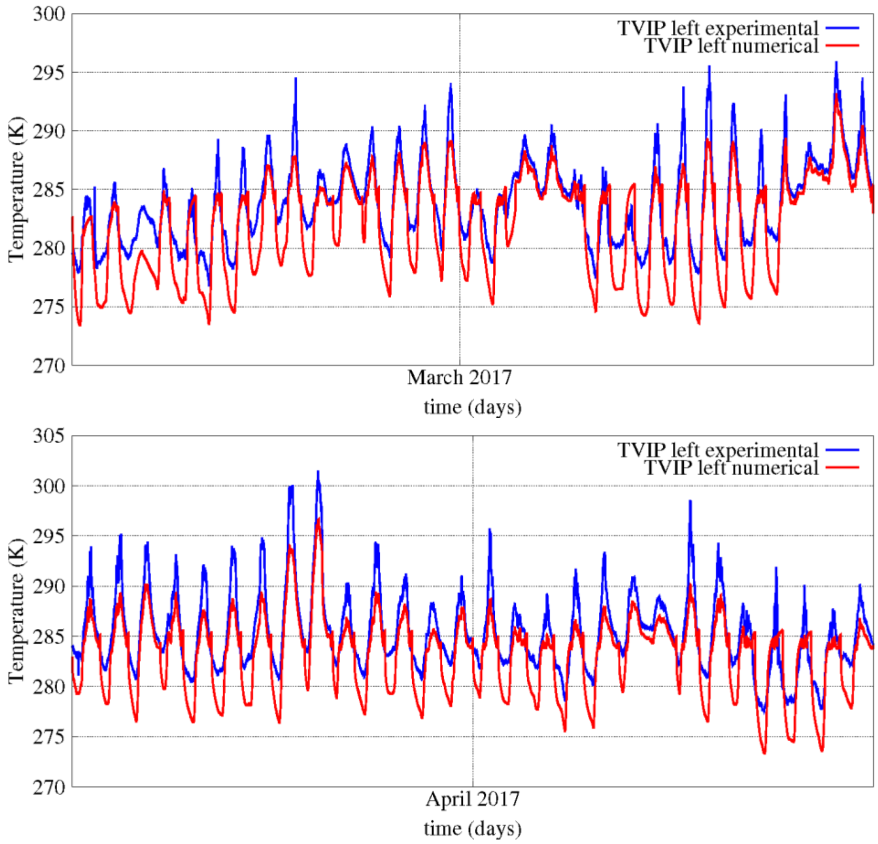

Fig. 10 Comparison of VIP surface temperature, confining the channel, obtained numerically and experimentally for March 2017 (top) and April 2017 (bottom).

The data corresponding to these selected variables are comparatively presented in Figures 8-10. The numerical data here presented for these considerably large periods of time –of the order of months- is in significantly good agreement with the gathered experimental data, thus providing a reasonable confidence in the potential of the numerical model in anticipating the thermal and fluid dynamics performance of the studied PV façade.

It has to be noted that, the model outcome is consistent with the complex physical phenomena taking place in the PV ventilated façade, as the temperature evolution data can fully follow the trend of the experimental temperature evolutions registered in two depicted key locations (see Figures 9 and 10). As for the air velocity within the ventilation channel, the numerical outcomes correlate very well with the availability of solar radiation, however they somewhat overestimate the velocities registered by the anemometer located at the top location of the channel (see Figure 8). Similarly, the estimated temperatures, while reproducing the phenomena correctly, are a few degrees lower than the experimental readings. These discrepancies can be attributed to many circumstances, such as:

- 1D numerical model vs 3D physical phenomenon: The employed numerical model is necessarily a 1D model, due to the impossibility of the detailed numerical resolution of the complex phenomena within the air channel for prolonged periods of time, typically one year. Any higher order model, such as CFD models, is not feasible for the present study.
- 1D model necessarily employs empirical data, such as friction factor or heat transfer coefficient which are derived for general situations which may not be in line with the actual studied case.
- The empirical data employed is derived for steady-state conditions, while the present study involves a transient behavior.
- The placement of the physical sensors, cables and other connection devices within the air velocity affects the overall behavior of the flow in the ventilation channel. These details are not considered in these simulations.
- The inlet and outlet geometry of the channel deviates from the initially studied case, which can justify important discrepancies with respect to the flow configuration.
- The employed anemometers have associated errors which can lead to discrepancies.
- Shadows are reported to be partially present on the studied façade, which can cause virtually higher or lower available radiation data on the façade.
- Temperature indoors is considered as a given constant value throughout the simulations.

To have a closer look at the model performance, data corresponding to the 1st week of April 2017 is depicted in Figure 11. The data is in line with the main conclusions mentioned above regarding the agreement of the numerical and experimental data, considering the assumptions that are included in this numerical study.

Thus it can be said that, the numerical tool, after being validated using the experimental data gathered in the John Laing Building, certifies the proper functioning of the ventilation channel placed behind the PV panel. The channel is shown to effectively dissipate the heat accumulated in the PV panel element, thus avoiding it to reach temperatures in which the correct functioning and overall efficiency of the PV element would be negatively affected.

Overall, the present numerical methodology for the long term thermal and fluid dynamics behavior analysis of a PV Ventilated Façade is shown to be an effective tool to design and optimize similar configurations. It is especially interesting to note that, due to the modular design of the validated software, new and more efficient materials or different innovative architectural solutions which are daily emerging in the market can be readily implemented in this validated numerical tool to address each time a wider range of situations regarding the retrofitting of the buildings.

4. Analysis of PV Ventilated Façade technology extrapolated to whole building

As an additional step of the present work, the numerical tool is employed to analyze the heat dissipation behavior of the channel, in the event that the PV ventilated façade technology is applied to the total available opaque surfaces present in the western façade of the demo building. In line with the objectives of the RESSEEPE project, it is of importance to extrapolate the results of the demo site module to the whole façade, thus highlighting the overall savings that could be provided by this retrofitting technology.

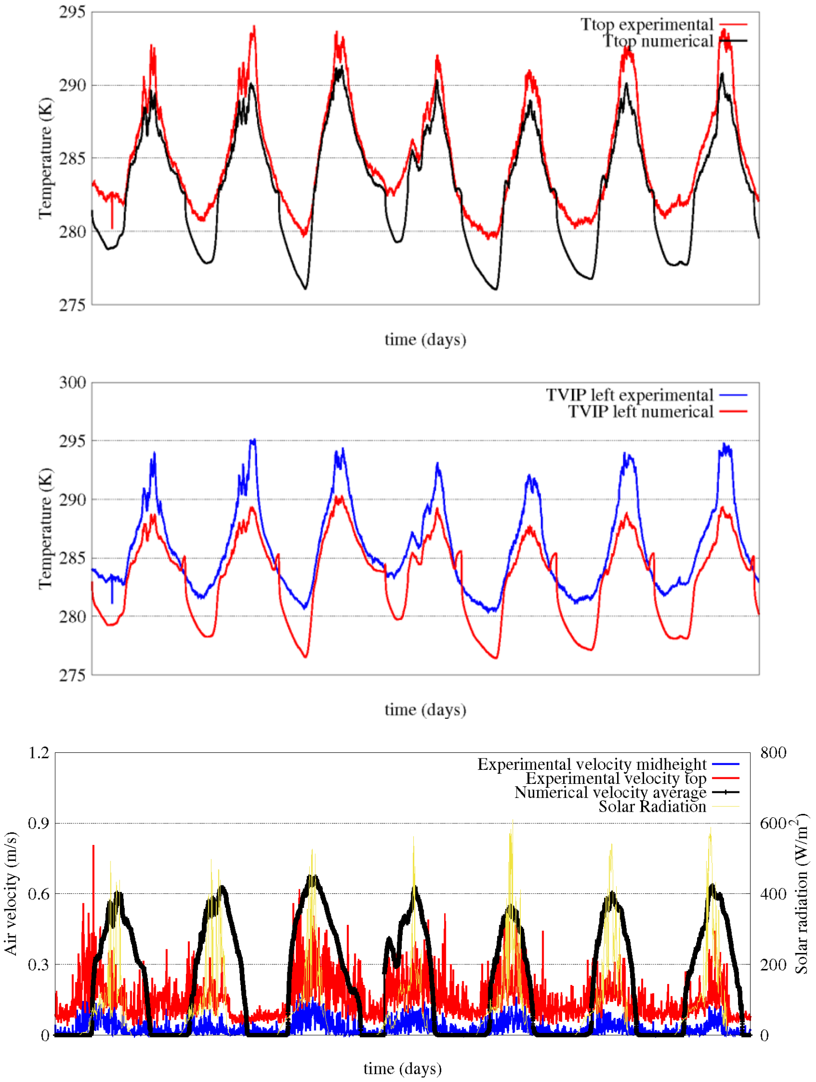

Fig. 11 Numerical vs experimental data for the 1st week of April. Temperature at the outlet of the channel (top), temperature at VIP surface (middle), average channel air velocity (bottom).

In Figure 12, the instantaneous total heat which would be evacuated by means of the ventilation channels is compactly depicted during the periods of winter and spring. This calculation is carried out by means of the already presented and validated numerical tool, using as boundary conditions the meteorological data gathered in the demo site, for the hypothetical case of installing the identical PV Ventilated Façade to all the available opaque spaces, excluding the already existing windows. Note that the evacuated heat, represented by the blue lines, have higher influence at higher levels of incident solar energy. During the winter months, the available solar energy is reduced and the outdoor ambient temperatures are relatively lower, thus the effect of the ventilation channel is not expected to be critical during these months, as confirmed by the outcomes of the numerical tool. However, from the detailed results depicted in Figure 13, it can be observed that the façade would effectively remove important portions of heat during the times of high solar availability, such as in May, by means of the ventilation channel.

Table 1 Total incident solar energy and the dissipated portion by the ventilation channel during 6 months.

Month	Incident Heat (kWh)	Dissipated Heat (kWh)	Percentage (%)
December	1375	203	14.8
January	1369	146	10.7
February	2578	760	29.5
March	6636	2371	35.7
April	11395	4784	42.0
May	11606	4788	41.3

In Table 1, the monthly total incident solar energy is given together with the dissipated portion by means of the PV Ventilated Façade. The tabulated data shows that, in the hypothetical case of installing this technology to the whole western façade of the John Laing building, over 40% of the absorbed heat by the PV panel would be effectively dissipated, leading to the optimum and efficient functioning of the PV panel.

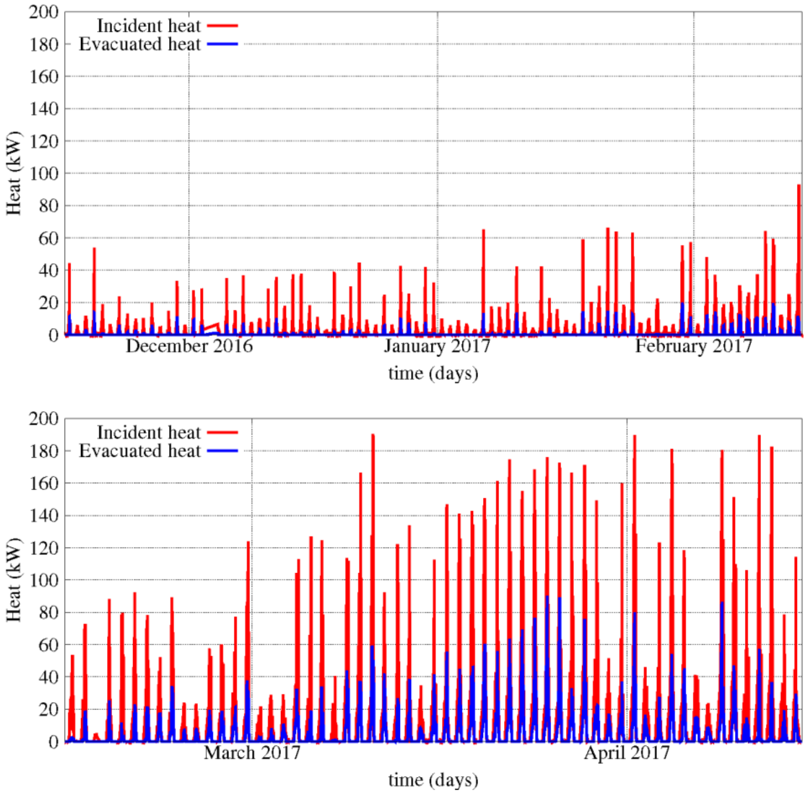

Fig. 12 Incident vs evacuated heat calculated for the hypothetic implementation of the technology to the whole façade.

In order to complement the data presented in **¡Error! No se encuentra el origen de la referencia.**, and to study the improvement experimented by the system thanks to the presence of the ventilation channel, the validated tool has been employed to comparatively study the influence of the ventilation channel on the PV panel temperatures. Note that, according to the technical specifications of the implemented panels in Coventry demo site, the efficiency of the electricity production of the panels reduce approximately by 0.451 % for each ºC of temperature rise experimented in the mean temperature of the cells. To that end, an additional simulation has been performed, simulating the thermal behavior of the façade for an identical system, but without the channel, i.e. the PV Panel is modelled to be attached directly to the VIP element. Considering the projection of this technology to the whole western façade of the John Laing building, the additional electrical energy delivered to the system is depicted in Table 2. Note that, the daily average PV panel temperatures are evaluated for the periods where there is solar availability within a day, i.e. during sunshine hours. The data reveal the key function of the ventilated façade, which make the PV panel function close to the ideal temperature conditions, and thus contributing it to deliver a considerably higher amount of electrical energy when compared with a hypothetical solution without ventilation channel.

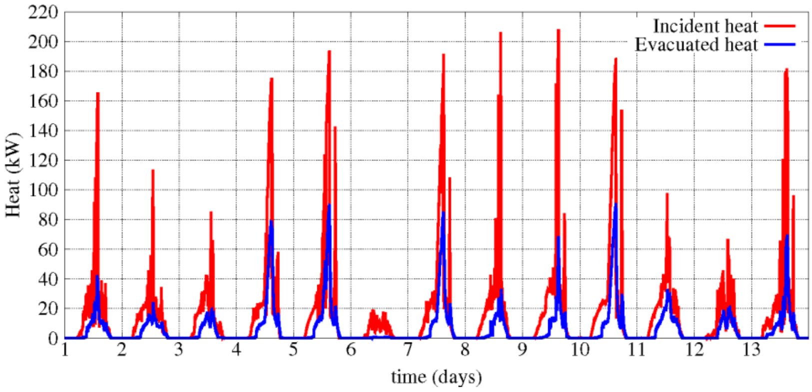

Fig. 13 Hypothetical instantaneous evacuated heat during the first two weeks of May 2017.

Table 2 Projection of the improvement of the electrical energy generation due to the presence of the ventilation channel for the meteorological data gathered in May 2017.

Day	Daily average PV panel temperature without channel (º C)	Daily average PV panel temperature with channel (º C)	Additional electrical energy delivered to the system (kWh)
1	27.975	21.089	9.38
2	24.622	19.056	6.53
3	24.205	19.216	5.63
4	36.878	25.405	28.23
5	36.527	25.009	31.09
6	14.354	13.966	0.19
7	38.207	26.269	30.87
8	26.303	21.255	7.73
9	29.523	23.260	12.78
10	36.562	25.237	32.09
11	30.433	22.162	13.81
12	28.305	21.219	8.08
13	31.207	22.351	17.35

In summary, the analysis extrapolated to the whole building by means of the validated numerical model shows that PV Ventilated Façade can be an interesting solution, evacuating the excess of heat through the ventilation channel by means of natural convection, thus contributing to the corresponding ventilation of the PV Panel, enhancing its efficiency. The analysis is carried out, not only for the particular module instrumentalized, but also for the whole western façade of the demo building, on the hypothesis of applying the mentioned technology to the entire façade.

5. Conclusions

It has been shown in the demo site located in John Laing Building in Coventry University by means of instrumentation that the designed and installed module of PV Ventilated Façade is functioning properly, as the ventilation channel effectively serves to evacuate the excess of the heat to enhance the overall performance.

The numerical methodology, employed in the design stage of the PV Ventilated Façade, is properly validated by means of experimentation. It has been shown that, besides the limitations of the assumptions, which are necessary so as to provide feasible numerical simulations for complex phenomena in physically large domains such as buildings and for typically extended periods of time, the numerical tool is capable of reproducing the general behavior of the retrofitted PV Façade studied in the present study.

Although the tested period does not cover a representatively long time span, however the initial outcomes in terms of both energy efficiency and the reliability of the system are promising.

The final outcome of this study is the experimental validation of an existing numerical tool which is capable of design, optimization, and long term performance prediction of PV Ventilated Façades or similar retrofitting or newly-built architectonical solutions. Additionally, due to its modular structure, the present tool can be extended to a wider range of retrofitting solutions, with the straightforward implementation of the numerical models of the newly emerging innovative materials and devices.

6. Acknowledgments

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