Outdoor performance assessment of a super-insulated opaque façade panel integrating PV, PCM, and thermal mass activation

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Abstract. Curtain Wall Façades (CWF) represent a widespread envelope technology for non-residential buildings. CWFs usually alternate transparent (visual) modules and opaque (spandrel) elements to create a variety of façade design alternatives. To be compliant with the local energy regulations, thick insulation layers have to be generally installed in the opaque elements. Nevertheless, to achieve an higher integration level of the opaque façade elements with the current curtain wall stick framing systems, slim elements have to be developed.
In the framework of the Horizon 2020 Project Powerskin+ a new concept of opaque slim multifunctional façade modules which combine super insulation (VIP - Vacuum Insulation Panels), energy harvesting (Perovskite PV), latent heat storage capabilities (PCM - Phase Change Materials), and heat generation (electric heating foil) is under development.
In this paper, the results of a first prototype, that was preliminary tested in outdoor test cell are presented. The experimental monitoring results allows to demonstrate the effectiveness of the façade in providing outstanding thermal insulation level. Moreover, the behavior of the integrated PCM and its thermal activation system was analyzed to have a better understanding of the PCM activation process and of the capability of the system to be adopted as a radiant wall system.

INTRODUCTION

In the last few years, the design of energy-efficient façade solutions represents a crucial aspect that needs special attention, especially in the nZEB oriented retrofit of the existing buildings.
Currently, this goal can be pursued by adopting the so-called Responsive Building Elements (RBEs), which allow the possibility to manage energy demand and take advantages of the outdoor environment contributions. Among the most promising RBE technologies, an increasing interest has been observed for the Advanced Integrated Facades (AIFs) that are able to control energy and mass flows between the building envelope and the external environment under different boundary conditions [1,2]. In particular, in this paper, a specific typology of AIF, the Multifunctional Façade Modules (MFMs), developed within the Horizon2020 Powerskin+ project [3], is analysed. The project aims at developing a prefabricated off-site lightweight transparent and opaque system that integrates solutions to refurbish existing Curtain Wall Façades (CWFs) in non-residential buildings. The newly developed opaque module is

characterized by a very limited thickness and the integration of high-performance insulation solutions (VIP - Vacuum Insulation Panels), renewable energy harvesting systems (Perovskite PV solar cells), advanced functional nanocoatings, embedded heating system for thermal mass activation, latent heat thermal energy storage systems (PCM - Phase Change Materials) and electric storage (second life Li-ION batteries). Powerskin+ façade concept and opaque module operation are presented in Fig.1.

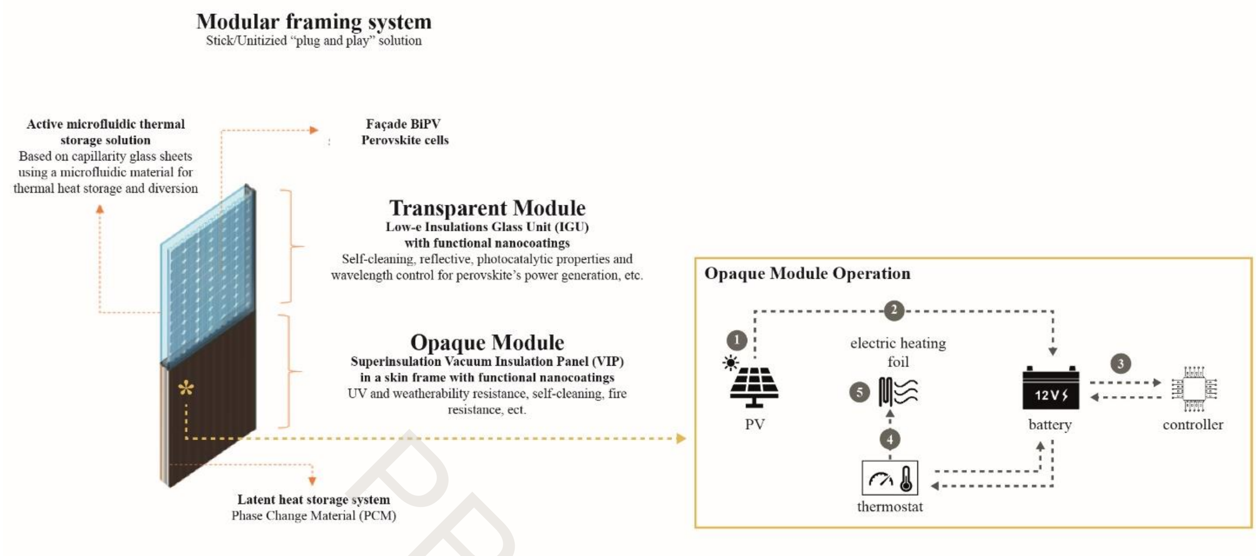


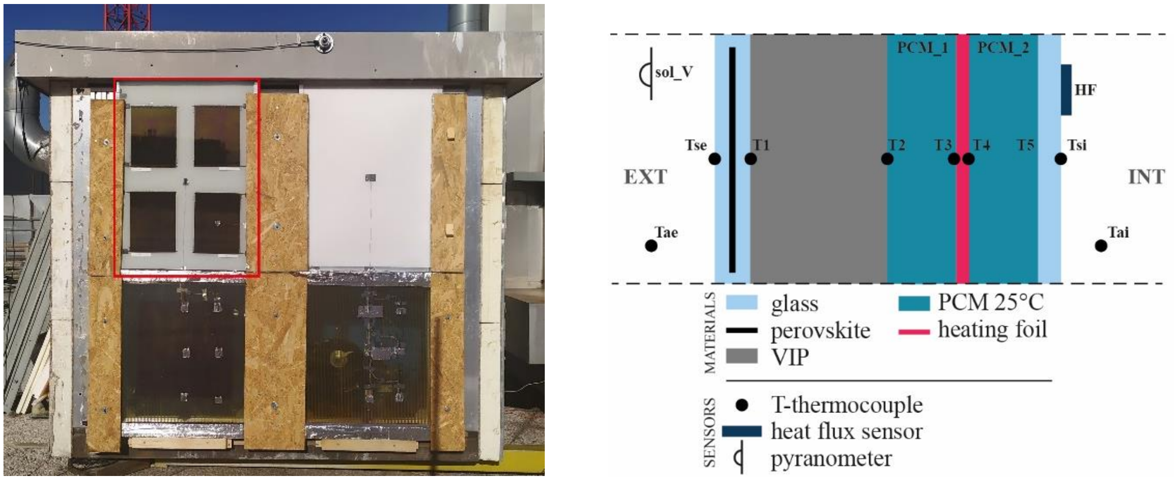
FIGURE 1 Powerskin+ façade concepts and details of the functionality of the opaque module [3].

The present study shows the results of an experimental monitoring campaign in which a prototype of an opaque slim multifunctional façade module was tested in an outdoor test cell. The experimental monitoring campaign aims to:

- demonstrate the effectiveness of the façade in providing outstanding thermal insulation level;
- verify the full exploitation of the latent heat thermal storage of the embedded PCM;
- verify the capability of the system to be adopted as a radiant wall system;
- assess the operational condition of the VIP and the PV layers to minimize heat stress phenomena and high-temperature operation;
- provide indication for the module design optimization.

FAÇADE CONFIGURATION AND TESTING PROCEDURE

The study was conducted on a prototype of an opaque slim multifunctional façade module that was preliminarily tested in an outdoor test cell (Fig. 2a). Specifically, the panel analysed with dimensions of 600x800 mm and thickness ≤ 50 mm combine (from outside to inside) energy harvesting (glass laminated Perovskite PV), super-insulating layer (Vacuum Insulation Panels), latent heat storage double layer (salt hydrate Phase Change Material macro-encapsulated in polymeric pouches with a melting temperature of 25°C), and embedded heat generation (electric heating foil). Moreover, in the tested prototype, an antireflective coating was used on the external glass. The layer combination of the module is represented in Fig. 2b and details of the different layers are given in Table 1.



(a) (b)

FIGURE 2 The analysed façade prototype installed in the outdoor test cell, monitored module is highlighted in red (a). Functional layer of the tested prototype and sensor positions (b).

TABLE 1. *Properties of different materials integrated in the prototype analyzed.*

	Material	t [mm]	λ [W/mK]	w [kg/m^2]
1	Double laminated glass embedding Perovskite PV	6	1	15
2	VIP	15	0.0016	3.15
3	PCM_1	7	0.17	5.32
4	Heating foil	0.4	0.4	0.38
5	PCM_2	7	0.17	5.32
6	Tempered glass	4	1	10

In field performance measurement

The monitoring campaign has been performed in winter conditions (Oct 27th – Feb 28th). A small-scale (internal dimensions of 1.5x1.5x1.5 m) test-cell of the Department of Energy of Politecnico di Torino (Italy) was used to install the opaque module on the south façade. The boundary conditions were monitored considering the air temperature and horizontal and incident global solar radiation. Type-T thermocouples were installed in the test cell to monitor the internal air temperature and the surface temperature of each interface of the module layers. Moreover, a heat flux sensor (Huksflux HFP01) was placed on the internal side of the panel to assess the heat gains and losses. The sensors were connected to a data-logging system (Datataker DT85) which collected data with a time-step of 5 minutes.

The collected data were analysed to assess: i) the thermal transmittance of the module; ii) the PCM latent heat storage activation and exploitation; iii) the capability of the system to be adopted as a radiant wall system, iiii) the VIP and PV layer temperature to assess the risk of overheating

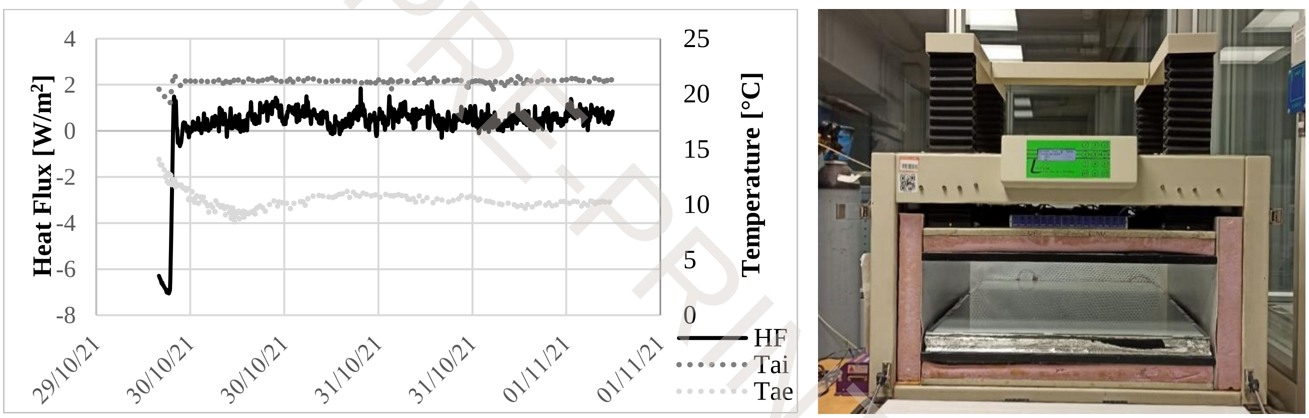
The indoor air temperature in the test cell was constantly kept at the desired set point (20±0.5 °C) by means of a thermostat connected to an electric heater (operating power of 1kW). Moreover, the embedded electric heating foil has been activated every day from 8 a.m. to 6 p.m. with a constant power of ~103 W/m^2.

FIRST RESULTS

Thermal transmittance measurements

To evaluate the module thermal insulation properties, the heat fluxes have been analysed to assess the thermal transmittance (U-value) of the component.

The thermal transmittance (U-value) of the opaque façade module has been measured by applying the ISO 9869 [4] standard. As expected, the measured heat fluxes in the outdoor test cell were very low (average value below 1 W/m^2, as presented in Fig. 3a) leading to measurement uncertainty on the heat flux that was higher than 30%. So, for this super-insulated building element, it was not possible to obtain an accurate assessment of the U-Value even if the analysed data refers to cloudy days with a very stable temperature difference between the indoor (Tai) and the outdoor (Tae) of about 10°C (Fig. 3a dotted lines). For this reason, the U-value was measured in controlled laboratory conditions using the Heat Flow Meter method according to the EN 12667 standard [5]. In Fig. 3b the experimental apparatus a TA instrument FOX 600 single sample heat flow meter is presented. The experimental test was carried out by applying a temperature difference between the upper and the lower plate of 20°C with an average temperature of 10°C. The U-value has been determined as the reciprocal of the thermal resistance including the internal (Rsi) and external (Rse) standard surface heat transfer coefficient (according to EN ISO 6946 [6] a value of 0.13 and 0.04 m^2K/W was considered for Rsi and Rse respectively). As a result, the laboratory U-value was about 0.099±0.003 [W/m^2K]. Table 2 shows the transmittance values obtained from the Heat Flow Meter compared with the one determined by using the standard calculation method (EN ISO 6946).



(a) (b)

FIGURE 3. Measured heat fluxes in the outdoor test (a). Thermal transmittance measurement with the heat flow meter apparatus (b).

TABLE 2. Thermal transmittance

Thermal transmittance measured by Heat Flow Meter (EN 12667) [W/mK]	Thermal transmittance calculated (EN ISO 6946) [W/mK]
0.099±0.003	0.103

Heat storage activation and exploitation

To verify the full exploitation of the latent heat storage of the embedded PCMs a sunny day (13/12/2021) was selected for detailed analysis (monitored boundary conditions are plotted in Fig. 4).

The temperatures of the PCM layers, shown in Fig. 5, are the average values of the temperatures (Tavg) collected by the thermocouples placed in the interfaces of the two PCM layers (Fig. 2b): where Tavg_PCM_1 refers to the average temperature (T2, T3) of the outermost PCM layer (PCM_1) and Tavg_PCM_2 to the average temperature (T4, T5) of the innermost component (PCM_2). An electric heating foil 12V DC with a power output of ~103W/m^2 has been embedded between the two PCM layers. During the heating foil activation period (8:00 – 18:00) the outer PCM_1 layer shows a temperature variation between 20°C (8:00) and 43.80°C (17:00) with an amplitude of 23.80°C while the PCM_2 layer (inner side) shows a temperature variation between 20°C (8:00) and 39.50°C (17:00) with an amplitude of 19.50°C.

In Fig. 5 the daily temperature profile of the PCM layers (left) are compared with the results of the partial enthalpy vs temperature (right) of the macro-encapsulated PCM (the test has been carried out using the Dynamic heat flow meter method according to the ASTM C1784 [7]).

The partial enthalpy vs temperature curves show that during the melting phase (grey line) the transition occurs between 24°C and 29°C, whereas during the cooling phase the transition starts at 27°C and ends at 24°C with about 1°C of hysteresis considering the peak enthalpies. Therefore, comparing the temperature profiles of the PCMs (left) with the trends of the partial enthalpies (right), it is evident that the PCMs largely exploit their latent heat during the melting phases. In fact, PCM_1 melts completely in about 1 hour and PCM_2 in about 2.5 hours, while both PCM layers solidify in about 4 hours. Moreover, due to the heating foil activation from 8:00 to 18:00 PCM layers reach temperatures much higher than their nominal phase transition temperature. As a general comment, a selection of a higher nominal PCM melting temperature for the outermost PCM layer will potentially turn to a better exploitation of the latent heat in both layers.

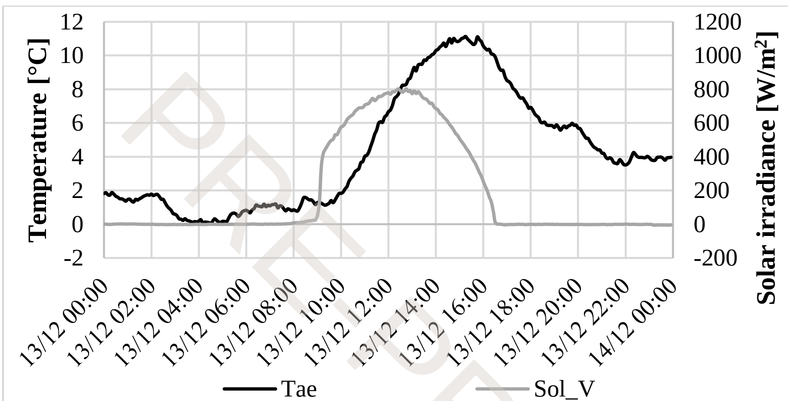


FIGURE 4. Boundary conditions: external air temperature (T_ext), vertical solar irradiance (Sol_V) on the reference day (13/12).

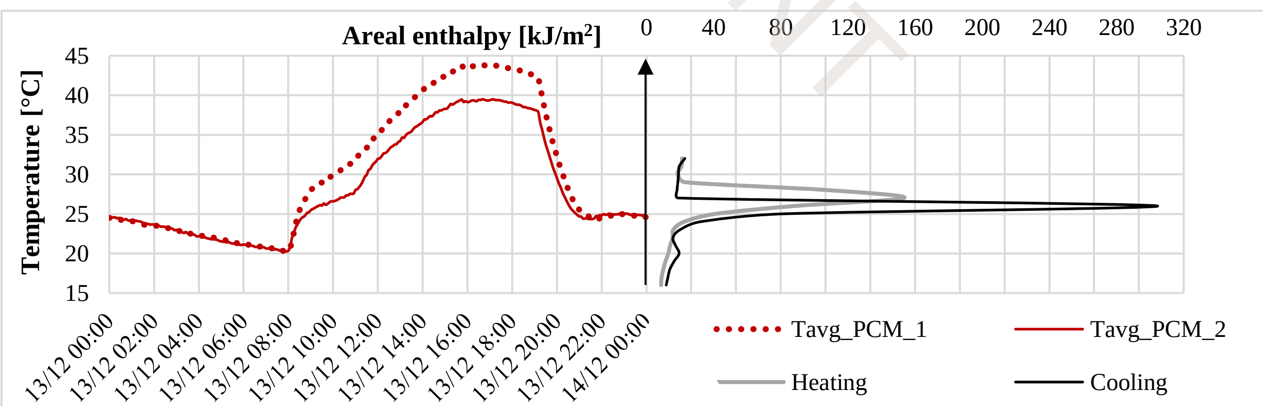


FIGURE 5. Comparison of PCM layer temperatures and PCM enthalpy distribution.

Suitability of the system to be adopted as a radiant wall

The electric heating foil integrated in the façade module has the double functionality of activating the thermal mass of the PCM to be used as thermal storage, and of making the opaque module a radiant wall element for environment

heating purposes. The heating element used is an electric heating foil with a nominal power of 130 W/m^2 and an active surface of ~0.25 m^2.
To verify the suitability of the system to be used as a radiant heating system the temperature and the heat fluxes were analysed. The monitoring data (heat flow, interior surface temperature) were collected considering a reference winter day (13/12/2021) during which the electric heating foil was activated from 8:00 to 18:00.
According to ASHRAE 55 standard [8] in the case of a radiant wall, for heating, the upper limit of the permissible surface temperature is 20°C higher than the mean radiant temperature. Therefore, assuming that the average radiant temperature of the analysed room is equal to the air setpoint temperature (20°C in winter conditions) the maximum surface temperature is 40°C. Figure 6 shows the cumulative frequency trend of the internal surface temperature of the wall, where it is noticeable that the surface temperature never exceeds the value of 40°C (for 100% of time the temperature is below 30°C)

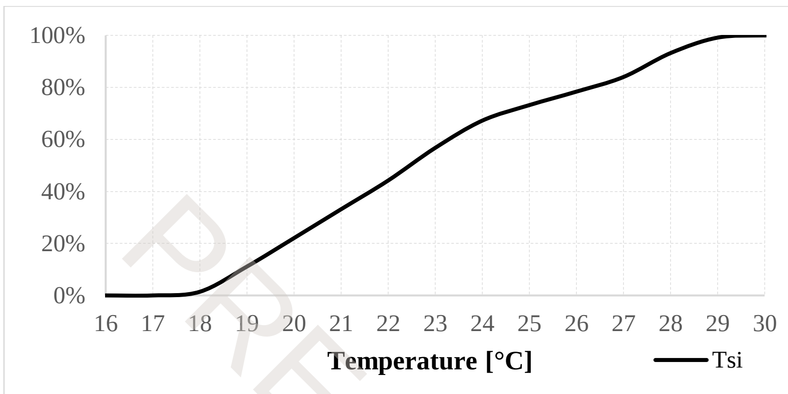


FIGURE 6. Cumulative frequency of the interior surface temperature (Tsi).

VIP and PV operating temperatures

Among all the collected parameters, the temperature achieved on both side of the VIP layer were monitored to assess the occurrence of heat stress phenomena. In [9] and [10] is reported that the VIP panels, and especially the barrier materials have to be protected to avoid exposure at temperature higher than 60°C (maximum temperature for long-term exposure) and 80°C (for short term exposure). The risk is connected to the fact that high temperatures are one of the main drivers of the gas transmission phenomena through the VIP envelope. Moreover, high surface temperatures might lead to the risk of barrier delamination phenomena.
In Fig. 7 the cumulative frequencies of the monitored temperature in the internal side of the VIP (T2) and on the external side of the VIP (T1 - VIP_PV interface) were plotted. As far as the internal temperature (solid line) are concerned, the values were always below the temperature limits (60°C) for all the monitoring periods. While the temperature of the interface between the external side of the VIP and the PV layers (T1) have revealed temperatures that exceed the maximum operating temperature limit (60°C for long term exposure) for more than ~15% of the time. This overheating phenomenon can be explained by the presence of the high solar absorption of the PV modules that is not able to dissipate its heat on the internal side since it is in contact to a super insulating VIP layer. Moreover, it is worthy to be mentioned that high temperature in the PV layers also jeopardizes the PV efficiency. So, to increase the expected service life of the VIP and achieve higher PV production efficiency, different design configuration variations has been proposed and will be tested in the framework of the project. These include the application of an additional PCM layer and the design of a ventilated air gap to reduce peak operational temperatures.

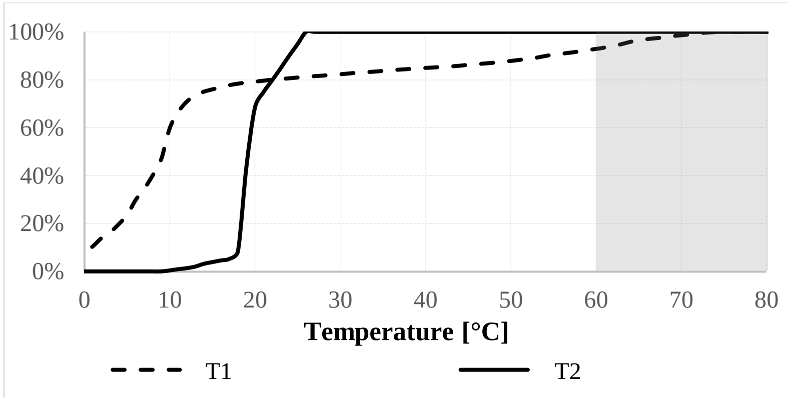


FIGURE 7: Cumulative frequency of the VIP interface temperatures.

CONCLUSION

The presented study is aimed at assessing the performance of a novel multifunctional opaque façade, under operational conditions, through the evaluation of the thermal insulation performance, the active exploitation of the latent heat thermal storage, and the possibility to use the module as a radiant wall heating system. The data collected shows very promising results for all the above-mentioned performances/functions. Laboratory measurements have revealed an outstanding insulation performance (U-value) of about 0.099 W/m^{2}K, which is in line with those calculated using the standard method.

For the measurement performed on the PCM activation, the embedded electric heating foil was able to completely exploit the PCM's latent heat (PCM fully melted) in ~1 hour for the outer PCM layer and ~2.5 hours for the inner side PCM layer respectively. So, to obtain a similar transition time for melting the two PCM layers, a higher melting temperature should be adopted for the outermost PCM layer.

To evaluate the opportunity to adopt the panels as a radiant wall, an analysis of the surface temperature was carried out. Results allow verifying that the internal surface temperature is largely below 40°C (maximum surface temperature of the radiant wall if an indoor mean radiative temperature of 20°C is assumed). Finally, the analysis of the temperature reached by the VIP and the PV modules in winter conditions has revealed the risk of overheating. This effect might potentially lead to shorter service life for the VIP and to a lower PV operating efficiency. To mitigate these drawbacks, different design options are under study to reduce the peak module temperatures, this will include the application of a PCM layer and of a ventilated air gap.

The information collected during this first small-scale outdoor experimental monitoring will be used to develop an optimised full-scale prototype that will be installed in outdoor laboratory test room and in the Powerskin+ project demo buildings.

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