ANALYSIS OF THE ENERGY PERFORMANCE OF A NEW OPAQUE SLIM MULTIFUNCTIONAL FAÇADE MODULE

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Abstract

Curtain Wall Façades (CWF) represent the most common vertical envelope solutions for non-residential buildings. To be adapted to different climates and building typologies, CWFs alternate transparent (visual) modules and opaque (spandrel) elements to create a variety of design alternatives that might combine different Window to Wall Ratio (WWR). Nevertheless, especially for the opaque components, to be compliant with the local energy regulations, thick insulation layers have to be installed back to the glazing units, thus reducing the indoor space and to a certain extent interfering with the aesthetical value of the façade.

To improve the building energy efficiency while increasing the indoor environmental quality, new multifunctional opaque adaptive façade solutions with high technological integration are currently under development.

In the framework of the Horizon 2020 Project Powerskin+ a new concept of opaque slim multifunctional façade modules which combine super insulation (Vacuum Insulation Panels), energy harvesting (Perovskite PV), latent heat storage capabilities (Phase Change Materials), and heat generation (electric heating foil) is under development.

A preliminary assessment of the thermal behaviour of different spandrel panel design alternatives, all characterised by low thickness (<75 mm), was performed by means of dynamic thermal simulation in WUFI® Plus software. In this study, the heating and cooling energy need of a single office was evaluated. The simulation results allow proving the effectiveness of the designed concept, which have demonstrated a significant reduction of the heating and cooling need, if compared to state of the art spandrel panel. The outcomes of this preliminary simulation activity have also highlighted that the implementation of advanced control strategies represent an essential step for a large exploitation of the performance of this type of multifunctional façade elements.

1. INTRODUCTION

The significant environmental impact of the building sector, due to the demand for energy and related greenhouse gas emissions, has led to stricter regulations that insist on the need to design nearly Zero Energy Building (nZEB). The aim is to conceive the building as an integrated organism characterized by a "reactive" and "dynamic" behaviour, to maximize environmental quality and minimize energy consumption.
In this perspective, the design of building envelopes becomes critically important. A focus is placed on the design of Multifunctional Facades, one of the most promising facade technologies in controlling energy and mass flows between the building and the external environment [1].

Multifunctional facade is a type of adaptive facade that implements multiple functions in the same building envelope. Multifunctional Façades Module (MFM) are systems able to modify their functions and characteristics in response to the boundary conditions with the aim of improving the performance of the building [2].

The adaptability and flexibility of these types of building envelopes can be achieved through innovative use of conventional materials or the use of advanced materials.

In the framework of the Horizon 2020 Project Powerskin+ a truly innovative slim curtain wall opaque modules (spandrels) [3] based on the smart integration of super-insulative elements (Vacuum Insulation Panels), solar energy harvesting (Perovskite PV),latent heat storage capabilities (Phase Change Materials) and heat generation (electric heating foil), all in one single combined active/passive management system is under development [4]. These modules allow the energy retrofit of existing tertiary buildings and the construction of new Nearly Zero Energy Buildings (nZEB).

In this paper the performance that might be achieved by the developed opaque façade concept were investigated.
An experimental study was carried out to analyse the multilayer element thermal behaviour and to collect data for validation of numerical simulation at the component scale.

In a second step, a simulation study at the building scale was carried out. For this analysis a typical office environment was simulated to analyse the impact on the energy performance of different opaque module configuration.
The results revealed that the application of the developed opaque module configurations allows considerable savings in energy terms compared to the application of a state of art spandrel panel even by using lower thickness. Nevertheless, the results have also highlighted that to better exploit the potentials of multifunctional façade configurations, the implementation of advanced control strategies represent an essential step.

2. METHODS

2.1. THE ANALYSED CONFIGURATIONS

From the point of view of the façade concept analysed in this paper, the objective was to design adaptive and multifunctional façade modules that assume the following functions:

- latent heat storage capabilities by using innovative materials such as Phase Change Materials (PCM);
- energy production, through the application of integrated Perovskite-based photovoltaic modules;
- high-performance insulation solution in greatly reduced thickness, due to the use of super-insulative elements such as Vacuum Insulation Panels (VIP),
- the integration of a heating system through electric heating foil.

Therefore, different functional layer combinations were hypothesised including PCM, PV, VIP, Heating foil.

In this study, three different opaque panel configurations were analysed:

a) BENCHMARK: it represents the state of the art for opaque curtain wall components and has been used as a reference. It is a spandrel panel characterized by the presence of an external layer of laminated glass (3+3 mm), a closed air cavity (50 mm), 100 mm of polyurethane and an internal layer of gypsum board (9.5 mm).

b) PASSIVE: it tries to maximize the solar contributions coming from outside using innovative materials such as PCM. It is characterized by a greatly reduced thickness of the panel that is less than 60 mm using innovative and super-insulating materials such as VIP that are very useful for space constrained and slim construction.

c) ACTIVE: it is the one that implements the most technologies and materials, in fact it is characterised by the presence of a photovoltaic panel that power an electric heating foil that has the double function of activating the adjacent PCM and of making the opaque module a radiant element for winter conditioning of the internal environment. Moreover, even in this configuration, the presence of a super-insulating material such as VIP allows for a very low overall panel thickness of less than 70 mm.

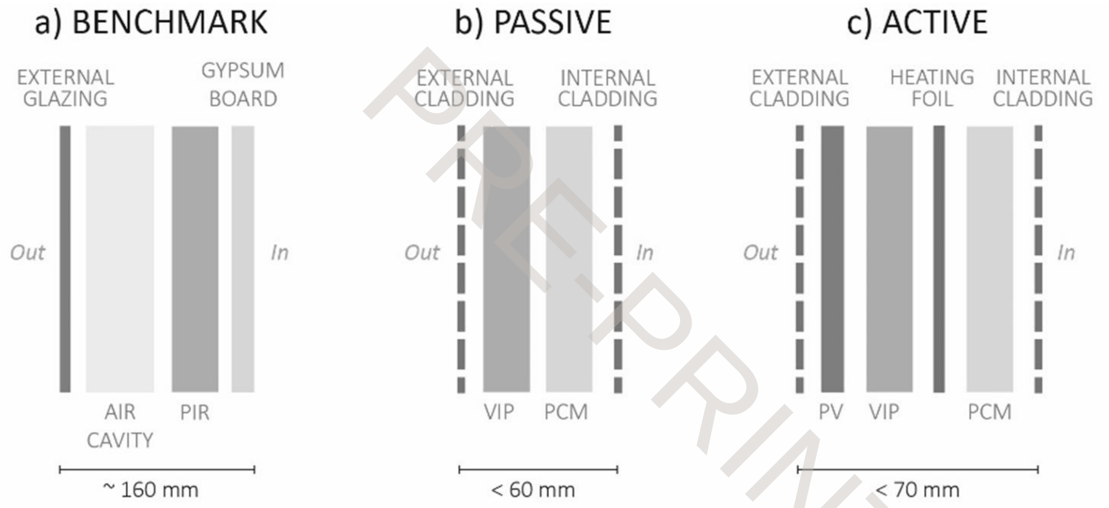

Figure. 1: The analyzed opaque configurations: a) Benchmark; b) Passive; c) Active.

2.2. ANALYSIS AT COMPONENT SCALE

Firstly, a simulation analysis was carried out at the component scale using the WUFI® PRO software. This software can simulate opaque envelope components under dynamic conditions and allow determining the behaviour of different functional layers i.e. latent heat storage of PCMs, and thermal activation by means of heating foils (internal heat source).

In order to fully evaluate the thermal behaviour of the materials analysed within the hypothesised configurations, some preliminary measurements were carried out in dynamic conditions on the ACTIVE configuration through the use of a Dynamic Heat Flow Meter Apparatus Lasercomp FOX 600. This instrument is compliant with ASTM C518-17 [5] and EN 12667 [6] standards, and is able to generate a temperature difference between the two sides of the sample and measure the heat flow through itself and the relative surface temperatures. Moreover, the instrument software was modified to perform dynamic test under periodic stabilised sinusoidal solicitation.

Specifically, a prototype corresponding to the active configuration was tested. This is characterised by the presence of an integrated photovoltaic panel in the form of a sheet of Perovskite, which, in winter, power a heating foil. Since the Perovskite sheet was not available, the test was limited to the integration of the heating foil inside the layers, in this case powered by electricity. In addition, in this stratigraphy there are materials such as PCM, VIP and glazing system. The test, conducted in dynamic regime, was carried out in winter conditions (with the heating foil active).

The experimental results obtained, which consist of a series of temperatures measured by the thermocouples and reported with a specific timestep, were plotted in order to graphically represent the temperature trend at each interface of the multilayer prototypes and were subsequently compared with those obtained from the simulations done with WUFI®PRO. The software made it possible to build a model identical to the real one and to define the same conditions as the experimental test adding a heat source equivalent to the power supplied by the heating foil during the test. In this way, it was possible to compare the measured values with the simulated ones, then the RMSE (Root Mean Square Error) was calculated. The results of the prototype tested in winter conditions, measured in four different interfaces, are shown in Figure 3.

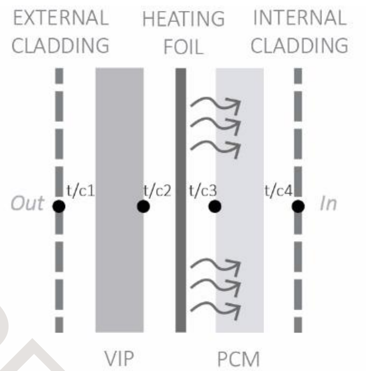

Figure. 2: Tested prototype scheme

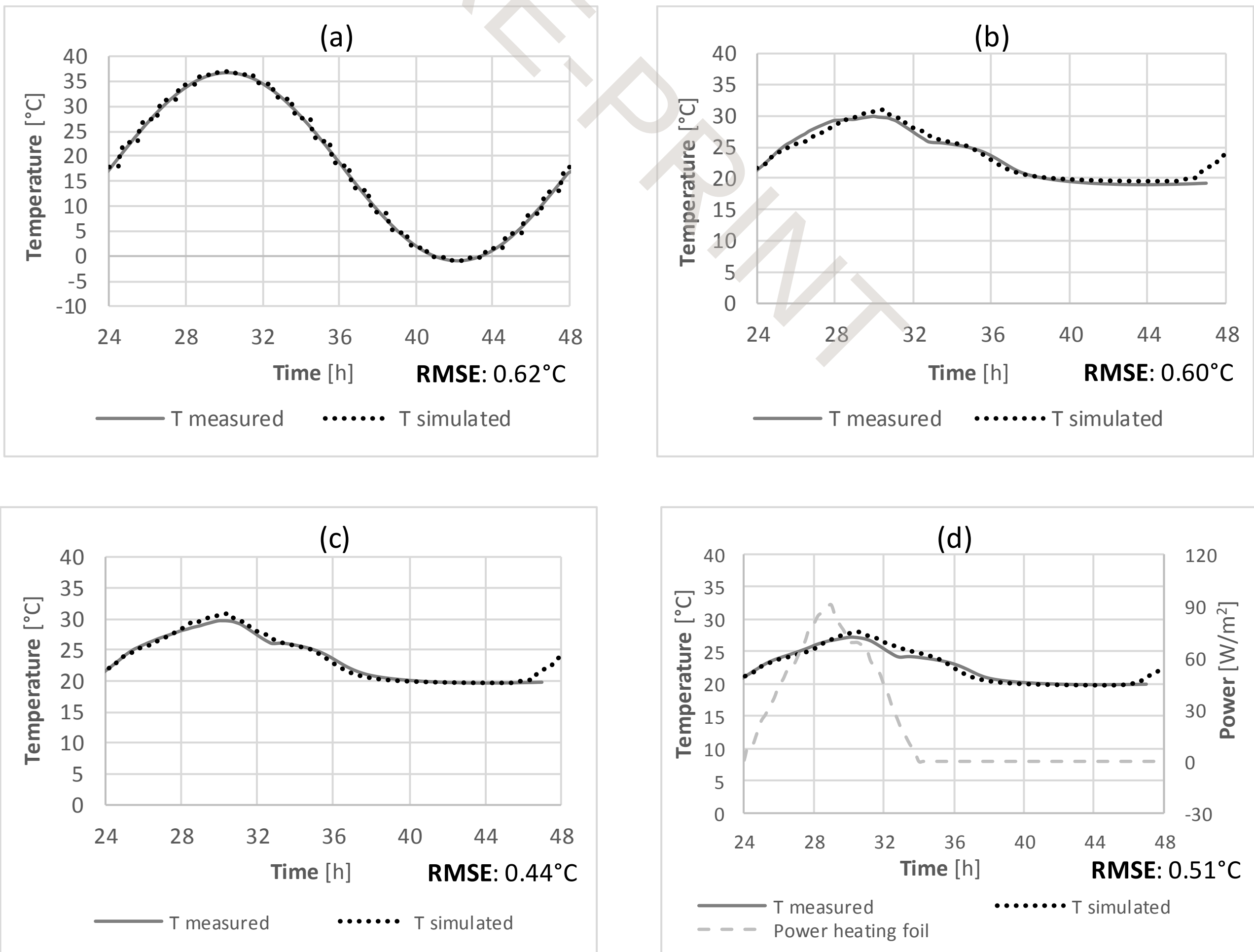

Figure. 3: Comparison between measured and simulated temperature of (a): External cladding (t/c1), (b): VIP / heating foil (t/c2), (c): heating foil / PCM (t/c3), (d): Internal cladding (t/c4)

In Figure. 3 it can be observed that in each of them the simulated temperature curve is approximately coincident with the measured temperatures. Moreover, the RMSE, which is an indicator of the average error that expresses how much the simulated values deviate from the measured ones, varies within an acceptable range (0.44°C - 0.62°C). So, the simulation model has been considered validated.

3. SIMULATION AT BUILDING SCALE

A building scale analysis was performed using the WUFI® PLUS software. This software allows to simulate the thermal dynamic conditions in the building components and to analyse their impact at the building scale (indoor temperatures, heating/cooling loads).

The software requires the definition of the boundary conditions and properties of the simulated environment:

- Orientation and location

The analysed environment is characterized by one external south oriented wall. Turin location was analysed and weather data was retrieved from the WUFI climates database.

- Dimensions

A typical office with dimensions 3.6m x 4m x 3m (h) has been simulated (Figure 4). The net floor area is 14.4 m^2. The facade is characterised by high performance materials and systems (Configuration a) Benchmark; b) Passive; c) Active) and has dimensions of 3.60m x 3m (h)with a Window to Wall Ratio (WWR) of 16%. All the other partitions, roof and floors were considered adiabatic.

- Internal Loads

For the internal loads, related to the occupants, a single office occupancy schedule was assumed with occupation from 7 a.m. to 6 p.m.

- Ventilation

To ensure adequate thermal comfort to users who will occupy the office, different ventilation has been set according to the working hours. In the summer period night natural ventilation was considered 0 - 9 a.m., with 6 ACH (Air Change per Hour); during the remaining hours of the day the air change is 1 ACH. In the winter period the ventilation is constant and is equal to 0.5 ACH for both night and day conditions.

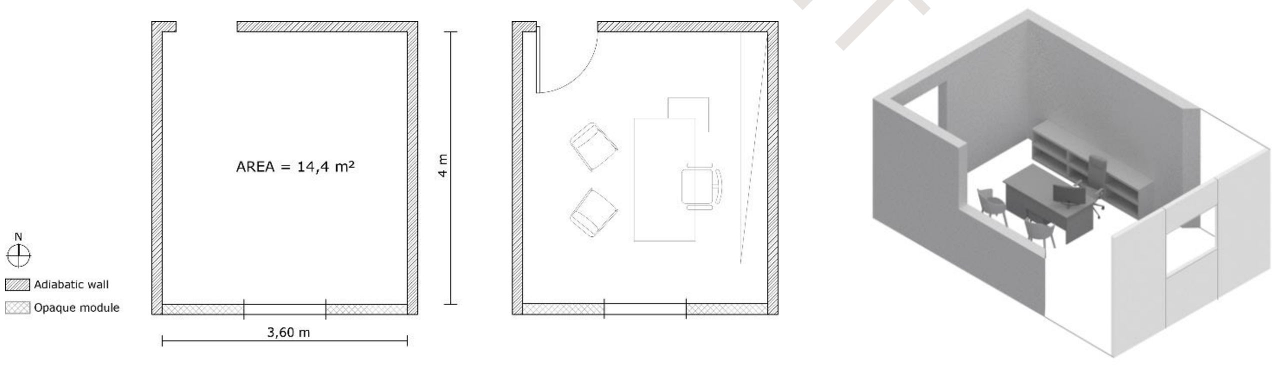

Figure. 4: Office dimensions: plan and axonometric view

4. RESULTS AND DISCUSSION

After the simulations, a general comparison between the various configurations was made.
Therefore, the three configurations were compared: the Benchmark (a), the Passive configuration (b) (VIP + PCM) and the Active configuration (c) (VIP + PCM + heating foil + PV panel).
For each configuration, the annual energy demand was initially analysed.
Figure 5 show that for the benchmark configuration the monthly heating and cooling demand fluctuates between -2 and +2 kWh/m² with an overall heating demand of 8.04 kWh/m² (October to March) and a cooling demand of 4.97 kWh/m² (April to September).

The passive configuration (Figure 5b) has a slightly lower energy demand than the benchmark configuration thanks to the presence of the PCM which through their latent heat thermal storage (LHTS) is able to provide a peak load shifting and reducing heating and cooling peaks [7]. In fact, the total values of heating and cooling demand are respectively equal to 7.14 kWh/m² and 3.34 kWh/m². It follows that the use of this configuration compared to the benchmark provides energy savings of 11% for winter heating and 33% for summer cooling.

The active configuration (Figure 5c), on the other hand, have revealed a much lower energy requirement than the Passive configuration.
In this case, total heating values of 0.64 kWh/m² (considering the months of December and January) and a cooling value of 3.60 kWh/m² (in the months of May-September) have to be highlighted.
Compared to the benchmark this significant reduction in energy demand of 92% and 28% for heating and cooling respectively, is due on one hand to the presence of the PCM, which reduces the energy demand in summer and winter, and on the other hand to the presence of the integrated heating foil which activate the PCM and provide free heating (for the PV panels it was assumed that a 100% of the electric energy produced by the PV was converted in thermal energy from October to April) . The use of photovoltaics (assumed efficiency 10%), drastically reduces the heating demand in winter period, reaching a value of 0.64 kWh/m².

From the graph it emerges that, especially for the Active configuration (c), some months have not been considered in the heating and cooling balance calculation (white bars):

- Heating demand in May, September, and October, because the night ventilation (6 ACH) was set for the whole month, this might generate heating demand even in summer and mid-season. This heating demand can be easily avoided by controlling the night ventilation when it is not needed;
- Cooling demand from February to April and from October to November, because the integrated heating foil produces an excess of thermal energy that overheat the indoor environment in winter and mid-season. This can be avoided just by delivering the electric energy to the grid or to electric storage system.

To reduce those abovementioned aspects, a possible solution is represented by the integration of advanced control system which allow to operate the night ventilation in summer and to optimize the management of the electric energy produced by the integrated PV system to activate the latent heat thermal storage of the PCM only when needed.
Finally, Figure 6 shows a comparison between the 3 configurations relative to the heating and cooling demand. It can be seen that the total energy demand goes from 13.01 kWh/m² for the Benchmark (a), to 10.48 kWh/m² for the passive configuration (b), to a value of 4.25 kWh/m² for the active configuration (c). Therefore, the passive and active configurations provide overall energy savings of 19% and 67% respectively if compared to a state of the art Spandrel element. Moreover, it is worthy to be mentioned that the active configuration might potentially reach the highest energy savings compared to the benchmark, especially in the winter period when the heating demand could be almost neutralised.

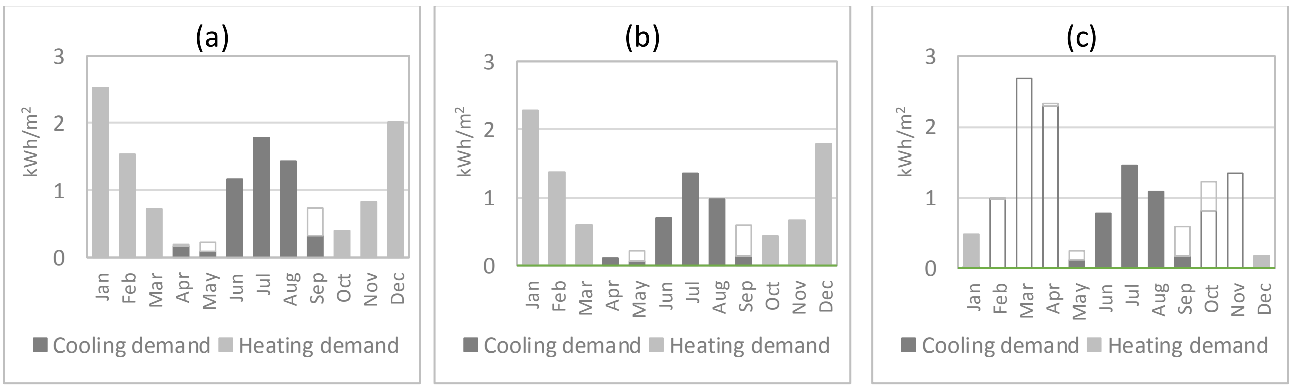

Figure. 5: In order: heating and cooling demand of Benchmark, Passive and Active configuration

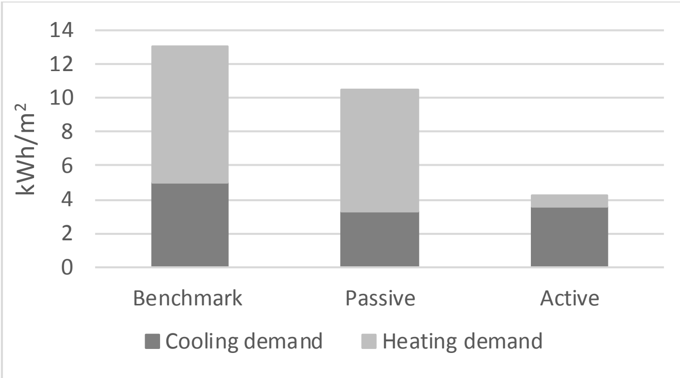

Figure. 6: Heating and cooling demand comparison

5. CONCLUSIONS

The goal of developing, through a process by phases, the design of opaque modules of Multifunctional Façade Modules characterised by a low thickness and high thermo-energetic performance was pursued integrating super-insulative elements, solar energy harvesting, latent heat storage materials and heat integrated heat generation device.
The analysis at building scale conducted through the simulation model developed with the WUFI® PLUS software and validated by means of the values obtained from the experimental tests on a multilayer component have permitted to extend the analysis at the building level by comparing different developed configuration with a standard state of the art opaque façade element (Spandrel).
The results shown that the use of the passive configuration, which involves the integration of a VIP and a PCM instead of a traditional spandrel, leads to a reduction in the overall thickness of the panels of 63% and energy consumption of 11% in heating demand and of 33% in cooling demand.
Whereas, the use of the active configuration, which also implement PV and integrated heating foil device, results in a reduction of 56% in thickness, of 92% in heating requirements and of 28% in the cooling demand.
However, it is important to highlight that the use of the active configuration requires a control system to maximise the use of the energy produced by the integrated photovoltaics.
These preliminary analyses, carried out in the framework of the Powerskin+ project, have represented a first step for the development of a truly innovative opaque façade component characterised by reduced thickness and very high energy performance. Within the research project, the ongoing activities are oriented to further optimise the technology and to demonstrate the system effectiveness under real operating conditions in different demo-buildings.

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