PCM Integrated in BiPV Ventilated Façade Concepts: Experimental Test Cell Platform and Initial Full-Scale Measurements

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\textbf{Abstract.} Recently, a wide range of novel façade solutions directly utilizing solar energy has been described as Building Integrated Photovoltaic (BiPV). However, there are still barriers (e.g. cells’ overheating) to overcome in order to promote widespread application of BiPV concepts. Therefore PV/PCM systems have been already studied to improve the performance of PV, however their integration in building (BiPV/PCM) is still not adequately investigated. In this regard, the main objective of this paper is to present one of the viable way of investigation a novel combination of BiPV/PCM. This can utilize PV cells cooling principle at behind of the BiPV layer in ventilated façade. The key research methods are based on the experimental and building energy simulation studies. For this purpose, a specific experimental test platform was developed to provide experimental measurements on ongoing long-term full-scale level in Brno, Czechia. Two types of ventilated BiPV façade are tested there with/without PCM layer behind the PV cells. The paper introduces the test platform which is used for evaluation of specific aspects of integrated PCMs in BiPV management and demonstrates the initial thermal response measurements. The influence of PCMs on the real performance of the BiPV façade and effectivity of application of latent thermal energy storage used on reduction of the peak operating temperatures of the PV modules as well as shifting of air temperature inside the façade cavity is analysed. Finally, the extensive measurements provide real performance data that will be used to verify the building energy simulations.

1. Introduction

Harvesting and utilization of solar energy by photovoltaic (PV) system is one of the most promising type of using renewable sources. Integration PV devices as external layer of façade systems has a still growing attention in building sector, mainly due to its on-site electric energy generator without noise and other disturbing effects. The symbiosis between exploitation of renewable energy sources and laws of building physics needs to be considered from more complex approach, specifically due to ensure its economically viable life-time. Building integrated photovoltaic (BiPV) systems applied into a building envelope limit their efficiency and durability due to insufficient cooling principles mainly during hot sunny days. Decreasing and mitigating PV operating temperature can be realized in two main ways (active or passive). Application of phase change material (PCM) on the rear side of PV module can
provide decreasing of PV temperature on the one hand and also thermal energy storage on the other. The storage is taking place in the certain range of melting/solidification temperature of PCM.

Novel type of façade system should be firstly tested by using certain experimental procedures before it will be subsequently applied in a real position through a building. Façade elements are multi-functional part of an overall building envelope system with various responses on different parts of outside climatic conditions. Basically, the façade's assessment can be performed by means of three main facility categories [1]: outdoor real-scale facilities, laboratory indoor facilities and outdoor test cells. Each has a specific advantage and disadvantage for the estimation of actual behaviour of building component.

The outdoor test cell was used in this research. It can fill gap between two other above mentioned test procedures, by allowing to keep the necessary indoor conditions (small volume of compensating space behind the test sample) without occupancy effects, while letting outdoor climatic conditions (fully mimic stochastic process typical for a certain climate zone). For this purpose, the experimental outdoor test cell has been created at Centre AdMaS, Brno University of Technology, Brno, Czechia, for measuring thermal and energy performance of novel type of façade.

2. **Integration of PCM into ventilated BiPV façade**

Each part of building envelope should be fine-tuning according to boundary conditions in both sides (exterior and interior) and its inertial dynamic changes or demands. Façade elements with PV cells provide on-site electricity production from impinging solar radiation, however from façade engineering point of view, thermal (latent) energy storage layer can significantly influence heat transfer process between interior and exterior, increase the thermal capacity of building as well as reducing cooling/heating demands. Elarga et al [2] developed a physical-mathematical model for simulation and evaluation of the dynamic thermal behaviour of the PV/PCM system in double skin façade. The integration of a PCM layer into the façade cavity leads to a reduction in the monthly cooling energy demand in the range of 20-30%, while the effect of PCM on the heating energy demand is limited. However, these results are particularly relevant for hot climate zones. Decreasing PV operating temperature leads to an increase in the electrical energy generation in the range of 5-8% when the façade system is equipped with the PCM.

Proper and viable integration of PCM layer into a certain façade system is very complex problem and big challenge for researches and scientific community. Waqas et al. [3] provided a comprehensive literature review about the current status of PV/PCM technology along with its research gaps and challenges. A review elaborates different aspects of this technology, such as system development, performance evaluation, PCM selection, heat transfer enhancement, simulation and application in practise. However, the PV/PCM system has not be experimentally tested in a ventilated façade type as an external cladding construction yet.

According to the above-mentioned works, BiPV/PCM façade system was developed and experimentally tested in this research. Two façade systems were investigated by using the outdoor test cell, building integrated photovoltaic (BiPV) ventilated façade with/without PCM layer at the rear side of PV module. The main observations were focused on the differences between BiPV and BiPV/PCM façades (heat energy flows). The intention of PCM integration is based on the assumptions, the first one, that the produced heat energy from PV module can be additionally stored in the PCM encapsulated in the certain structure of a container and the second one it provides mitigating peaks of PV operating temperature and simultaneously increasing PV efficiency [2]. Additionally, the façade cavity works as a thermal buffer zone, a ventilation channel or a combination of both [4] and is influenced by the PCM especially by thermal inertia point of view. Building heat energy transfers through the façade is still changing over the time and significantly affect energy flows in interior space. Thermo-physical interaction between both, typical BiPV and BiPV/PCM ventilated façades are demonstrated in figure 1. During hot sunny days, PCM absorbs heat from the PV and during night time it release away, this phenomenon is express by PCM temperature-enthalpy function which determinates amount of latent heat capacity during phase transition from solid to liquid phase.
The overall structure of BiPV/PCM system generally requires the higher values of thermal conductivity and heat capacity of PCM layer, due to ensuring the instantaneous heat dissipation from PV module. Development of this structure is quite complex problem, mainly for its realization (PCM volume expansion, proper heat transfer connection between PV and PCM layer) and was followed by the several research studies. Huang et al. [6] studied experimentally and numerically the effect of geometrical parameters of the PV/PCM system and internal metal fin design (in PCM layer) on thermal behaviour. It was concluded, that the using the fins in the PCM container has a significant effect for the uniform temperature distribution within the PV/PCM system. However, in some cases (very low PCM layer thickness), attaching fins inside the PCM can rapidly drop the PCM temperature, but its phase change takes place very quickly and as soon as the PCM is entirely molten thereupon the PV operating temperature rises very steeply [7]. Malvi et al. [8] investigated by their numerical study that a 10% increase of the PCM thermal conductivity can enhance the PV output by 3%. The principle of ensuring thermal stability by PCM in PV system it is necessary to study in detail the heat transfer processes involved in the system (figure 2).
3. Experimental outdoor test cell development

Ventilated façade element with integration of PCM has been experimentally tested in several positions of PCM layer within the façade construction. However, currently there have not been performed any experimental research studies with this type of BiPV/PCM façade structure, where the position of PCM layer is on the rear side of PV. Diarce et al. [10] carried out experimental measurements of ventilated active façade with PCM in its outer layer by means of a real-scale PASLINK test cell facility, located in the city of Victoria-Gasteiz in Spain. De Garcia et al. [11] experimentally tested the thermal performance of a ventilated double skin façade with PCM in its air channel, during the heating season in Puigverd de Lleida in Spain by using two identical house-like cubicles. Although, these two above-mentioned research studies were performed without PV module, it can provide better understanding for using PCM layer in ventilated façade system. Horn [12] experimentally studied non-ventilated mullion-transom BiPV façade type with PCM layer on the rear side of PV module by using outdoor test cell for one year. Pereira et al. [13] used Genetic Algorithm method for the BiPV/T-PCM system efficiency optimization which was installed in an office building façade. The results show that the system can achieve a maximum overall efficiency of 64% with winter and 32% with summer configuration.

In this research, the objective is to analyse and evaluate the influence of the façade system in the efficiency of the PV modules. The measurement campaign is carried out by means of experimental outdoor test cell created and located at Centre AdMaS. The test cell with outer dimensions (3.0 m × 2.43 m × 3.09 m) is specially developed for testing and studying advanced façade elements. Two façade samples (reference and experimental) is measured on south oriented part of the test cell with dimensions (3.0 m × 1.2 m). Initial structure of the test cell was only with four supporting steel columns on each edge of living type of a container with floor and roof. Parts of the envelope were necessary to make them separately (figure 3). The test cell outside three walls were separately mounted as lightweight structure filled with 150 mm mineral wool (with vapor and vapor-open membranes on sides) enclosed by gypsum board at inside and ventilated wood cladding at outside. The remaining south oriented wall was mounted also as lightweight structure filled with 100 mm mineral wool enclosed by gypsum board at inside and wooden supporting elements for PV cladding at outside (figure 4). Internal compensation spaces were created for detailed investigation of the façade systems by means of internal heat comfort. The spaces (1.2 mm × 1.0 mm × 2.3 mm) are mounted behind each façade sample, thermally insulated (50 mm polystyrene) and separated from each internal structure, due to influence of other heat transfer processes. Thermally-controlled space around the compensation spaces is ensured by one local heating/cooling unit.

Figure 3. Sequential process of creating envelope of the outdoor test cell.
The measurements apparatus is divided into two separated groups according to different energy flows. The first group consists of 40 sensors connected to the data acquisition station and it collects data related to thermal (temperatures) and fluid dynamic (air flow movement in the façade cavity) phenomena. The arrangement of thermal sensors is depicted in figure 5. Inside the compensating space is installed one black ball thermometer and on the experimental wall is mounted heat flux sensor. These acquired data will be used for the performance assessment of the façade in terms of heat transfer and thermal comfort phenomena.

The second group is related to performance of electricity production from façade PV modules that consists two inverters, each for the one PV string (BiPV façade – the first string, BiPV/PCM façade – the second string). PV models in one string are interconnected in serious electrical connection and directly connected to the inverter according electrical scheme depicted in figure 6. The inverter has MPP (Maximum Power Point) tracker with the voltage range (80 ~ 450 V) and equipped with Wireless monitoring and communication. Both groups will used for assessment of energy efficiency (heat and electric energy) as well as for validation of simulation model in a certain computational software.

**Figure 4.** Supporting construction for investigated façade systems on the outdoor test cell.

**Figure 5.** Fragment of ventilated BiPV/PCM façade with arrangements of sensors.
4. Experimental results

The first insight into experimental results were achieved under real outdoor conditions for one selected day (28.8.2018) with high solar radiation and high outdoor temperature in summer time. The façade cavity (120 mm width) was only naturally ventilated, where the air flow moving was ensured by two opens at the bottom and top of the façade. The time step used by the data acquisition station was set by one minute. The main attention was focused on the PV operating temperature (thermo-couple placed on the rear side of PV module) with PCM layer in comparation with reference sample BiPV without PCM. Integration of PCM layer can decrease PV operating temperature during hot outside peak temperature (figure 7). Significant distinction between tested samples was in their overall thermal capacity which was demonstrated on the overall heat fluxes through façades (figure 9) as well as on the air temperature in the façade cavity at the top position of PV modules (figure 8).

![Figure 6. Basic electrical scheme for PV panels connections.](image)

![Figure 7. Influence of PCM layer on the PV operating temperature in BiPV/PCM, BiPV façade.](image)
5. Conclusion
The novel type of ventilated BiPV/PCM façade system was presented with the construction and building heat transfer principles. Appropriate characterization and energy performance of the investigated façade is provided by the certain experimental campaign. The presented outdoor test cell with the measurements apparatus has suitable properties for the proper investigation in real climatic conditions. According to the first insights of the experimental results, the maximum decreasing of peak PV operating temperature is around 14 °C by using PCM layer, and around 5 °C of air temperature in façade cavity (absorbing
latent heat energy). Heat fluxes through the façade with PCM is quite low in comparison with reference sample without PCM by 3 W.m⁻² (thermal inertia, delaying). However, during the night time, the air temperature inside the façade cavity is a bit high about 2 °C due to emitting heat energy (PCM solidification) as well as the function of heat fluxes. The main problem during the realization of test sample is connection between PV panel and aluminium container with PCM, which should be performed as a solid connection without any small cavities (radiation and free-convection heat transfer), otherwise the heat dissipation will be decreasing.

Overall, the PCM integration presented in this study shows potential of application in BiPV ventilated façade concepts and further research will focus on detailed analysis of long-term experimental measurements and numerical modelling. A comparison between the results obtained experimentally and from the building energy simulation will also allow validating further changes made in the tested BiPV concept.

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