International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 407

Parametric study on thermal management of BIPV ventilated double glass façade with PCM elements

T. Žižak[1*], C. Arkar[1], S. Domjan[1], S. Medved[1]
University of Ljubljana, Faculty of Mechanical Engineering, Laboratory for Sustainable Technology in Buildings
*corresponding author. E-mail address: tej.zizak@fs.uni-lj.si

ABSTRACT

This study evaluates the cooling effect of latent heat storage (PCM) on integrated PV cells between two glass layers in a double-glazed ventilated building-integrated photovoltaic (BIPV) façade. Transient CFD simulations were performed to investigate the potential of thermal management. The varying parameters were: PCM thickness, PCM thermal conductivity, PCM latent heat storage capacity, BIPV glass thickness, and air velocity in the ventilated gap. A regression model with interactions was made for evaluating the relative impact of thermal management on overheating hours compared to a reference system without PCM. The results show the importance of enhancing the thermal conductivity of PCM, with the greatest impact in the initial enhancement and neglectable effect at higher values above roughly 1 W/mK.

Keywords: PV cell cooling, Building-integrated photovoltaics, Phase change materials, parametric modelling

NONMENCLATURE

Abbreviations	
BIPV	Building Integrated Photovoltaics
CFD	Computational Fluid Dynamics
PCM	Phase Change Materials
PV	Photovoltaic
Symbols	
$d_{glass,s}$	thickness of single glass layer
d_{PCM}	thickness of PCM
$G_{glob,90}$	solar radiation on vertical surface
$H_{l,PCM}$	latent heat storage capacity of PCM
λ_{PCM}	thermal conductivity of PCM
rel_OHH_{PV}	relative overheating hours of PV cells
T_e	temperature of outside air
T_{PV}	temperature of PV cells
v_{gap}	velocity of air in the gap

1. INTRODUCTION

International agreements, such as the Paris Climate Agreement [1], the European Green Deal [2], and the European Building Directive [3] present ambitious goals for decreasing pollutant emissions, including CO_2. With the building sector responsible for 40% of final energy use [2], new technologies and/or improvements to existing technologies will be required. In addition to the need for new and refurbished buildings with low primary energy demands, the utilization of local renewable energy sources is needed to achieve net Nearly Zero Energy Buildings.

Solar energy utilization with building-integrated photovoltaic (BIPV) systems promises energy savings in urban environments [4]. As the efficiency of PV cells decreases with increasing temperature, recent research has been focused on PV cell cooling. A combination of latent heat storage (PCM) and a ventilated gap has proven to lower the PV cell peak temperatures, with authors reporting an increase in electricity production up to 20% [5,6]. However, the most significant improvement was in the cases in which PCM material with enhanced thermal conductivity was used and/or the PCM material was placed directly on the back side of the PV cells, without the glass layer, which is not the case of glazed BIPV structures studied in the presented research.

One problem of PCM materials is their relatively low thermal conductivity at around 0.2 W/mK, which results

Selection and peer-review under responsibility of the scientific committee of the 12th Int. Conf. on Applied Energy (ICAE2020).

in slow heat transfer. Thermal conductivity enhancement can be done by adding fins or (nano)particles with high thermal conductivity. Gil et al. [7] have reported a 25% enhancement of effective thermal conductivity by adding fins to thermal storage elements. The addition of different nanoparticles can substantially improve the thermal conductivity; for example, Li [8] reported an increase to 0.936 W/mK for paraffin with the addition of nano-graphite particles. Tian et al. [9] reported an enhanced thermal conductivity of 2.09 W/mK for paraffin-based PCM with an addition of carbon fibers and expanded graphite.

Kant et al. [6] have studied the energy generation of forced-ventilated opaque BIPV with PCM at different operation conditions and PCM properties. Optimal parameters were not found in the range of parameters values. General conclusion of the study is that PCM with higher thermal conductivity and higher latent heat capacity is more effective.

Although Medved et al. [10] studied the impact of PCM inserts on ventilated glazed BIPV structures, their study was limited to constant radiative and convective surface heat transfer coefficients, constant latent heat storage capacity and fixed front and back BIPV glass layer geometry.

1.1 Goals of the research

Because in a previous study [10] it was found that PCM inserts could increase the PV cell overheating, the present study shows the boundary conditions of impact parameters that lead to decreased PV cell overheating using PCM heat storage installed on the BIPV inner glass layer in the case of integrated photovoltaic cells between two glass layers of a double-façade ventilated structure.

2. OBJECT OF RESEARCH

2.1 CFD simulation model and boundary conditions

The object of research is a ventilated BIPV glazed façade system as shown in Fig 1. PV cells are integrated between two glass layers with a packing factor of 60%. A ventilated gap separates the BIPV element and triple glazing element towards the inside of the building.

Transient numerical simulations were performed with PHOENICS CFD software. The problem is treated as being two-dimensional. Boundary conditions of solar radiation on vertical surface $G_{glob,90}$ and outside air temperature T_e were taken from experimental measurements on a clear sunny day and are shown in Fig 2. Solar radiation was modeled as an internal source inside each glazing element and PV cell surface according

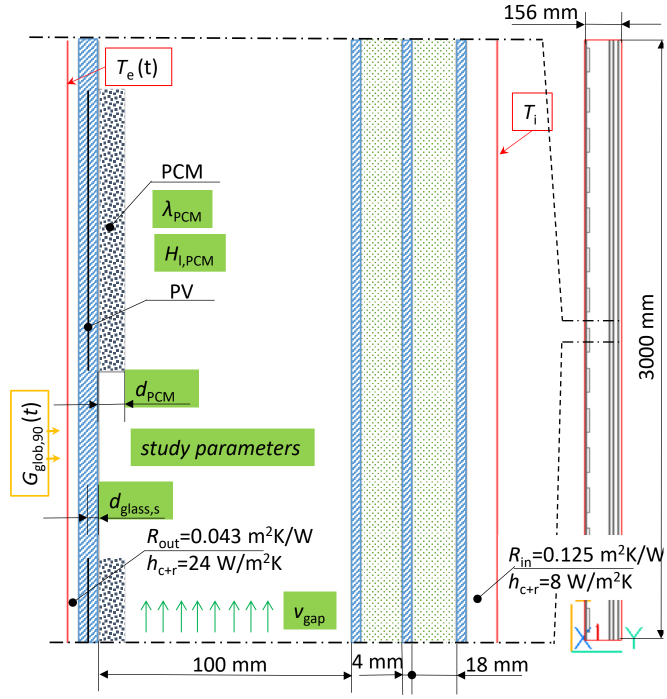

Fig 1 CFD model scheme with boundary conditions, varying parameters are presented in green frames.

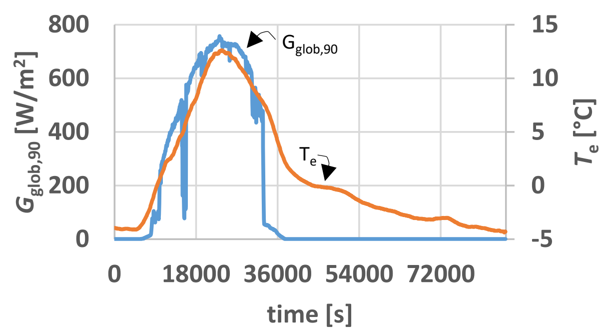

Fig 2 Boundary conditions used as representative sunny day

to absorption factors taken from WINDOW 7.6. Software. Outside and inside boundary conditions are modeled as constant combined surface heat transfer coefficients. Outside temperature and solar radiation sources are modeled as discrete values for each time step, which is 300 seconds. Inside air temperature is constant at 22°C.

PCM elements were placed on the inside of the BIPV facade with the same proportion as PV cells, no additional shading is assumed. The thermal response of latent heat storage is modeled as a change of specific heat capacity of material according to its temperature. The shape of the specific heat capacity curve is taken from manufacturers' data and experimental measurements [10]. For different latent heat storage capacity parameters (see chapter 2.2.), the temperature range of the phase change remains the same, but the specific heat capacity values are multiplied by a factor accordingly. For all cases, the phase change temperature (peak of specific heat) is 25°C. As microencapsulated paraffin is assumed, the convection of the liquid phase is not modeled.

2.2 *Parametric modeling*

Simulations were designed with a Taguchi orthogonal array experimental design for minimizing the computational cost. Five chosen parameters with four levels result in an L16 orthogonal array meaning 16 simulations. Eight more simulations were made with parameters that had the most significant contribution to increase the accuracy.

The parameters (and levels) considered in the study are: BIPV single glass layer thickness $d_{glass,s}$ (2mm, 3mm, 4mm, 5mm), velocity of air in the gap v_{gap} (0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s), thickness of PCM d_{PCM} (5.2 mm, 10.4 mm, 15.6 mm, 20.8 mm), thermal conductivity of PCM λ_{PCM} (0.2 W/mK, 0.8 W/mK, 1.4 W/mK, 2 W/mK), latent heat storage capacity of PCM $H_{l,PCM}$ (20 kJ/kg, 80 kJ/kg, 140 kJ/kg, 200 kJ/kg)

The assessment indicator used in this study is overheating hours of PV cells OHH_{PV} during the representative sunny day:

$$OHH_{\mathrm{PV}} = \int_{sunrise}^{sunset} (T_{\mathrm{PV}} - 25°C)\,\mathrm{d}t$$

The effect of thermal managing by PCM was determined by relative OHH improvement comparing façade structures with PCM to the glass BIPV structure as reference case:

$$rel\_OHH_{\mathrm{PV}} = \frac{OHH_{\mathrm{PV}} - OHH_{\mathrm{PV,ref}}}{OHH_{\mathrm{PV,ref}}}$$

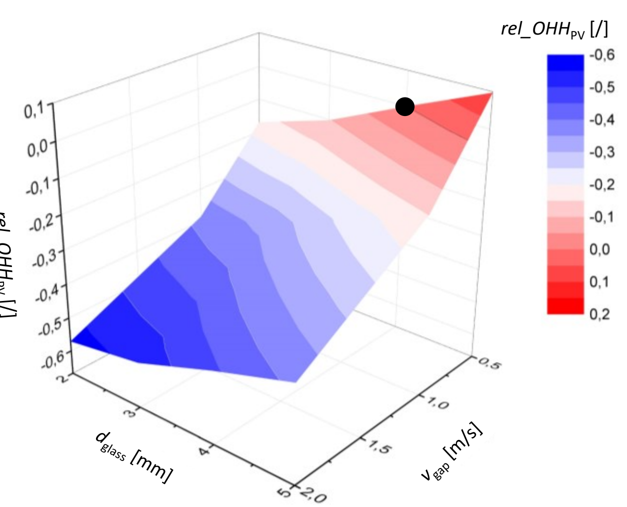

Fig 4 BIPV structure without PCM.

Where negative values indicate cases that lead to decreased overheating of PV cells.

The reference structure was chosen to be BIPV with 4 mm ($d_{glass,s}$) + 4mm thick double glass layer without PCM. Based on the results of the simulations, two multiple regression models with interactions were constructed, with variables (p-value lower than 0.05): $d_{glass,s}$ and v_{gap} for BIPV structure model and d_{PCM}/λ_{PCM}, $d_{PCM} \cdot H_{l,PCM}$, $d_{glass,s}$, v_{gap} and d_{PCM} for BIPV structure with PCM model. Statistical indicator R^2 for the regression models are above 0.97.

3. RESULTS

3.1 *Parametric study of BIPV without PCM*

Fig. 4 shows the effect of air velocity in the ventilated gap and the thickness of the single glass layer on the relative overheating hours of BIPV structure without PCM. The reference system has the thickness of $d_{glass,s}$ equal to 4 mm, while natural convection was assumed with v_{gap} 0,5 m/s(● in Fig. 4). It can be seen that with the increase of thickness, overheating hours increase, while the increase of velocity has the opposite effect as overheating hours decrease. At the lowest observed $d_{glass,s}$ and the highest v_{gap}, rel_OHH_{PV} is reduced by 55%.

3.2 *Parametric study of BIPV with PCM*

Fig 5. shows the impact of PCM parameters on the rel_OHH_{PV}. With the increase of latent heat storage capacity of PCM, the rel_OHH_{PV} is decreased. For example, a PCM with thermal conductivity of 1.0 W/mK and thickness of 10.2 mm results in roughly 10% fewer

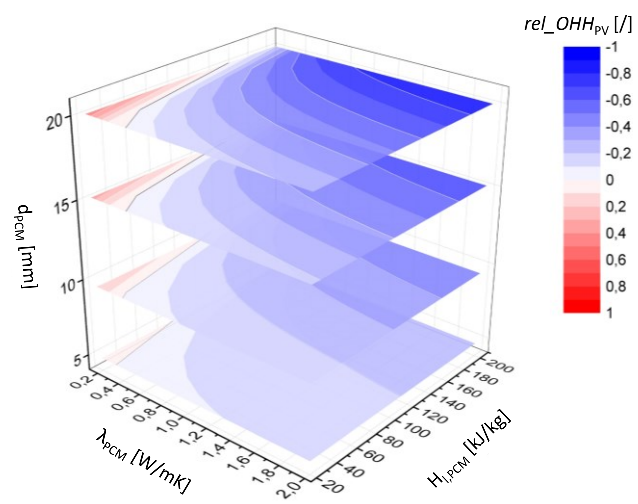

Fig 5 BIPV structure with PCM: v_{gap}=0.5 m/s, $d_{glass,s}$ =4 mm, varying PCM parameters.

overheating hours (rel_OHH_{PV}=-0.1) with latent heat capacity 20 kJ/kg and 20% fewer with latent heat capacity 80 kJ/kg comparing to BIPV structure without PCM. An increase in thermal conductivity also decreases rel_OHH_{PV}; however, the effect is not linear, and after roughly 1 W/mK the conductivity effect curve flattens substantially. For conductivities at around 0.2 W/mK, the addition of PCM material in most cases does not lower the overheating hours compared to reference without PCM for the studied case of integrated PV cells between two glass layers.

Figure 6 shows the impact of increasing the PCM thickness. The increase in thickness will further decrease the rel_OHH_{PV} for the cases where at minimal thickness of 5.2 mm and the right combination of thermal conductivity and latent heat capacity the rel_OHH_{PV} is negative. An example of such combination is thermal conductivity of 0.38 W/mK and latent heat capacity of 140 kJ/kg, which at 5.2 mm thickness results in 12% fewer (rel_OHH_{PV}=-0.12) and at 20.8 mm 31% fewer overheating hours compared to BIPV structure without PCM.

Fig. 7 shows the effect of glass thickness and velocity in the gap on rel_OHH_{PV}. Thicker glass in the BIPV structure increases rel_OHH_{PV}. PCM inserts will improve properties of BIPV structure if glass layer is thinner than 4.5 mm at any air velocity in the ventilated gap. Surface heat transfer coefficients on the PCM inserts are lower due to the lower surface temperature comparing to the inner glass temperature in case of BIPV without PCM, which can be observed as an increase of rel_OHH_{PV} with increased air velocity in the ventilated gap.

Fig. 8 shows the effect of glass thickness and velocity in the gap on rel_OHH_{PV} for the case of PCM with high thickness, high thermal conduction, and high latent heat capacity. In this case, PCM decreases overheating hours compared to the reference BIPV without PCM in the whole range of studied parameters, with more than 50% fewer overheating hours for single layer glass thicknesses lower than 4 mm compared to the reference BIPV without PCM.

CONCLUSION

This paper presents a sensitivity analysis of thermal management of PV cell temperature according to construction parameters of the double-skin glass BIPV façade structure and thermal properties of PCM based on the PV cell overheating hours. According to authors' knowledge, such a structure has not yet been studied.

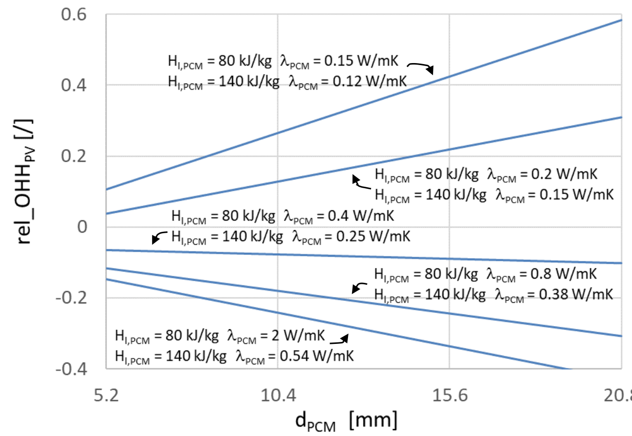

Fig 6 BIPV structure with PCM: v_{gap}=1 m/s, $d_{glass,s}$=4 mm.

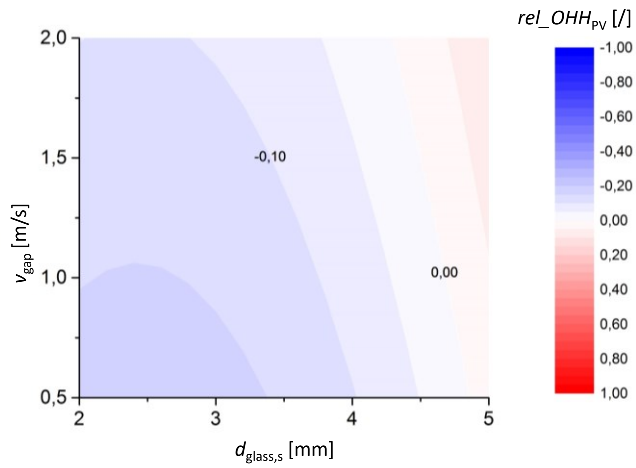

Fig 7 d_{PCM}=5.2 mm, λ_{PCM} =0.6 W/mK, $H_{l,PCM}$=60 kJ/kg

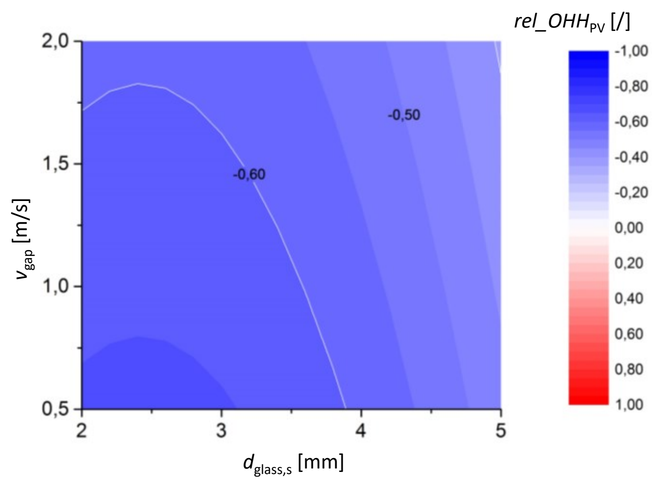

Fig 8 d_{PCM}=20.8 mm, λ_{PCM} =1.0 W/mK, $H_{l,PCM}$=140 kJ/kg.

The research clearly shows the directions for developing more efficient BIPV facades as well as the limitations of thermal management of PV cell efficiency regarding the PCM material properties. In further research, general meteorological conditions will be studied as well as the impact of dynamic meteorological conditions on thermal managing of ventilated glass BIPV façade structures.

REFERENCE

[1] The Paris Agreement; United Nations Framework Convention on Climate Change, UN, 2020.

[2] The European Green Deal; EC, Brussels, 2019.

[3] Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency; EU Brussels, 2018.

[4] Young TC, Jeehwan K, Hongsik P, Byungha S. Building energy performance evaluation of building integrated photovoltaic (BIPV) window with semi-transparent solar cells. Applied Energy 2014;129:217-227.

[5] Indartono YS, Suwono A, Pratama FY. Improving photovoltaics performance by using yellow petroleum jelly as phase change material. International Journal of Low-Carbon Technologies 2016;11:333–337.

[6] Kant K, Pitchumani R, Shukla A, Sharma A. Analysis and design of air ventilated building integrated photovoltaic (BIPV) system incorporating phase change materials. Energy Conversion and Management 2019;196:149–164

[7] A. Gila, G. Peiróa, E. Oróa,c, L. F. Cabeza: Experimental analysis of the effective thermal conductivity enhancement of PCM using finned tubes in high temperature bulk tanks. Applied Thermal Engineering 142 (2018) 736-744.

[8] M. Li, A nano-graphite/paraffin phase change material with high thermal conductivity, Appl. Energy 106 (2013) 25–30.

[9] B. Tian et al., Synergistic enhancement of thermal conductivity for expanded graphite and carbon fiber in paraffin/EVA form-stable phase change materials, Sol. Energy 127 (2016) 48–55.

[10] S. Medved, C. Arkar, S. Domjan, T. Žižak: Performance of multilayer glass and BIPV façade structures. In: Eco-efficient Materials for Reducing Cooling Needs in Buildings and Construction: Design, Properties and Applications; A volume in Woodhead Publishing Series in Civil and Structural Engineering. Elsevier B.V., pp. 169-202.