7th International Building Physics Conference

IBPC2018

Proceedings

SYRACUSE, NY, USA

September 23 - 26, 2018

Healthy, Intelligent and Resilient Buildings and Urban Environments

ibpc2018.org | #ibpc2018

PV-PCM system integrated into a double skin façade. A Genetic optimization based study for the PCM type selection.

Hagar Elarga[1*], Andrea Dal Monte[2], Francesco Goia[3], Ernesto Benini[2]

[1]Denmark Technical University-DTU, Denmark
[2]University of Padova, Italy
[3]Norwegain University of Science and Technology, NTNU, Trondheim, Norway

[*]*Corresponding email: Hagel@byg.dtu.dk*

ABSTRACT
This paper reports the results of a genetic optimisation based numerical analysis of a PV-PCM system integrated into a double skin façade. The aim of the research activity was to develop and test the performance of a proposed simulation approach to identify the optimal configuration of the PCM layer, in terms of temperature transition range, and thickness, to assure the best energy performance of the façade system.
Furthermore, because of the intimate relationship between the PCM's features and the ventilated cavity to define the performance of the façade system, the domain of exploration included as variable the airflow rate and ventilation schedule.
The evaluation of the performances of the PV-PCM glazed facade is carried through an on-purpose developed, transient 1-D (with finite difference method) heat transfer model, which integrates a suitable representation of the PCM's system (through the so-called enthalpy method) to include the thermophysical behviour of such a type of materials. This numerical model is implemented in MATLAB and coupled to TRNSYS in order to calculate the dynamic thermal energy profiles of a fictitious building equipped with such a façade.
The subsequent single objective optimization is based on a genetic algorithm, which looks for the best PCM type and schedule of ventilation in order to optimize the summer thermal energy performance in two case-study cities, Venice and Chicago.
The results show how the proposed genetic optimisation algorithm is capable of identifying the most suitable configuration (that differs in each climate) after a relatively small number of generations (ca. 25). Furthermore, the optimisation approach used in this study leads to the identification of configurations capable of assuring a reduction in the cooling energy need (objective function) in the range 28% to 19 %, when compared to non-optimal configurations, for the two case-study cities.

KEYWORDS
Simulation based optimization, PV-PCM modules, PCM type, Buildings energy savings.

INTRODUCTION
Designers often use dynamic thermal simulation programs to analyse thermal and energy behaviours of a building and to achieve specific targets, e.g. reducing energy consumption, environmental impacts or improving indoor thermal environment (Garber, 2009). Two approaches are commonly considered at the simulation process. The first is the parametric method, which consists of changing the input of one variable at a time to evaluate the effect on the design objectives, while all other variables are kept unchanged. It is often time-consuming and it only results in partial improvement because such an approach cannot fully consider the complex and non-linear interactions of different variables in the simulation (Nguyen et al,

2014). The second approach is the simulation-based optimization and it usually achieved through iterative methods, which construct infinite sequences of progressively better approximations to an "optimal" solution, i.e. a point in the domain of possible values that satisfies an optimality condition (Wetter, 2009). The optimization of Phase change materials (PCMs) technology implementation has been the centre of attention of many researchers due to its exclusive assets for thermal regulation of buildings (Cascone et al.2018 and Soares et al., 2014). Huang et al. (2014) performed an optimisation of the thermal properties of an envelope in an energy-saving renovation of existing public buildings. They concluded that the performance parameters for the renovation of existing buildings should be determined for each orientation. Ascione et al. (2014) carried out a study on the retrofitting of an office building in which they added a PCM plasterboard to the inner side of its exterior envelope. It was found that a refurbishment, by means of PCM wallboards, seemed to be more appropriate for a semi-arid climate. Ramakrishnan et al. (2016) performed a parametric optimization for the retrofitting of a typical Australian residential building by installing bio-PCM mats on the ceiling. The investigated variables included, the phase transition temperature, the thickness of the PCM layer and the night ventilation rate that guaranteed the best indoor thermal comfort. It was found that depending on the climatic condition, the optimal phase change temperature was about 3–5 °C higher than the average outdoor air temperature. Furthermore, selection of a proper PCM thickness and night ventilation are important to maximise PCM efficiency and minimise costs. Saffari et al. (2017) have investigated optimum PCM melting temperature of a wallboard integrated into a residential building envelope. It has been concluded that the proper selection of PCM enhanced gypsum technology as integrated passive system into the building envelopes. Soares et al. (2014) have concluded that 10% to 62% savings in energy consumption can be achieved utilizing PCM passive technology through building prototypes located in warm temperate climates. However, few of the available modelling studies concerning the implementation of PCM-PV systems make use of simulation-based optimization.
The present simulation based optimization is an extension of previous works (Elarga et al., 2017). Optimizations were automated by coupling between the dynamic building simulation model, the PV-PCM façade module and the optimization engine. A library of 18 PCM types containing the specifications and thermal characteristics of these materials (obtained from Rubitherm) has been integrated in the algorithm and the optimization has run for two cities Venice and Chicago.

METHODS

The optimization numerical approach consists of two steps: the pre-processing phases and the optimization phases.

- The Pre-processing step included the following elements.

The definition of a fictitious double skin façade that integrates a PV-PCM system where the façade consists of outer clear glass layer (g1) with a thickness of 8 mm and U value of 5.3(W/m^{2}K), middle and inner glass layers (g2 &g3) with a thickness of 4mm and U value of 5.6(W/m^{2}K). The applied Cavity ventilation technique is outside to outside and the considered PV-PCM area equals 70m^2 which is 100% from the overall façade area, a future study will address the optimum façade composition percentage, scheme is illustrated in Figure 1a.

- The modelling and the definition of the design conditions of a double glazed skin, ventilated facade office zone area of 80m^2 was carried out with TRNSYS software (Klien et al. 2004).
- Since TRNSYS does not include a defined TYPE to model a glazed PV-PCM facades, it was necessary to separately model the PV-PCM façade in MATLAB. This model is based on a finite difference method scheme (based on a grid with 15 fixed nodes grid as shown in Figure 1b. Each glass layer has been represented by 2 nodes and for the PCM layer a sensitivity analysis has been carried out to estimate the required nodes number i.e. 5 nodes, combined

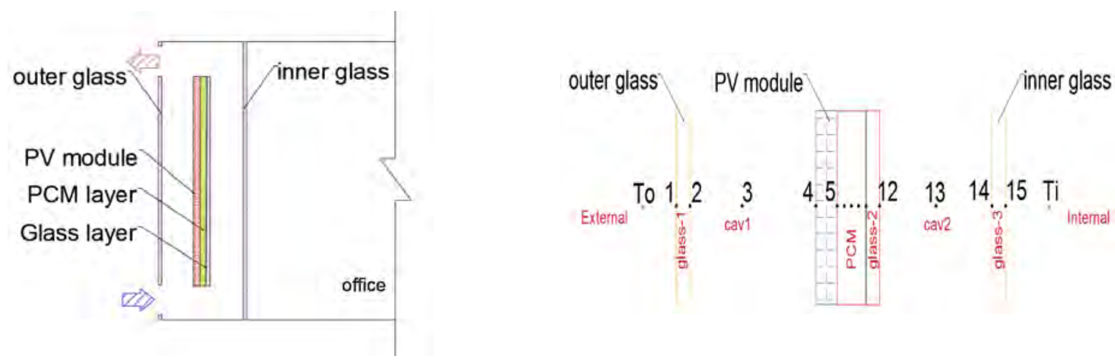
with the enthalpy method (Voller, 1997) in order to model the non-linear behaviour of the PCM layer. For more details, refer to (Elarga et al., 2016). The governing equations are:

$$C^A = \frac{dH}{dT} = \begin{cases} c_s & T \leq T_{m-\epsilon} \\ \left[\frac{c_s + c_l}{2} + \frac{L}{2\,\epsilon}\right] & T_{m+\epsilon} < T < T_{m-\epsilon} \\ c_l & T \geq T_{m+\epsilon} \end{cases} \quad (1)$$

Where:
ϵ: is an arbitrarily small value representing half the phase change temperature interval.
c_s : Solid specific heat capacity
c_l : Liquid specific heat capacity
H: Enthalpy

$$\sum a_{nb}\, T_{nb} - (a_p + \rho\, C^A) T_p{}^n = a_p\, \rho\, C^A\, T_p{}^{n-1} - \rho \cdot \frac{v}{\Delta\tau}\left[H_P{}^{\circ} - H_P{}^{n-1}\right] \quad (2)$$

Where:
$H_P{}^{\circ}$: Enthalpy node value of the previous time step
$H_P{}^{n-1}$: Enthalpy node value of iteration n-1
T_p : Nodal temperature value
a_{nb}: Nodal coefficients of neighbor nodes to control volume P
τ: Time Step
T_{nb}: Nodal Temperature of neighbour nodes to control volume P



a) b)

Figure 1: a) Sketch of the glazed PV-PCM façade; b) PV-PCM façade with fixed nodal grid

The integration between the MATLAB model and the TRNSYS model has been carried out using TYPE155 from TRNYS library, which reads external codes executed by MATLAB. The numerical algorithm starts by linking the required weather condition from TYPE16 to both the MATLAB and the zone built in TRNbld TYPE-56. Generally, it is mandatory to link the weather to TYPE-56 in order to operate the simulation model. On the other hand, for each listed inner zone on TYPE-56, there is availability to set its input data and boundary conditions as a user defined option. The PV-PCM 1D numerical code estimates the temperature and transmitted solar radiation for each of the fixed grid nodes including the last node which represents the inner surface layer temperature i.e. node 15. However, the transient interface between TRNSYS and MATLAB models occurs in air node 13. Climatic data of the Test Reference Year (TRY) are then used. For the case study presented in this paper, TMY for Chicago and Venice were adopted. The Optimization step included the following elements:

- Setting the objective function: the objective function is the reduction of required thermal energy for cooling purpose during summer season. However, in the present study, the simulation has run for the entire year to assure PCM thermal storage and transition consistency.
- Selecting and setting independent (design) variables that are part of the domain of search: *i)* PCM layer thickness, *ii)* schedule and starting hour of cavity ventilation, *iii)* PCM type selected from the integrated 18 PCM types library on-purpose developed for this study. The technical data of the PCM list are shown in Table1:

Table 1 List of properties of 18 commercial-grade PCMs (source: Rubitherm GmbH))

Type	temp/ storage cap.	Type	temp/ storage cap.	Type	temp/ storage cap.
PCM-1	21°C /155kJ/Kg	PCM-7	25°C /180kJ/Kg	PCM-13	43°C /250kJ/Kg
PCM-2	21°C / 190kJ/Kg	PCM-8	28°C /250kJ/Kg	PCM-14	46°C /165kJ/Kg
PCM-3	22 °C/190kJ/Kg	PCM-9	31°C /165kJ/Kg	PCM-15	49°C /160kJ/Kg
PCM-4	24°C /160kJ/Kg	PCM-10	33°C /160kJ/Kg	PCM-16	54°C/200kJ/Kg
PCM-5	25 °C/170kJ/Kg	PCM-11	35°C /240kJ/Kg	PCM-17	55°C /170kJ/Kg
PCM-6	25°C /230kJ/Kg	PCM-12	41°C/165kJ/Kg	PCM-18	60 °C/160kJ/Kg

- Selecting an appropriate optimization algorithm and its settings: the adopted optimization algorithm was the mono-objective (MATALB-GA) and it was set to consider 6 design variables (mass flows of cavity 1 and 2, PCM type, PCM thickness and ventilation schedule in terms of starting hour and duration). The imposed lower and upper boundaries represent the space of exploration of the design variables, as reported in Table 2. The population consists of 20 individuals and the analysis run for 50 generations.

RESULTS

Optimization solutions evolution through generations

The mono-objective optimizations ran for 50 generation and succeeded in archiving an improvement for both the considered cities. The convergence trends show some similarities, with an important decrease of thermal load approx. (-16% for Chicago, -40% for Venice) reached around the 5th generation. After this, the optimization further improves the thermal performances by small steps. Finally, the overall decrease in thermal load is 17% for Chicago and about 43% for Venice.

Analysis of best solution

The best solution for each city is defined by the set of variables that led the minimum required thermal loads. For Venice city, the best individual was: PCM type-16 with melting temperature of 54°C and a storage capacity of 200 kJ/Kg; a PCM thickness of 0.03m; a ventilation duration of 18 hrs. The ventilation schedule has allowed an efficient PCM melting/solidification cycle to be exploited in order to take advantage of higher values of the material heat storage capacity occurred only during this transition. Seasonal cooling thermal loads have reached in this case 2793 kW h. Optimization of PCM dimensions was important to be investigated: the expected weight for this PCM layer in Venice case is about 0.072kg for a PV module area of (2m x 1.5m). On the other hand, in Chicago, the optimum solution was found to be: PCM Type 17 of 55°C melting temperature and 170 kJ/Kg storage capacity; PCM thickness of 5mm. With a ventilation schedule of 18 hrs, cooling thermal loads have reached 2622 kW h and the layer weight equals 0.012kg for PV module area of (2m x 1.5m).

Table 2: Optimization upper and lower pounds

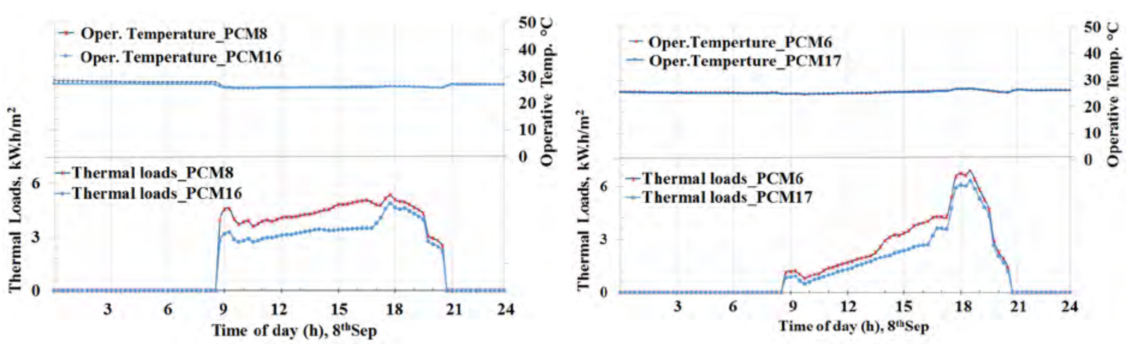
	cav1 kg/s	cav2 kg/s	PCM type	PCM thick m	Vent. start hr	Vent. duration hrs
Lb	60	60	1	0.001	12:00am	0
Ub	360	360	18	0.1	11:45am	5

Table 3: Best solution of variables

City	cav1 kg/s	cav2 kg/s	PCM type	PCM thick m	Vent. start hr	Vent. duration hrs
Venice	0.2	0.09	16	0.03	9:00am	10
Chicago	0.15	0.10	17	0.005	10:00am	9

DISCUSSIONS

The influence of the PCM type on the building configuration has been highlighted through a parametric study its only variable is the PCM type. While, the best solutions achieved through the optimization process remains constant (Table 2). In Venice, for the same indoor air operative temperature, seasonal thermal loads of the best configuration, 2.0 kW h m^{-2} (PCM-16), are increased up to 2.6 kW h m^{-2} by implementing a non-optimized type (PCM- 8), see Figure 3a. Furthermore, the energy savings for the overall season is 28% if the optimized (PCM-16) and non-optimized solution (PCM-8) are compared. In a similar way, the daily cooling energy consumption in Chicago (1.5 kW h m^{-2} in the best case) is increased up to 1.8 kW h m^{-2} when a different type is adopted (PCM-6) (Figure 3b) and the seasonal energy savings are 19% when the optimal solution is compared to a non-optimal one.



a) b)

Figure 2: Daily thermal loads and operative air temperature profile a) Venice, b) Chicago

CONCLUSIONS

The ventilation schedule, proper selection of the type and layer thickness of PCM are among the fundamental design parameters to achieve an efficient implementation of the latent heat storage technology in buildings. The present mono objective algorithm has focused on minimizing the cooling energy requirements of an office building at Venice and Chicago. The optimized solutions have been analysed varying only the PCM type through a parametric study. It has been shown that thermal energy savings could be achieved by selecting the proper PCM type. However, designers may also need to evaluate different trade-off settings, taking into consideration multidisciplinary aspects and their interactions in order to identify the best, suitable, solutions. Accordingly, the present optimization algorithm might be increased in comprehensiveness to include more objectives such as the indoor comfort, the PV electrical performance, the cost of the material and the electrical consumption of the ventilation system; façade composition leading to a multi-objective optimisation process, where the complexity lies in the definition of the optimisation function.

REFERENCES

Ascione F, Bianco N, De Masi RF, de Rossi F, Vanoli GP.2014. Energy refurbishment of existing buildings through the use of phase change materials: energy savings and indoor comfort in the cooling season. *Applied Energy*, Vol.113, pp. 990–1007.

Cascone Y., Capozzoli A., Perino M, 2018. Optimisation analysis of PCM-enhanced opaque building envelope components for the energy retrofitting of office buildings in Mediterranean climates. Applied energy, Vol.211, pp. 929–953.

Elarga H., Goia F. and Benini E., 2017. PV-PCM integration in glazed buildings. Numerical study through MATLAB/TRNSYS linked model" in *Building Simulation Application conference, Bolzano Italy*, vol. 3, https://www.researchgate.net/publication/313572061.

Elarga H, Goia F., Zarrella A., Dal Monte A., and Benini E., 2016. Thermal and electrical performance of an integrated PV-PCM system in double skin facades: A numerical study, *Solar Energy*, Vol. 136, pp.112-124.

Elarga H., Monte A.D., Andersen R. K, Benini E., 2017. PV-PCM integration in glazed building. Co-simulation and genetic optimization study, *Building and Environment* Vol 126, pp. 161-175

Garber R. 2009. Optimization stories: the impact of building information modelling on contemporary design practice. *Architectural Design,* Vol. 79, pp. 6–13.

Huang J, Lv H, Gao T, Feng W, Chen Y, Zhou T. 2014. Thermal properties optimization of envelope in energy-saving renovation of existing public buildings. *Energy and Buildings* Vol.75, pp.504–510.

http://www.rubitherm/

Klien S., Beckman W., Mitchell J., Due J., DueN., Freeman T., Mitchell J., Braun J., Evans B. , Kummer J., 2004. "Trnsys 16, a transient system simulation program, user manual", *Solar Energy Laboratory. Madison, WI: University of Wisconsin-Madison*

Nguyen A., Reiter S., Rigo P., 2014. A review on simulation-based optimization methods applied to building performance analysis, *Applied Energy*, Vol. 113, pp. 1043–1058.

Ramakrishnan S, Wang X, Alam M, Sanjayan J, Wilson J. 2016. Parametric analysis for performance enhancement of phase change materials in naturally ventilated buildings. Energy and buildings, Vol.124, pp. 35–45.

Saffari M., Gracia A.D., Fernández C., Cabeza L.F., 2017. Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings, *Applied* Energy, Vol. 202, pp. 420–434.

Soares N, Gaspar AR, Santos P, Costa JJ, 2014. Multi-dimensional optimization of the incorporation of PCM-drywalls in lightweight steel-framed residential buildings in different climates. Energy and Buildings, Vol. 70, pp. 411–421.

Voller V. 1997.An overview of numerical methods for solving phase change problems,
Advances in numerical heat transfer, Vol. 1, pp. 341-380.

Wetter M. 2009. Generic optimization program – user manual. Technical report LBNL-5419, *Lawrence Berkeley National Laboratory,* Vol. 3.