Optimization assessment of the energy performance of a BIPV/T-PCM system using Genetic Algorithms

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Abstract

In this paper, the efficiency optimization of a BIPV/T-PC is investigated using Genetic Algorithm approach. The system in study is installed in a façade of an office building in Lisbon. Based on an updated mathematical model, theoretical simulation has been conducted for BIPV/T-PCM in this case for the existing system set-up (geometry-air gap width, ventilation, system layers). The system was tested experimentally also and the numerical model using Matlab has been validated (Pereira 2015). In this paper the thermal and electric efficiencies were calculated and in order to optimize the system performance Genetic Algorithm was used. The results shown that the system can achieve a maximum total efficiency of 64% with winter configuration and 32% with summer configuration.

1. Introduction

In the case of Building Integrated Photovoltaic systems (BIPV) as is well known, only approximately 16% of the solar energy incident on a PV, is converted to electricity, the remaining, being absorbed and transformed into heat (Bouzoukas 2008). The component transformed into heat can cause overheating problems in the case of Photovoltaic panels (PV) integrated systems (Aelenei et al. 2014). Elevated operating temperatures, on the other hand, reduce the solar energy conversion efficiency of photovoltaic module. By ventilation of the air gap behind the PV module, the heat released in the conversion process from PV can be successfully recovered for indoor heating (BIPV/T), and/or by using Phase Change Materials (PCM) can be stored for leveling the temperature difference between indoor and outdoor and a rapid stabilization of PV modules temperature (BIPV/T-PCM). In the framework of a project for integrated of PV systems in buildings façade, a study on using BIPV with heat recovery (BIPV/T) and combination with storage element (BIPV/T-PCM) was developed having in mind to avoid PV overheating and improve the overall efficiency of the system through a combination of geometrical parameters and properties. The BIPV/T-PCM prototype was installed in the SolarXXI building façade (Aelenei & Gonçalves 2014). A dynamic model of the thermal behavior of the system was developed and validated by Pereira (Pereira 2015), considering different climatic conditions and consequently utilization strategies (winter and summer). The overall energy efficiency of the system was calculated for winter and summer condition and utilization strategies. The simulation results were optimized through Genetic Algorithms enabling to find the best combination between the ventilation (flow rate), dimensions of the air gap and PCM layer and the latent heat capacity, maximizing the overall energy efficiency of the system.

2. Dynamic modeling of the system

The system was modelled using a 1-D dynamic simulation program with the real climatic data from the winter period measured on the building site. A control-volume based finite-difference scheme was used to solve the model equations developed under MATLAB/SIMULINK® with SIMSCAPE® library on a staggered grid. This software has a user-friendly interface and good flexibility. The SIMSCAPE® library permits a very dynamical simulation. In Fig. 1 (a) it can be observed the system configuration and the software models interface (b).

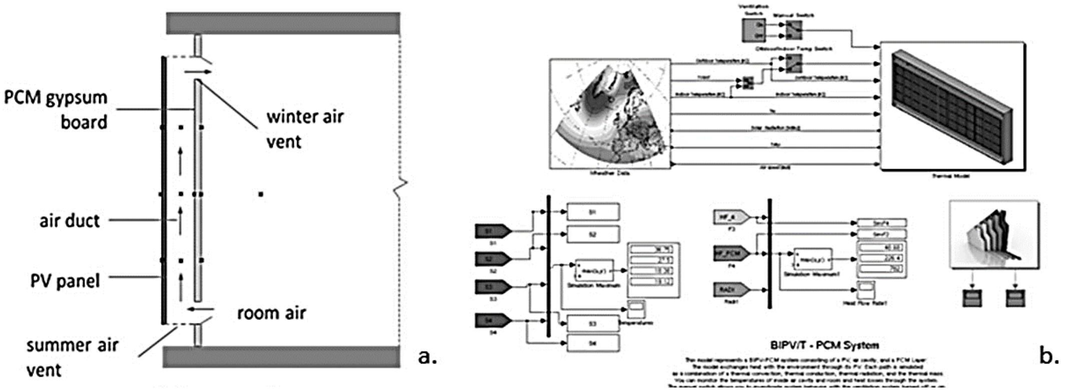

Fig. 1. (a) System configuration; (b) Software interface

2.1. Thermal model

A heat transfer across the system can be considered as a set of nodes connected together by a thermal network, each with a temperature and capacitance. The numerical analysis considers the schematic thermal network of Fig. 2.

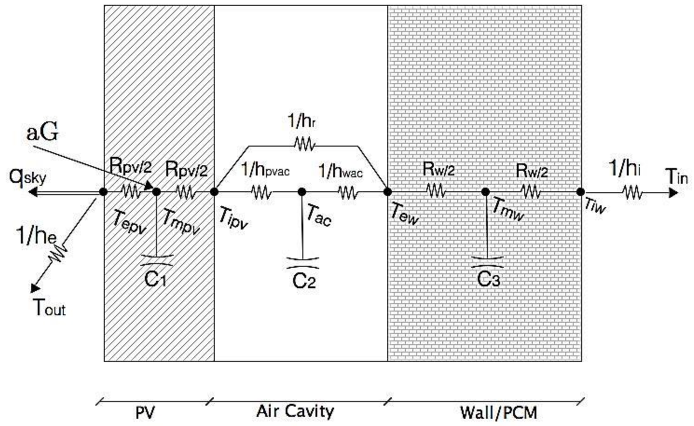

Fig. 2. Model studied – Thermal network.

2.1.1. Heat transfer across PV panel

For the PV panel layer, the energy balance can be obtained as shown in equation (1), where h_e represents convective heat transfer coefficient for exterior (Test et al. 1981) and T_{sky} is the sky temperature employed to calculate the radiative heat losses to the exterior (Duffie & Beckman 2013). T_{out} and G represent the outside ambient temperature and solar radiation, respectively, which were experimentally deduced.

$$-\frac{\left(T_{epv}-T_{mpv}\right)}{R_{pv}/2}-\varepsilon_{pv}\cdot\sigma\cdot\left(T_{epv}^{4}-T_{sky}^{4}\right)-h_e\left(T_{epv}-T_{out}\right)=0 \qquad \text{Eq. (1)}$$

$$M_{pv}\cdot Cp_{pv}\cdot\frac{dT_{mpv}}{dt}=\alpha_{pv}\cdot G+\frac{\left(T_{epv}-T_{mpv}\right)}{R_{pv}/2}-\frac{\left(T_{mpv}-T_{ipv}\right)}{R_{pv}/2} \qquad \text{Eq. (2)}$$

2.1.2. Heat transfer within air gap

The heat transfer in the air gap is governed by natural convection although the radiation effects are considered assuming a view factor (FRpv-pcm) of 1 between planes (Kalogirou 2009). The convective heat transfer coefficients inside air cavity are influenced by the operation mode of the system (open or closed vents). When vents are closed, the heat transfer coefficient assumes the Kalogirou (Kalogirou 2009) correlation for vertical collectors, whereas when the vents are open the convective heat transfer coefficient is based on Duffie and Beckman (Duffie & Beckman 2013) correlation for natural ventilation described by Samar et al. (Jaber & Ajib 2011). The mean air velocity in gap is obtained by solving Bernoulli´s equation and assuming linear variation for air density and temperature as described in Kalogirou (Kalogirou 2009). The energy balance within the air gap is described by the following equations:

$$\frac{\left(T_{mpv}-T_{ipv}\right)}{R_{pv}/2}-h_{pvac}\left(T_{ipv}-T_{ac}\right)-h_r\left(T_{ipv}^4-T_{ew}^4\right)=0 \quad \text{Eq. (3)}$$

$$M_{air}\cdot Cp_{air}\cdot\frac{dT_{ac}}{dt}=h_{pvac}\left(T_{ipv}-T_{ac}\right)+h_{wac}\left(T_{ac}-T_{ew}\right) \quad \text{Eq. (4)}$$

$$h_r\left(T_{ipv}^4-T_{ew}^4\right)-h_{wac}\left(T_{ac}-T_{ew}\right)-\frac{\left(T_{ew}-T_{mw}\right)}{R_w/2}=0 \quad \text{Eq. (5)}$$

2.1.3. Heat transfer across PCM gypsum board

The energy balance for the PCM gypsum board can be obtained from equations (6) and (7) where h_i is the interior heat transfer coefficient based on the Santos et al, (Santos & Matias 2006) and q_i is based on the Athienitis (Athienitis et al. 1997) approach for PCM model.

$$M_w\cdot Cp_w\cdot\frac{dT_{mw}}{dt}=\frac{\left(T_{ew}-T_{mw}\right)}{R_w/2}-\frac{\left(T_{mw}-T_{iw}\right)}{R_w/2}+q_l \quad \text{Eq. (6)}$$

$$\frac{\left(T_{mw}-T_{iw}\right)}{R_w/2}-h_i\left(T_{iw}-T_{in}\right)=0 \quad \text{Eq. (7)}$$

2.2. System performance

The evaluation of the overall system performance was conducted by means of total system efficiency (η_0) which is the sum of the thermal efficiency (η_t) and the electrical efficiency (η_e) (Chow 2010):

$$\eta_0 = \eta_t + \eta_e \quad \text{Eq. (8)}$$

The thermal efficiency (η_t) is calculated as a function of the heat gains into the room divided the solar radiation (G, W/m^2) multiplied by the area of the control volume (A, m^2). In ventilated cases the gain into the room are considered to calculated as the sum of the heat flux through the wall (q_{int}, W) plus the air flow coming from air cavity to the interior room (q_V, W) (Lin et al. 2011):

$$\eta_{tw}=\frac{q_{\text{int}}+q_V}{G\times A} \quad \text{Eq.(9)}$$

$$\eta_{ts}=\frac{q_V-q_{\text{int}}}{G\times A} \quad \text{Eq. (10)}$$

the energy conversion efficiency (η_e) of a solar panel is the percentage of the solar energy to which the panel is exposed that is converted into electrical energy. This is calculated by dividing a panel's power output (P, W) by the total incident solar radiation (G, W/m^2) and the surface area of the solar panel (A, m^2) (Chow 2010). However, increased thermal efficiency may result in reduced electrical efficiency. A constraint is therefore added to the optimization. In this case, the purpose of this restriction, set by equation (11), is to ensure the maximum electrical efficiency of the PV panel.

$$\eta_e = \frac{P}{G \times A}\left(1 - \beta_c\left(T_{mpv} - T_{NOCT}\right)\right) \qquad \text{Eq. (11)}$$

3. System optimization using Genetic Algorithms

Implementing genetic algorithms requires the prior definition of essential parameters for the optimization routine. It starts by specifying the initial parameters and randomly creates an initial population of individuals within these limits. Then the suitability of each individual is checked by the objective function. Genetic operators that modify the population with the aim of improving it are applied. This iterative process, corresponding to successive generations, continues until it reaches convergence (Ávila 2002). Fig. 3 (a) shows the flowchart of a simple routine optimization through genetic algorithms.

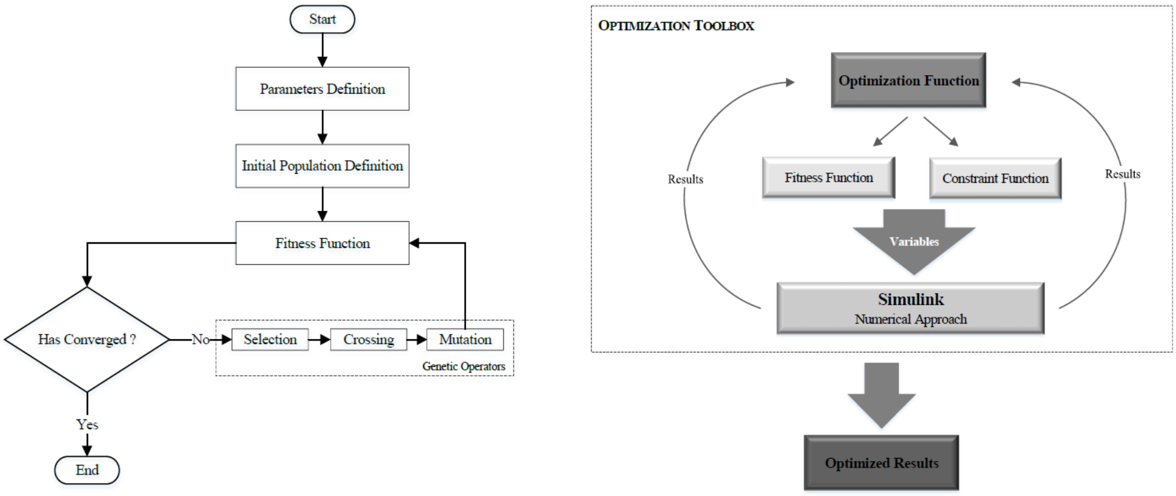

Fig. 3. (a) Flowchart of a simple routine optimization through genetic algorithms (Ávila 2002), (b) Functional diagram of the optimization toolbox

In the problem under consideration in this flowchart, the Fitness Function is the energy efficiency mentioned in equation (8), which aims to maximize. After careful analysis of the base model data, the selected variables are those shown in Table 1.Variables were chosen for their degree of influence on the system.

- **Ventilation** is always an important variable in this type of system. By changing the intensity, the rate of energy transfer between the air cavity and the surrounding environment is adjusted. On the other hand, increasing the intensity cools down the photovoltaic module.
- The **air cavity thickness** influences not only the mass flow rate but also the heat transfer by radiation and conduction between the first and second layer. The increased flow also cools down the photovoltaic module.

- The **PCM thickness** has an influence on heat transfer by conduction in the second layer. High values of this variable may indicate the need for isolation.
- The **latent heat** phenomenon is the novelty in this type of system. By introducing this variable in the optimization process, it is intended to understand its influence on the behavior of the gypsum board, and on the absorption and release of energy that will regulate the temperature of the photovoltaic module and the interior room.

The corresponding parameters of the Fitness Function and the initialized in the respective intervals are:

Table 1. Optimization parameters

Parameter	Variable	Range	Units
Ventilation	Vch	[0,035 – 10]	m/s
Air Gap	AirCavityThickness	[0,02 – 0,1]	m
PCM Thickness	PCMthickness	[0,025 – 0,050]	m
Latent Heat	LatentHeat	[1000 – 50000]	J/kg

Optimizations are complex operations and require the use of powerful software. Matlab$^{®}$, in which the numerical approach was implemented, has an optimization toolbox that can apply various methods, including genetic algorithms. This toolbox requires synchronization between the Matlab$^{®}$ code language, Simulink$^{®}$ environment and Optimization Function. For this reason, a Fitness Function, Constraint Function and an interface between the source (Matlab$^{®}$) language and Simulink$^{®}$ environment was created. Fig. 3 (b) shows how this process is performed.

3.1. Optimization Scenarios

For any optimization process it is necessary to define the scenarios to be analysed. In this work, the system is divided into two different objectives. As in the base model (Pereira 2015), optimization will also be oriented in the winter configuration and the summer configuration. In these configurations, the entire optimization process and all the variables are unchanged. The difference is in the inputs and in the system behavior.

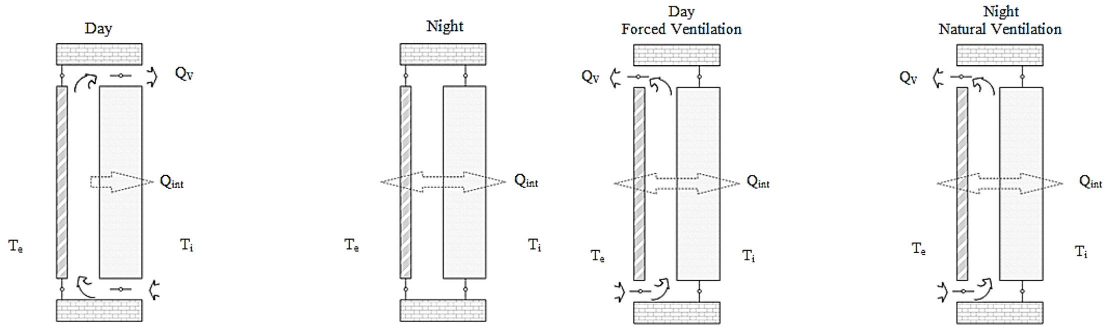

Fig. 4. Configuration for the optimization process for: (left) Winter (right) Summer

4. Results

4.1. Winter

The values of the variables of the optimization process for the winter season suggest forced ventilation during day, with an air velocity equal to 9.0835 m/s (Table 2). Although this velocity presents an unreal value, it represents a scenario hypothetically ideal for such a system. This velocity in conjunction with increased air cavity thickness (0.0865 m) increases the mass flow rate and the energy transfer to the interior room, simultaneously cooling down the photovoltaic module. The thickness of 0.0415 m creates a greater resistance to heat transfer by conduction, minimizing loss during the night when the ventilation is turned off and the vents are closed. According to the optimization process, the phase change material should have a release and absorption of energy in the form of latent heat equal to 18454.241 J/kg. This phenomenon will regulate and smooth the temperature peak of the material.

4.2. Summer

As expected, the optimization results (Table 2) indicate strong ventilation (9.978 m/s) and air cavity thickness of 6 cm, for the purpose of cooling the panel during the day. Same situation for air velocity value. In an ideal scenario, this velocity value shows what would be needed to achieve the desired objectives. In order to minimize the energy exchange between the exterior and the interior, the optimization process has increased the thickness of the gypsum board (4.49 cm). Increasing the variable "latent heat" (35150.576 J/kg) allows better regulation of the heat transfer between layers.

Table 2 Optimization variables: winter and summer optimization process results

Variable	Value (winter)	Value (summer)	Units
Ventilation	9.0835	9.978	m/s
Air Gap	0.0865	0.0618	m
Latent Heat	18454.241	35152.665	J/kg
PCM Thickness	0.0415	0.0449	m

As can be seen in Fig. 5, the maximum temperature reached by the photovoltaic module is 45 ºC, 15 ºC less than that shown in base model (Pereira 2015). It is the highest temperature suggested by the manufacturer for the proper functioning of the module.

The figure makes it clear that PCM gypsum board has a more “stable” configuration, as expected, with the surface facing the room maintaining a temperature of about 28ºC during the day and 15ºC at night.

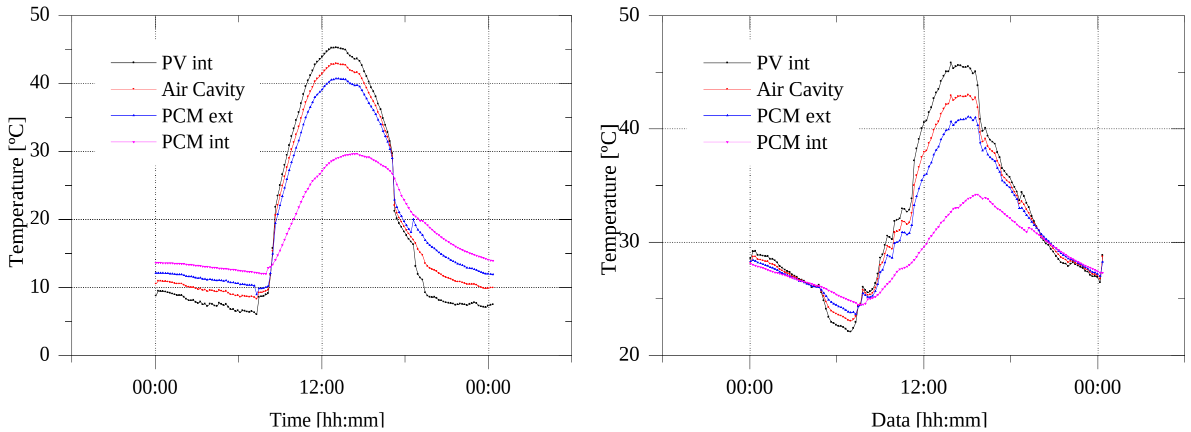

Fig. 5. System temperatures obtained from the optimization process: (left) Winter (right) Summer

Also, in Summer optimization scenario, the maximum temperature reached by the photovoltaic module is 46 ºC, 10 ºC less than that reached in base model (Pereira 2015). “PCM int” has substantially lower temperatures than “PCM ext”, reinforcing the idea of the resistance that gypsum board offers to the energy exchange between exterior and interior. The effect of temperature peak regulation by the latent heat phenomenon is clearly visible in the “stable” temperature profile presented by the “PCM int” curve.

4.3. Efficiency

Regarding the winter configuration, Fig. 6 (a) shows that an optimization of the system of about 40% was possible, shifting overall efficiency from 24% to 64%. As expected, the largest increase is related to thermal efficiency (16-54%), however the increase of electrical efficiency (8.4 – 9.9%) is also significant for this type of system.

In the summer configuration Fig. 6 (a), the optimization managed to change the thermal efficiency from a negative to a positive value, which caused total efficiency to increase to 36%. As mentioned previously, the electrical efficiency failed to achieve a significant increase (0.07%) due to the vertical positioning of the PV module.

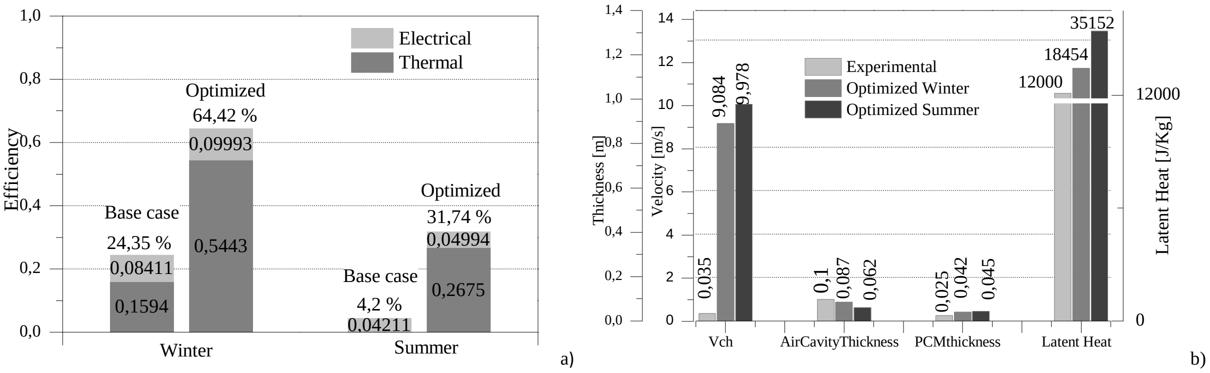

Fig. 6. Values of the variables resulting from the base model and from the winter and summer optimization processes.

It is evident in both optimization processes that the ventilation in the validated base model is quite poor. Looking at the values of the air velocity and the cavity thickness obtained from the optimization, it can be concluded that a greater flow is required for a higher energy transfer (inwards or outwards) and cooling of the photovoltaic module.

The values obtained for the variable relating to the PCM thickness, suggest the need to create some resistance to heat propagation. Decreasing the thermal conductivity constant or applying some type of insulation may be the solution to achieve the desired effect. However, increasing the storage and release capacity of the PCM, as suggested by the results of the variable relating to the latent heat (18454 – 35152 J/kg), may be the path to take. The optimization process unequivocally shows the influence of the PCM on controlling the temperature peaks (Fig. 6 (b))

5. Conclusions

From the base model, an optimization of the system was conducted using the genetic algorithm method. The optimization aimed to increase the efficiency of the system for two different configurations, winter and summer. The variables were the thickness of air cavity, the air flow velocity within cavity, the PCM latent heat and the thickness of the gypsum board. It was found that, with some changes in the variables analyzed, the system can improve to give higher efficiencies.

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