Thermal Analysis of a Building Integrated Photovoltaic (BIPV) System

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Abstract:

During the last few years photovoltaic (PV) panels are increasingly incorporated into the construction of buildings for generating electrical power (BIPV systems) or both electrical and thermal energy (BIPV/T systems). The integration creates heat in the gap between the PVs and the building's skin, which if not removed to be used to cover part of the heating load of the building (winter) or to the atmosphere (summer), it decreases the efficiency of the PVs and increases the cooling loads of the buildings in summertime. This study aims to evaluate the thermal behaviour of a BIPV system in order to decide whether natural ventilation of the air behind the PV is adequate to cool it down and remove the excess heat. The examination of the effect of the air gap of a BIPV system as well as the slope of the system or the amount of solar radiation are very important parameters as they can lead to better understanding of the conditions that allow the higher efficiency of the PV panels and accordingly higher efficiency of the BIPV system. The investigation of the above parameters is done experimentally in a laboratory with a large scale solar simulator (SS) and a representative apparatus of a BIPV system, able to change the air gap of the duct and the slope in order to simulate roof or façade installation. The experimental results are compared with 3D modelling simulation results obtained using COMSOL Multiphysics software.

Keywords:

Solar simulator, BIPV, integration, thermal behaviour, photovoltaics, BIPV/T.

1 Introduction

Traditionally, the usual way to install a PV system on a building is to install PVs with brackets and connections to the roof of the building. New technologies allow PV systems to be attached on the building's elements or even be a part of the building construction materials. The later are called Building Integrated Photovoltaic (BIPV) systems.

The integration of PV panels in a second skin creates heat behind the PVs, which can either be thrown to the environment or be used to heat the interior of the building. When the heated air is used to heat the building, then the system is called Building Integrated Photovoltaic/Thermal (BIPV/T).

Both BIPV and BIPV/T systems are formed by PV panels integrated on a second skin part of the building, and a formed air gap between the two skins. In BIPV systems the air gap is responsible to cool the PVs and remove excess heat to avoid building overheating and for the BIPV/T systems air gap is responsible to circulate the heated air and drive it into the building to provide space heating.

The ventilation of the air gap can be natural or mechanical. The investigated system in this study is a naturally ventilated BIPV system. This has a number of advantages, the most important of which is the avoidance of energy to power the fans, the operation with no noise and the avoidance of overheating which can happen when the fan stops in an active system.

However, in both systems in summertime, if the heated air is not removed from the duct, it lowers the efficiency of the PV panels because of the high temperature developed. Additionally, the excess heat increases the cooling loads of the building. According to Wang et al. [1], BIPV has significant influence on the heat transfer through the building envelope because of the change of the thermal resistance by the various building elements. Consequently it is important to find the configuration of the system that will increase the efficiency of the PVs and do not increase the cooling loads of the building in summer. For the BIPV/T Systems it is important to keep both electrical and thermal efficiencies high throughout the year. According to Brinkworth and Sadberg [2] the most important variable to be fixed in the design of a PV cooling duct is the depth, and hence the hydraulic diameter of its cross section.

Various researchers tried to understand the heat transfer and the air flow between the PV and the construction material in several ways. There are numerous studies which approached the analysis experimentally, theoretically or numerically. Studies can be also categorized from those who studied the forced ventilated systems and those who studied the naturally ventilated systems.

An extensive review by Agathokleous and Kalogirou [3] presented the various studies carried out for BIPV systems separated into naturally and mechanically ventilated systems, and studies which analysed the system experimentally or theoretically. It was concluded that most researchers studied the systems with mechanical ventilation because of the flexibility to adjust the air flow in the duct to remove the heated air or drive it into the building. Additionally, natural ventilation systems are more complex in terms of the air flow behaviour in the duct which is difficult to be predicted.

Gan [4] assessed the effect of the air gap between PV modules and the building envelope on the performance of the system in terms of the cell temperature for a range of roof pitches and panel lengths and to determine the minimum air gap that is required to minimize the PV overheating. The study was done with a CFD method and it was concluded that for single module installation, the air gap should be between 0.14 m and 0.16 m in order to minimise the mean temperature.

Kaiser et al. [5] performed an experimental study of cooling BIPV modules by forced convection in the air channel. The objective of this study was to examine the influence of the air gap size and the forced ventilation on the cell temperature and the electrical efficiency of the PV in a BIPV configuration considering different values of solar radiation, ambient temperatures and aspect ratios. The results presented showed that a critical aspect ratio close to 0.11 can be considered to minimize overheating of PVs.

Brinkworth et al. [6] found that due to an air flow in a duct behind the PV component, a reduction up to 20 K can be obtained on the PV. This reduction leads to significant increase in the electrical output and reduction of heat gain into the building. Additionally, Brinkworth et al. [7] developed a simplified method to estimate the flow rate in naturally ventilated PV cladding for buildings.

Yang and Athienitis [8] carried out an experimental procedure on a prototype open loop air based BIPV/T system with single inlet with the use of a large scale solar simulator. A two inlet system was also tested and found that the peak PV temperature in the two inlet system is lower than in the single inlet system which means that the degradation of the performance with high temperature is reduced in the two inlet system.

Zogou and Stapountzis [9] presented a study showing the results from flow visualization and hot wire anemometry measurements performed on the basic structural module of a double skin photovoltaic façade. The results of this study show that the selection of the flow rate and the heat transfer characteristics of the back sheet are critical to the performance of the PV façade.

Gaillard et al. [10] carried out an experimental study on the thermal response of PV modules on naturally ventilated BIPV. The authors proposed various techniques to monitor the performance of the system that can be used to study PV systems in complex environments.

As mentioned earlier, this study investigated a naturally ventilated BIPV system. It is considered that the system has an open ended duct formed between the PV and the building's wall, where the air enters the duct from the bottom and exits at the top. For this purpose, various experiments have been carried out to test the temperature distribution of a naturally ventilated system in terms of the inclination angle, solar radiation and the air gap width.

2 Naturally Ventilated BIPV System

Although mechanical ventilated systems are easier to be studied and thus their performance can be more easily predicted, the naturally ventilated systems have some very important advantages and many potentials. They do not require maintenance or extra cost for fan, they can be easily installed in comparison with the mechanically ventilated systems, they have no noise of a fan and no extra cost of electricity to operate the fan.

The system considered in this study is a single module system integrated on a second skin called wall considered as a building's wall as shown in Fig. 1. The system is subjected to radiation and no fan is employed to drive the air in the duct. Additionally, no wind or other disturbances are assumed to occur. Vertical and sloped systems are tested experimentally and the vertical position is tested with a simulation model in COMSOL Multiphysics.

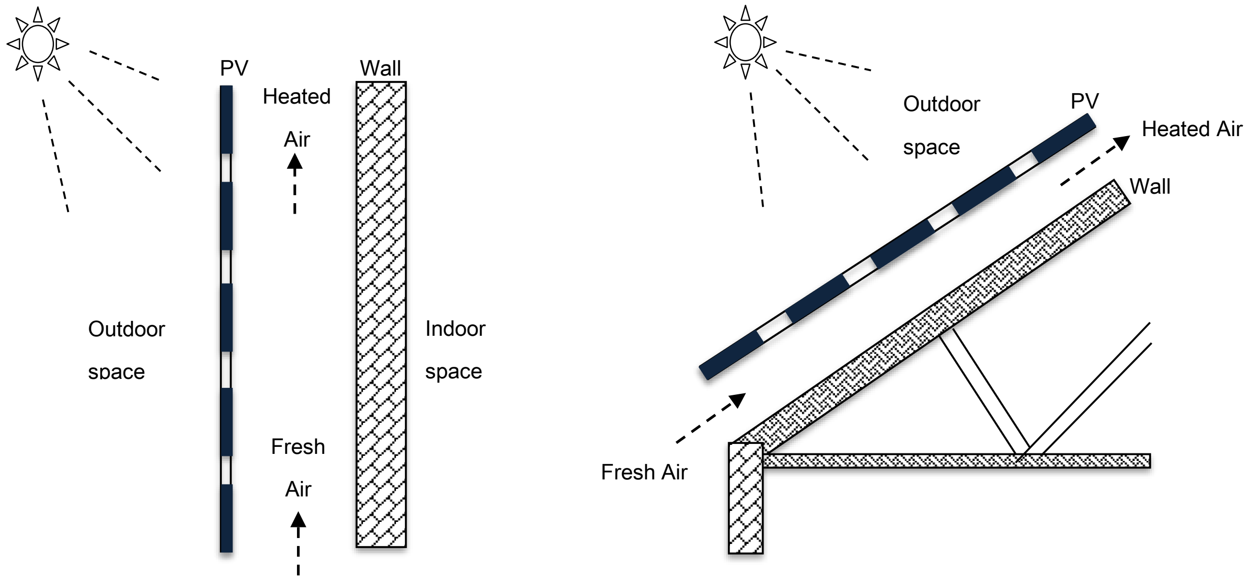


Fig. 1 Schematic diagram of the BIPV system investigated, in vertical position (façade installation) and inclined position (roof installation).

2.1 Experimental Model

BIPV systems as mentioned earlier, can be installed in building facades in vertical position or in roofs at inclined position. Accordingly, the slope of the system is one of the parameters that need to be investigated. In addition to the slope of the system, another important parameter investigated is the gap width. According to the studies from the literature presented earlier, the air gap widths mostly used are 0.1 and 0.15 m.

The scope of the experimental procedure was to record the temperature of the system under various configurations. The experiments are carried out in a laboratory with the use of a large scale solar simulator and a BIPV custom made experimental apparatus as shown in Fig. 2. Various thermocouples and data acquisition devices were used to record the temperature variations of the system under the different testing conditions. The signals from the thermocouples were recorder by DaqPro thermometry devices. In addition to these, a thermal camera is used to validate the temperature distribution recorded from the experimental set up.

The custom made experimental apparatus comprises a 180 W polycrystalline PV panel, 1.60 m long and 0.80 m wide. The back and the sides of the apparatus are made from wood forming an air duct representable to the air gap formed when a PV is integrated to the wall or roof of the building. Three inclination angles were tested 30º, 45º and 90º and two air gap width sizes 0.10 cm and 0.15 m. All tests were performed under high incident radiation of 800 W/m^2 and low radiation 400 W/m^2 and the ventilation of the system was natural since no fan was implemented to drive air through the duct. Table 1 shows the characteristics of the various instruments used in the experimental procedure.

As done in [11] in a study on the dependency of the PV performance to wind speed, inclination and orientation, the temperatures of front and back surfaces of the PV modules are assumed to be the same.

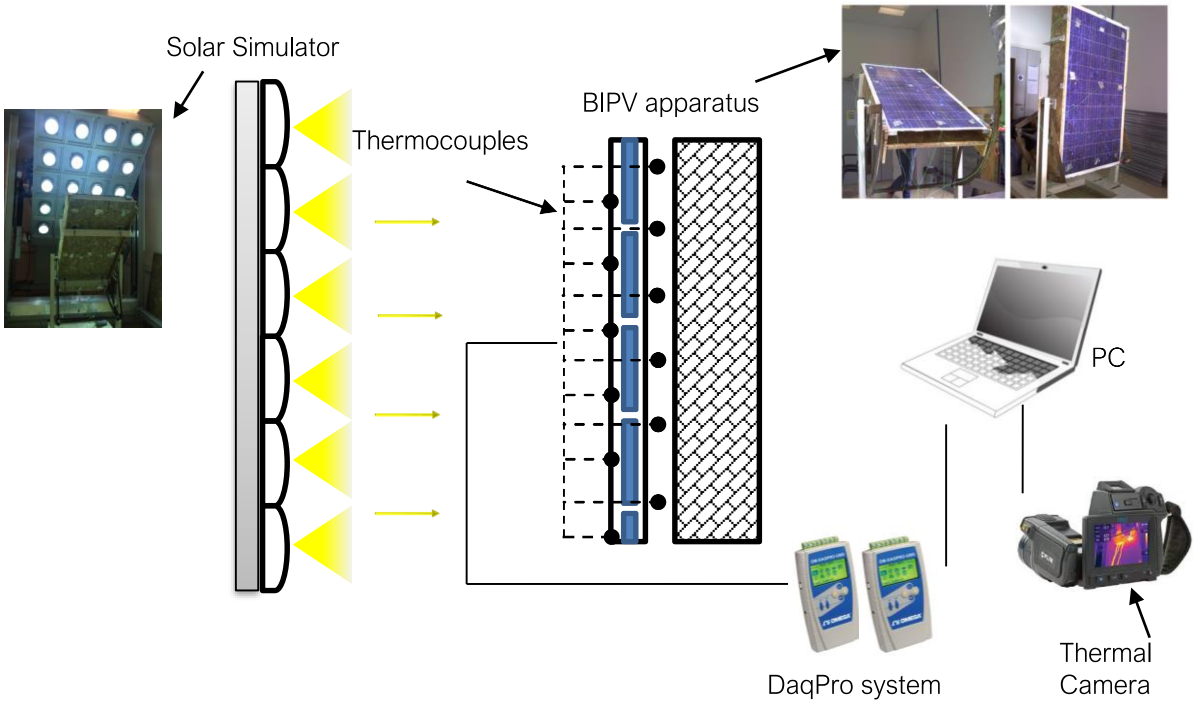


Fig. 2 Experimental set up.

Table 1. Characteristics of the equipment used in the experimental procedure.

Solar Simulator			
Radiation Range: 0-1200 W/m^2	No of lamps: 20 (575 W each)	Frame Area: 2.15 m x 1.65 m	Test area: 2 m x 1.5 m
Daq Pro			
Thermocouples: K- type	Accuracy: ±0.5 ºC	No of plugs: 8	Temperature: -250 ºC to 1200 ºC
Photovoltaic panel			
Area: 1.6 m x 0.8 m	Power: 180 W	Type: Polycrystalline	Efficiency: 14%

2.2 Simulation Model

According to Versteeg and Malalasekera [12], the combination of a fluid flow and heat transfer modeling cannot be sufficient without reference to experimental validations. For this study simulations are carried out to validate the experimental measurements performed to record the temperature profile of the experimental BIPV system, tested in a controlled laboratory environment under a large scale solar simulator providing constant incident radiation.

Consequently, COMSOL Multiphysics 4.3b software was used, with 3D geometry, in order to simulate the model assessed experimentally as shown in the previous section. A BIPV model was created to be at the same size with the experimental apparatus and equations from the theory are applied through the model in order to simulate the heat transfer mechanisms and the air flow in the duct. Only the system in vertical position is simulated, with 0.1 m air gap width and 800 W/m^2 constant incident radiation which represent the most common application of BIPV systems in building facades in hot climates.

The geometry of the BIPV model is shown in Fig. 3. The only material that has different dimensions from the experiment is the wall. In the experimental apparatus as mentioned earlier, the wall is represented by a wooden plate of 0.02 m thick, while in the simulation model a brick wall of 0.15 m thickness is considered.

The experimental results showed that the PV surface has lower temperature at the bottom and higher at the top and the wall's temperature had almost the same temperature in all its height with 1-2°C lower temperature at the bottom at the outer side (duct side). Thus, for simulation purposes, in order to define the boundary conditions, the system is assumed to be formed by one isoflux plate (front PV side) and one isothermal plate (back wall side).

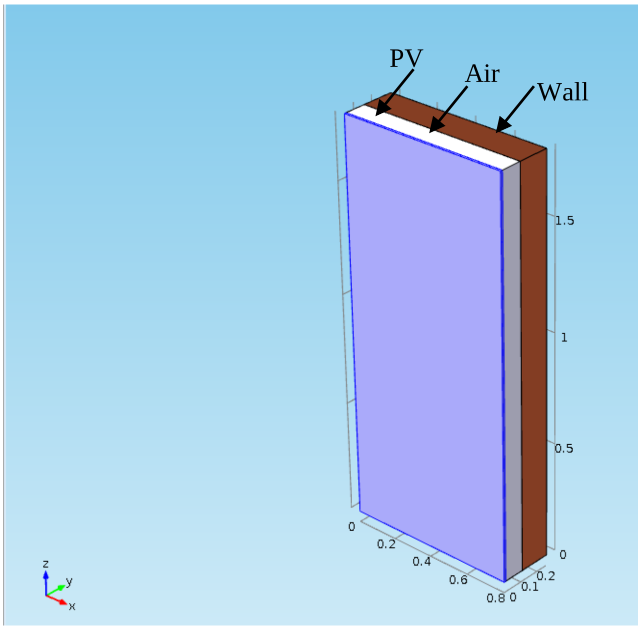


Fig. 3 The model geometry showing the PV, air and wall.

Various boundary conditions are applied to the model in order to simulate the real conditions. The external side of the PV panel gains heat from solar radiation and loses to the environment. In the boundary between the PV panel and the air gap heat flows from the hotter panel to the stream of air and at the air-wall boundary; the hotter air transfers heat to the wall. Constant solar radiation is assumed at the front surface of the PV while air flows in the duct formed between the PV and the wall, from the bottom side of the system and exits from the top. The convection is set to be natural and it was taken into account that it happens in all areas of the system which are the front of the PV, the back of the PV, the front of the wall and the back of the wall. The convective heat transfer coefficients were estimated each time with the appropriate equation because the conditions in each section of the system are not the same and the coefficients cannot be assumed to be the same everywhere or constant from the bottom to top of the system.

The convective heat transfer coefficients in the front surface of the PV and the back surface of the wall (facing indoors), are estimated by the use of empirical Nu number equation given by Churchill and Chu [13] for natural convection over vertical plates as shown in (1). The two Nu numbers, although estimated with the same correlation, are not assumed to be the same because of the different properties in the outside and inside and the different temperature of the vertical surface.

$$Nu = \left\{0.825 + \frac{0.387\, Ra_L{}^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}}\right\}^2 \quad (1)$$

Regarding the convective heat transfer coefficient in the duct, the estimation was challenging as there are not official published correlations referring to the specific system or similar conditions. As concluded by [3], the correlation that describes best the thermal conditions of a BIPV system is the one given by Bar-Cohen and Rohsenow [14] for isoflux plates, asymmetric heating:

$$Nu_{,L/2} = \left\{\frac{6}{Ra} + \frac{1.88}{Ra^{0.4}}\right\}^{-0.5} \quad (2)$$

To formulate the heat exchange process for a fluid flowing between the PV panel and the building's wall, time dependent partial heat transfer differential equations (PDEs) are used and solved in COMSOL Multiphysics. For the heat transfer in fluids, the following heat equation was used:

$$C_p \frac{\partial T}{\partial t} + \rho\, C_p\, u\, \nabla T = \nabla(k\, \nabla T) + \dot{Q} \quad (3)$$

Where t (s) is the time, T (K) is the temperature of the fluid, C_p (J/kg K) is the specific heat of the fluid at constant pressure, ρ (kg/m^3) is the fluid density, u (m/s) is the flow velocity, k (W/mK) is the thermal conductivity and $\dot{Q}$ (W/m^3) includes the heat transfer sources with positive sign if the heat is added to the fluid volume and negative if extracted from the volume (for instance when there is heat loss to the environment). In the case of heat transfer in solids, the same equation is used but the convective term of the equation is zero since the u=0.

3 Results Discussion

3.1 Experimental Results

As expected, the higher the solar radiation the higher the temperature of the system gets mostly affected is the PV temperature which is directly exposed to solar radiation. As can be seen in Fig. 4, for all the slopes tested, the 800 W/m^2 radiation causes higher temperature in all the system's components than in 400 W/m^2 (x-axis shows the system's three components and y-axis the temperature of each component).

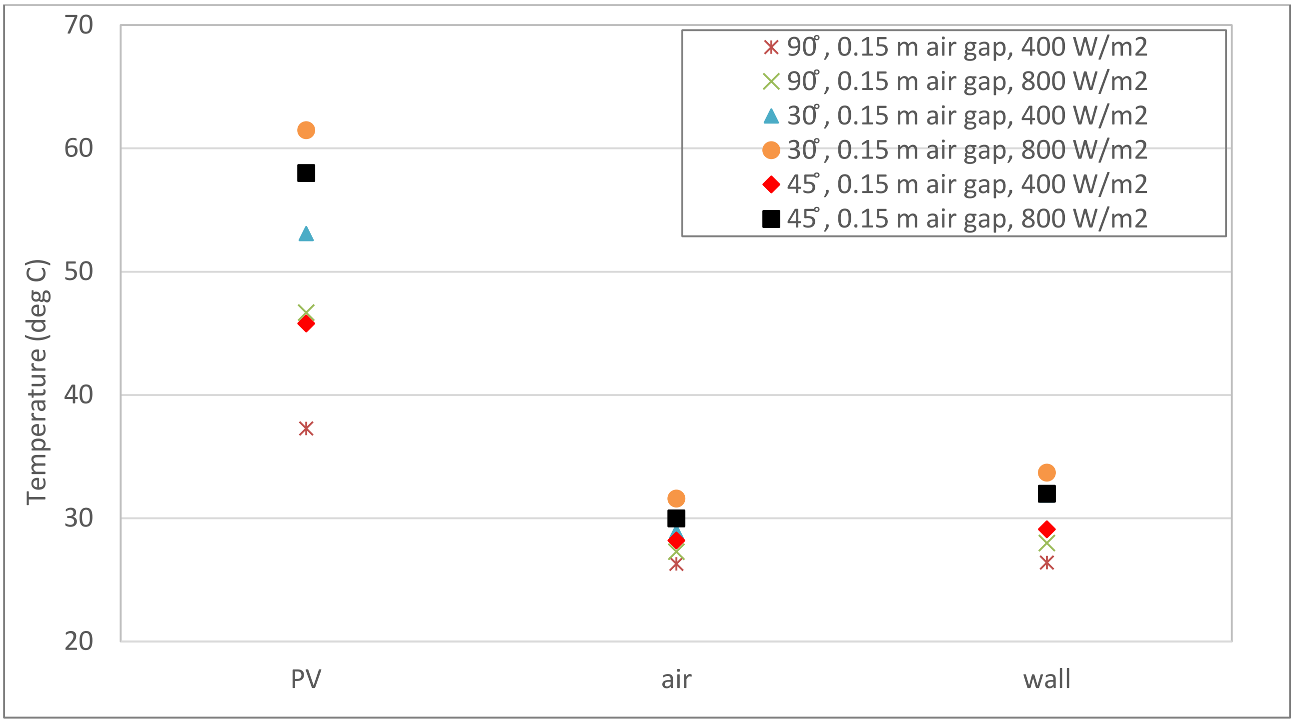


Fig. 4 Comparison of the radiation effect on the temperature distribution of the system tested in 0.15 m air gap in the three tested slopes 90°, 30 ° and 45°.

From the three plots shown in Fig. 4 the differences in temperature for the three slopes of the systems tested can be observed. The higher temperature is observed in the slope of 30° and the lower at 90°. Therefore, it can be concluded that the closer to the vertical position the PV is, the air moves better in the air gap and cools the system more. This observation is not affected from the incident radiation which in real sun is not perpendicular to the system because in the laboratory the radiation (from the solar simulator) was perpendicular to the system in all experiments. Accordingly, the differences in the temperature of the system in the tested slopes, is clearly due to the air circulation to the air gap and not due to the incident radiation to the PV surface.

A comparison of the temperature of the system for the three slopes tested is shown in Fig. 5. The system in vertical position develops lower temperatures in all measurement points and in 30° the system develops the highest temperatures. This is because for inclination of 90° the air particles are moving up with low resistance and the residence time of the particles in the conduit is less. This increases the air velocity and thus reduces the heat transfer from the PV to the working fluid. For the 30° angle, the particles move up and hit the cover which reduces the kinetic energy of the working fluid and reduce the resulted mass flow rate in the system.

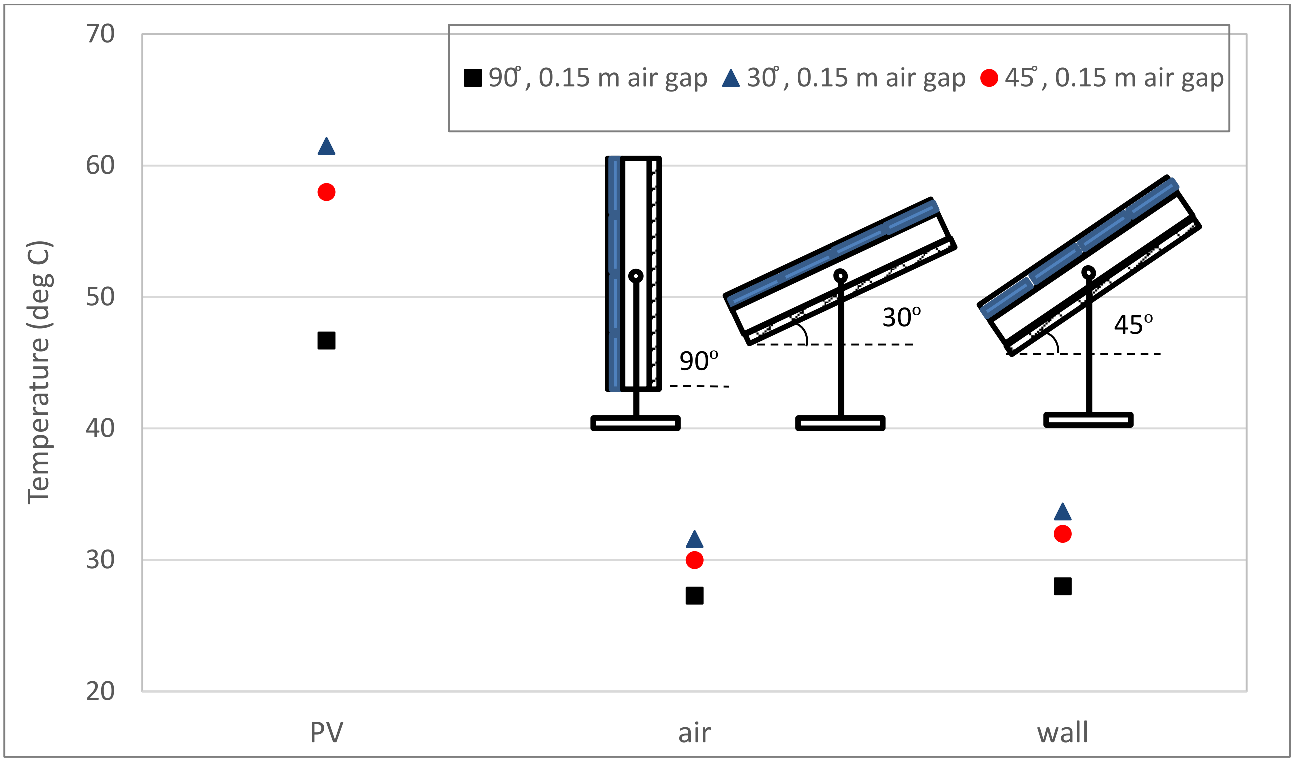


Fig. 5 Comparison of the temperature distribution of the system for the three angles of the system tested.

Fig. 6 shows three contour plots of the PV temperature distribution for the BIPV for 90°, 30° and 45° inclination. As can be seen, the plot in the center which shows the PV temperature distribution for 30° has the highest temperature at the top of the PV (60°C) and then the 45° (51°C), while the lower temperature is observed in the left plot for the system in vertical position (45°C). Since the system develops lower temperatures in the 90° position, it means that can work more efficiently under this conditions. This is in agreement with the works of Gan [4] and Lau et al. [15].

Additionally, from the results presented in Fig. 6 an important outcome is obtained. As can be observed, the temperature of the PV is not the same in all its area. The temperature at the PV's surface increases from the bottom to the top. The lower part is colder than the top part. This is because the air enters the duct from the bottom side and as a result keeps the temperature of the PV lower in the bottom side and then as the air gets hotter in the duct the temperature of the PV at the upper side where the hot air exits, is higher.

The temperature of the PV at bottom is the lowest and reaches the maximum at the top. This can be observed in all experiments. Comparing now the effect of the air gap size on the system's temperature, the two plots in Fig. 7 shows the temperature of the PV in vertical position with 800 W/m^2 radiation for the two air gap widths tested. As can be observed, the PV has higher temperature at the small air gap width (68°C) and lower temperature at the big air gap width (60°C).

In both Figures 6 and 7, colors of the contour plots should not be confusing since they are in-depended to each other. The color variation is individual for every plot and the range of representative temperature is shown on the scale on the right side of every plot.

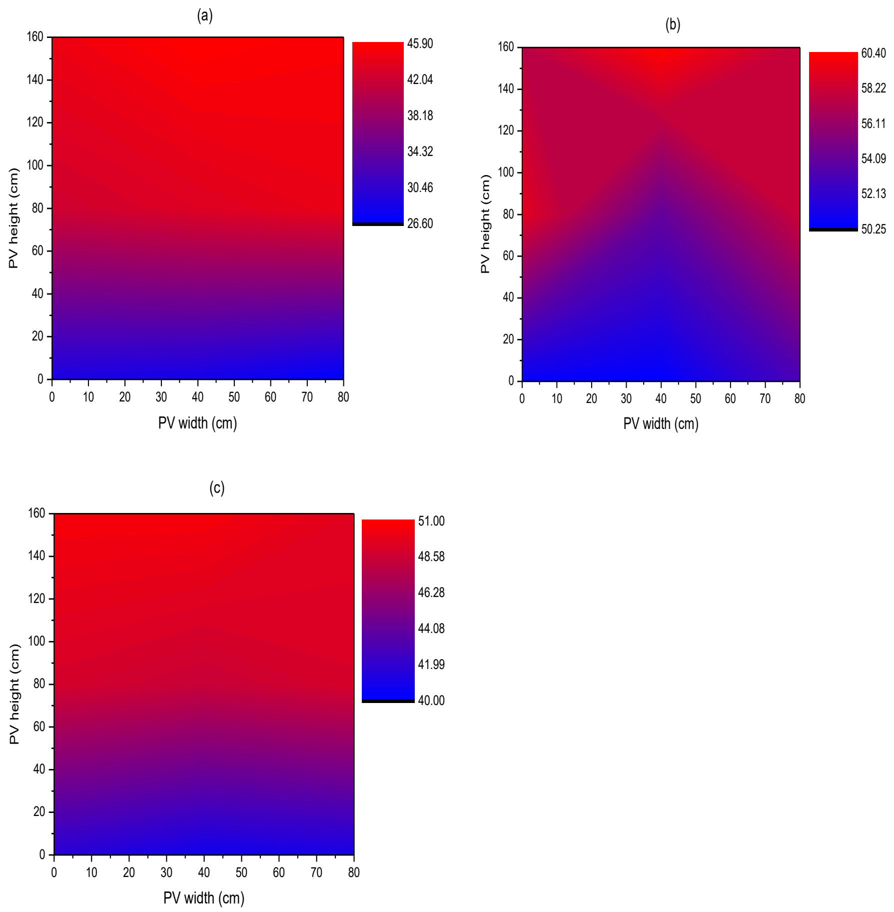
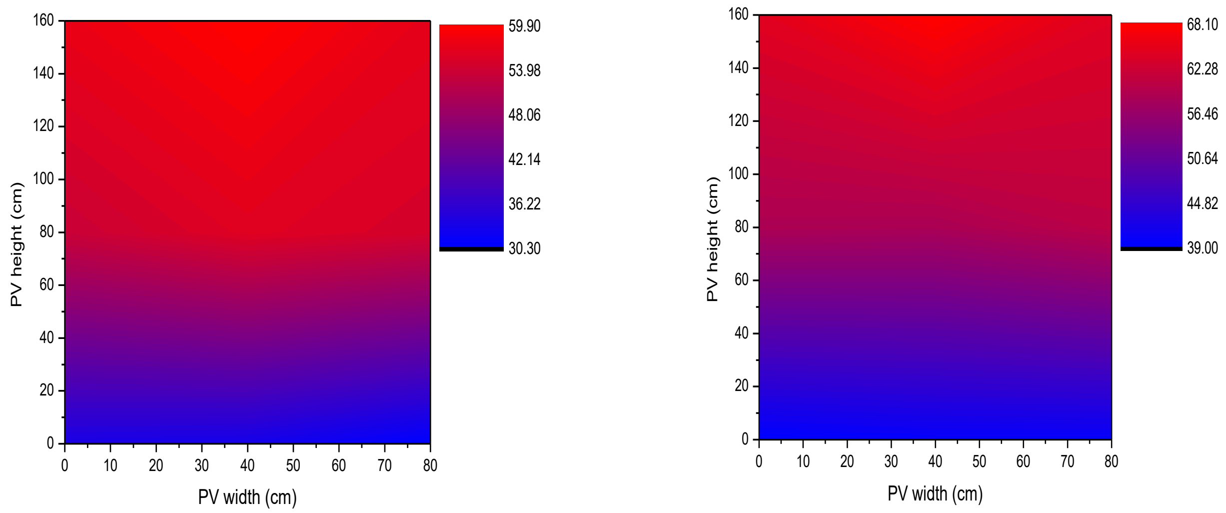


Fig. 6 Contour plots of the temperature of the PV surface (a) in vertical position, (b) in 30° angle and (c) in 45° angle.



(a) *(b)*

Fig. 7 Contour plots of the temperature of the PV surface (a) Vertical position 0.15 m air gap, 800 W/m^2 radiation, (b) Vertical position 0.10 m air gap, 800 W/m^2 radiation.

Fig. 8 shows the temperature of the system in all parts for the two air gaps tested, in vertical position. Lower temperatures appear when the system is in the vertical position and the air gap width is at 0.15 m. This is the best option for 400 W/m^2 and 800 W/m^2 incident radiation and for all slopes tested. Given these observations, it can be said that the air gap of 0.15 m can ensure cooling of the PVs in the BIPV systems in all radiation conditions at every slope.

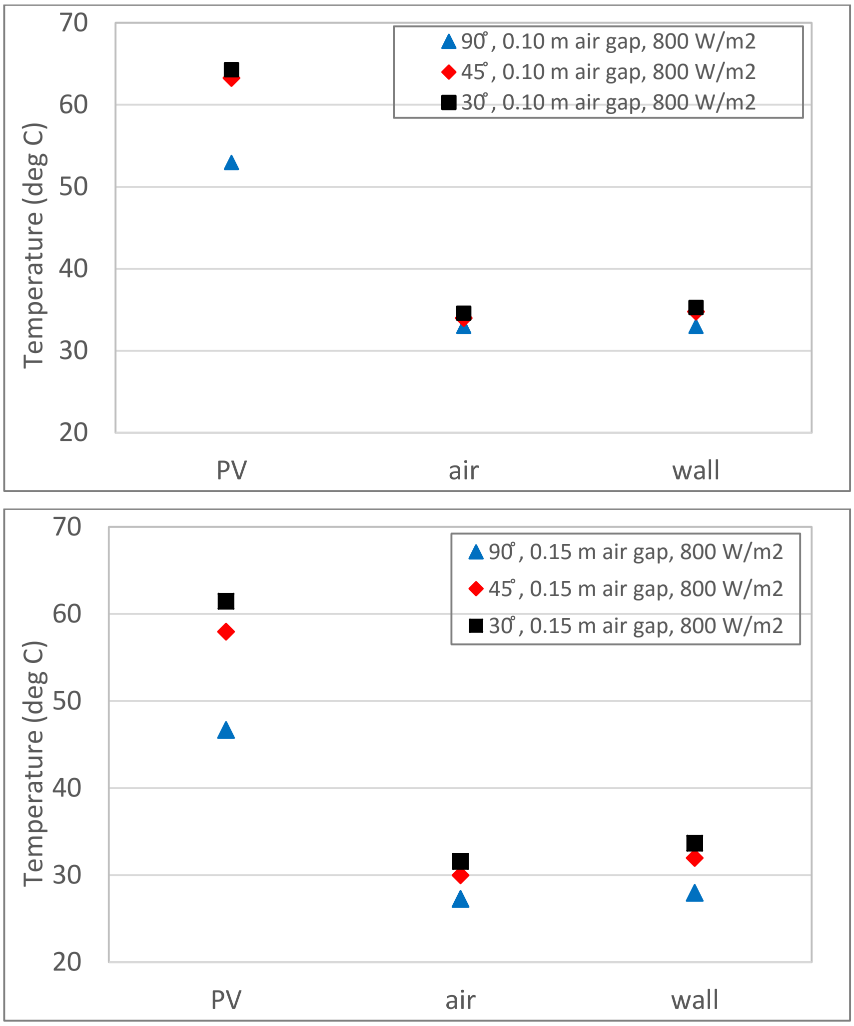


Fig. 8 Comparison of the temperature distribution of the system for the two air gaps tested in all tested slopes with 800W/m^2 radiation.

3.2 Simulation Results

As shown also from the experimental measurements, it was observed from the simulation results that the bottom side of the PV had lower temperature than the top side. That was observed from the first half hour of exposure to the solar radiation. The plots of Figs. 9, 10 and 11 show the temperature distribution of the PV, air and wall after two hours of exposure to radiation of 800 W/m^2 in vertical position. This is the same time that the experimental device was exposed to constant radiation from the solar simulator.

The maximum temperature at the top side of the system for the PV, air and wall at the second hour of exposure to radiation was 63°C, 55°C and 26.8°C respectively.

However, regarding the temperature distribution particularly in the PV, air and wall:

- The temperature of the PV is higher at the top surface than the bottom. Specifically, at the second hour of exposure to constant radiation of 800 W/m^2 the PVs bottom surface was at 50ºC and the top 63°C.
- The air in the duct can get at extremely high temperatures and thus can increase the cooling loads of the building and thus affect the energy balance of the building.
- Most of the wall’s volume has almost constant temperature (less than 2ºC variation from the bottom to the top) and thus the assumption made earlier that the wall can be considered as an

isothermal plate is correct. The colour variation should not be confused as it applies for a much smaller range as shown on the right of each plot.

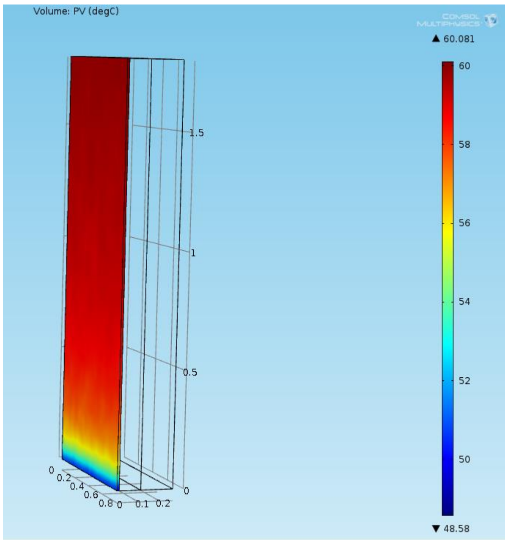


Fig. 9 The temperature distribution of the PV panel subjected to 800W/m² for two hours.

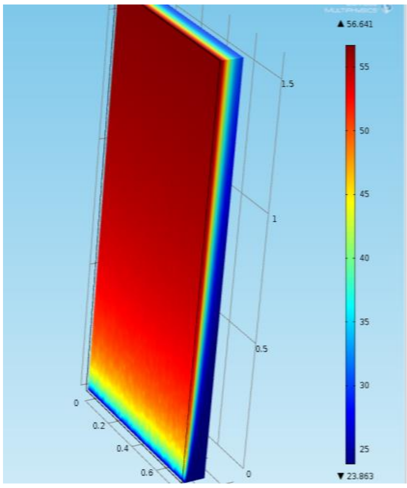


Fig. 10 The temperature distribution of the air subjected to 800W/m² for two hours.

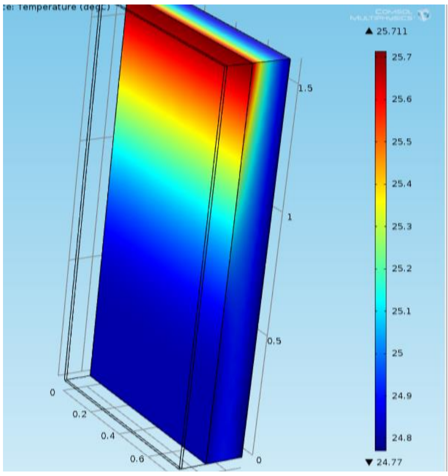


Fig. 11 The temperature distribution of the wall subjected to 800W/m² for two hours.

In order to have a clearer idea of the change of the temperature on the system, various boundaries on the system are selected to record their temperature (see Fig. 12). The temperature of the four boundary surfaces is shown in Fig. 13. As can be observed, the temperature of the wall inner surface as well as the temperature of the wall outer surface, remain almost constant during all the exposure time. The PV's maximum temperature reaches 63ºC and this is very close to the experimental results where the maximum temperature at the PV was 65ºC. The temperature at the boundary surface between the PV and the duct has similar trend to the line showing the temperature at the boundary at the front of the PV.

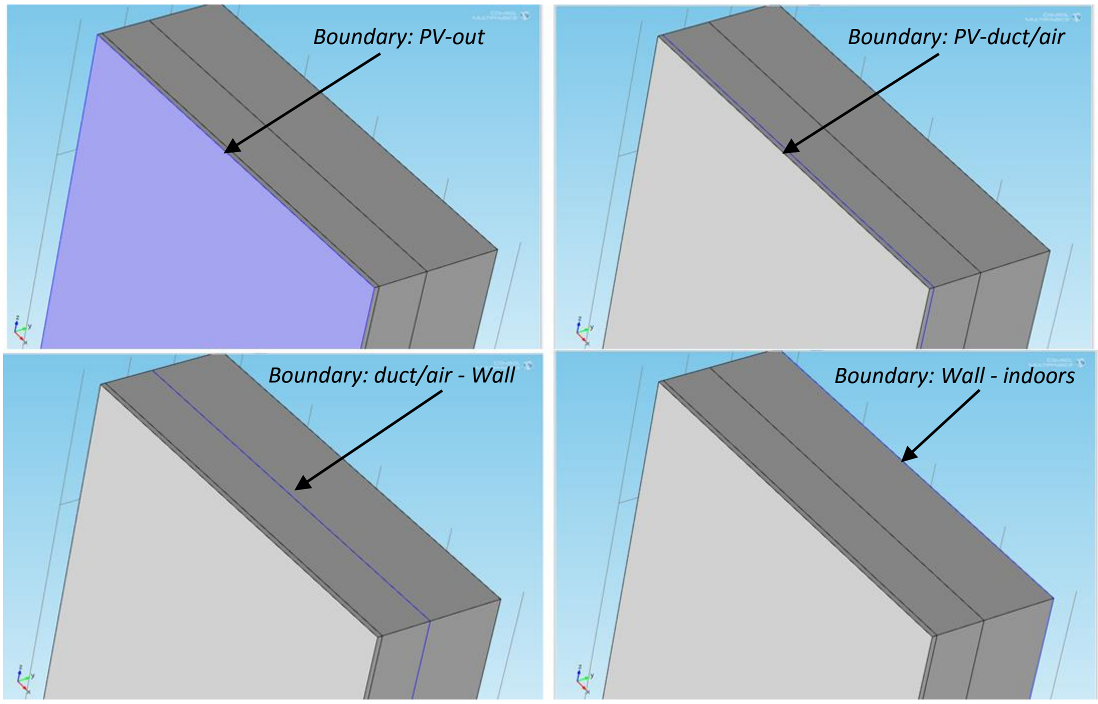


Fig. 12 Four boundary surfaces on the model selected to record their temperature variation during the system exposure on the incident solar radiation.

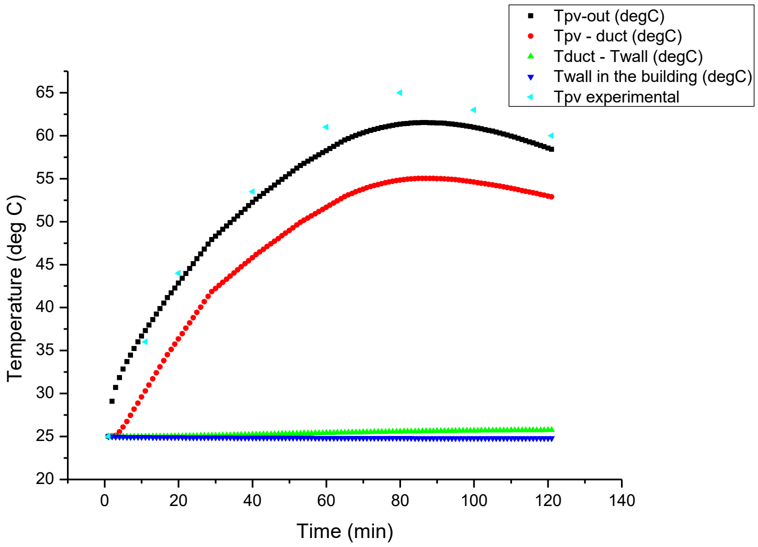


Fig. 13 Average temperature at the four boundaries of the system.

4 Conclusions

The thermal behaviour of the BIPV system is investigated with two methods; experimentally and with simulations. The general conclusion is that the results obtained from simulations are in a good agreement with the experimental results obtained in the laboratory with the use of the solar simulator.

- The temperature of the PV is not the same in all its area. It is observed from the experiments as well as from the simulation that the air flowing into the duct, keeps the PV surface at the bottom cooler than the top. Consequently, for further analysis and estimation of the convective heat transfer coefficients, the PV surface cannot be considered as an isothermal surface.
- The wall (second skin) temperature is not affected by the high temperature of the PV since both experiments and simulations showed that its temperature varies only by 1-2 ºC from the top to the bottom. Thus it can be considered as isothermal.

- The bigger the air gap the lower the temperature of the system and thus the higher its efficiency. The proposed air gap is 15 cm in order to keep high the efficiency of the system.
- The system in vertical position allow better air circulation through the duct. Consequently, the temperature of the system in vertical position is lower and in 30º is higher. The vertical position though is referred to BIPV façade and the 30º and 45º to roof BIPV systems. This is in agreement with the results from [4] and [15].

Beyond these, another observation is drawn regarding the thermal behaviour of BIPV systems. This involves the thermal behavior of the system in terms of its height. In both experiments and simulations, the system tested is of 1.60 m height, and the temperatures developed at the top side of the system showed to be around 64ºC on the PV's front surface and 55ºC in the air in the duct. Assuming that the system is composed of a number of PVs connected without open joints, the biggest the height of the system, the higher will be the developed temperature. Because of this, no more than one PV height should be used without inlet and outlet openings, because temperatures much higher than those obtained in this case will be developed. As concluded in the study of Sanjuan et al. [16], an open joint ventilated façade develops lower temperature than a sealed conventional façade system.

Nomenclature

Nu	Nusselt Number	L	Length of the duct (m)
Pr	Prandlt Number	$\dot{Q}$	Heat transfer rate from and to the system (W)
Cp	Specific heat of the fluid (J/kg K)	Ra	Rayleigh Number
u	Fluid velocity (m/s)	t	Time (s)
k	Thermal conductivity (W/m K)	T	Temperature (°C)

Greek symbols:

ρ Density of the fluid (kg/m^3)

Subscripts and superscripts:

L Length of the channel (m)

Acknowledgements

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