Air Flow Effect on the Temperature of a Building Integrated PV-Panel

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Abstract: This study examines the effect of air flow between the building integrated PV-panel and the wall of the building. To formulate the heat exchange process for a fluid flowing between the PV panel and the building wall, time-dependent, partial heat transfer differential equations (PDEs) are used and solved with the COMSOL simulations program. It is shown that in summer, the maximum temperature of a PV panel is observed on an east facing surface. The maximum temperature for a south facing panel is lower by about 27°C and that for a west facing surface by about 19°C. The air velocity in the air-gap between the PV-panel and the building wall lowers the mean temperature of the panel by about 35°C allowing for a significant increase in its efficiency. Finally the air-gap width is varied, keeping a steady velocity, and its effect is studied with respect to the temperature of the PV-panel.

Keywords: integrated PV-panel, air flow simulation, air-gap.

1. Introduction

The Renewable Energy Framework Directive sets a 20% target for renewable energy utilization and emissions reductions by 2020. Buildings account for 40% of the total primary energy requirements in the EU [1]. Therefore, developing effective energy alternatives for buildings, used primarily for electricity is of great importance. The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings.

A better appreciation of photovoltaic (PV) systems integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings, which is expected to rise dramatically in the next few years. This is further augmented by the recast of EPBD, which specifies that by the year 2020 the buildings in EU should have nearly zero energy consumption.

Meeting building electrical and thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures.

Among the renewable energy resources, solar energy is the most essential and prerequisite resource of sustainable energy because of its ubiquity, abundance, and sustainability. The systems that are usually employed in buildings are photovoltaic systems and solar thermal collectors. Photovoltaic systems are expected to take a leading role in providing the electrical energy needs, as they can contribute directly to the building electricity. Photovoltaics can supply the electricity required to the building or the generated electricity can be fed/sold to the grid. Direct grid connection is usually preferred as the system does not require batteries for energy storage and one takes advantage of higher electricity rates that can be obtained by selling the produced electricity to the grid.

In the last years, RES can be integrated on the buildings. The advantages of this method are that more space is available on the building for the installation of the required area of the RES and that the traditional building component is replaced by the RES one, which increases the economic viability of the systems. For example, photovoltaics are increasingly being incorporated into the construction of new buildings and are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades. Also photovoltaic systems may be retrofit-integrated into existing buildings.

The usual way to install a PV system on a house is to install it with brackets on a flat roof or on top of a sloping roof. The former is more pleasing aesthetically but the idea of building integration systems is to be able to replace a building element with the PV system and thus increase the prospects of the RES. Originally, one of the best typical applications considered to integrate PVs on buildings was as shading devices. These are installed over south facing windows, replacing the traditional overhangs. They also supply electricity from the PVs which are located at an optimal direction and angle to offer the maximum shading and also the maximum radiation capture.

Integration of the PV panels improves the cost effectiveness as they provide additional functions that involve active solar heating and daylighting. The following are some recognized methods of beneficial integration:

1. Integrating the PV Panels into the Building Envelope (BIPV)

This strategy involves the replacement of roof shingles or wall cladding with PV panels. It has significant advantages over the more usual “add-on” strategy. Not only does it eliminate an extra component (e.g., shingles), but it also eliminates penetrations of a pre-existing envelope that are required in order to attach the panel to the building. Architectural and aesthetic integration is a major requirement in this type of BIPV system. Not only can this strategy lead to much higher levels of overall performance, but it can also provide enhanced durability.

2. Integrating Heat Collection Functions into the PV Panel (BIPV/T)

PV panels typically convert from about 6 to 18% of the incident solar energy to electrical energy, and the remaining solar energy is available to be captured as useful heat. This is normally lost as heat to the outdoor environment. In this strategy, a coolant fluid, such as water or air, is circulated behind the panel, extracting useful heat. The coolant also serves to lower the temperature of the panel; this is beneficial, because the panel efficiency decreases with higher panel temperature. This strategy can be adopted in either an open-loop or a closed-loop configuration. In one open loop configuration, outdoor air is passed under PV panels and the recovered heat can be used for space heating, preheating of ventilation air, or heating domestic hot water - either by direct means or through a heat pump.

Two applications which fall into the above two categories are the PV roof and the PV façade. It should be noted that in this case the appropriate building component (roof or wall or their finish) is replaced by the PV. This is advantageous for the economic viability of the PV system but creates a number of problems that need to be resolved. These are the problems or rain penetration or protection and the increase of temperature of the building component and consequent thermal load of the building during summertime. For this purpose an air gap is created at the back of the PV and the basic building component through which usually fresh air is blown. This air can be directed into the building during winter time, in which case re-circulated air from the building is used or thrown away to the environment during summer time.

3. Integrating Light Transmission Functions into the PV Panel (BIPV/L)

This strategy uses special PV panels (semi-transparent PV windows) that transmit sunlight. As was the case for the previous approach, this strategy draws on the fact that only a fraction of the incident solar energy goes into electricity, and the remainder can be used for other purposes - in this case for useful light, thereby saving on the energy that electrical lights would otherwise draw. Thin-film PV cells that let some sunlight through are commercially available for this purpose. A major challenge is limiting the temperature rise of the windows, and controlling the impact of the associated heat gains, during times when building cooling is required. Compared to normal windows, these windows have a reduced light transmission and can therefore function as shading devices.

2. Mathematical Model

The aim of this study is to examine the effect of the air flow between the integrated PV panel and the wall of the building on the PV's temperature. For this reason, a model is designed with the use of COMSOL Multiphysics 4.3 in order to simulate the construction under several conditions.

Figure 1 shows a 3D view of the 3 m structure of the model with a PV panel, air gap and wall. As can be seen, the shape of the PV panel is not flat as it usually is. Because of the different shape of the PV panel, there is an air gap between the wall and the PV panel that it does not have the same width through all the structure. Figure 2 shows how the air moves in these different air gap sections and shows also the air velocity through them. It is assumed that the air velocity is higher in the parts with smaller width than in the parts with bigger air width.

To formulate the heat exchange process between a fluid flowing between the PV panel and the wall (Figure 1) basic heat transfer equations have been used.

For heat transfer in fluids the following heat equation may be used:

$$c_p \frac{\partial T}{\partial t} + \rho c_p u \nabla T = \nabla \cdot (k \nabla T) + Q, \qquad (1)$$

where t (s) is time, T (K) is fluid temperature, c_p (J/kg·K) is the specific heat at constant pressure, ρ (kg/m^3) is the fluid density, u is the flow velocity (m/s), k (W/m·K) is the thermal conductivity and Q (W/m^3) is one or more heat sources with positive sign if heat is added to the fluid volume and negative if heat is extracted from the volume (for instance when there is heat loss to the environment).

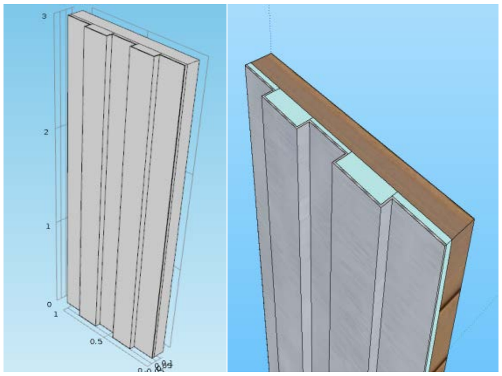

Figure 1. 3-D view of the air gap between the PV panel and the wall (dimensions in m).

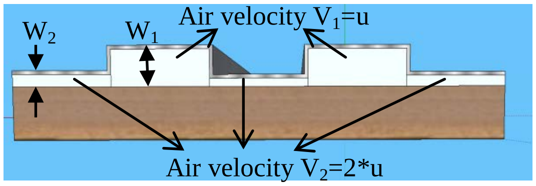

Figure 2. Assumed air velocity (V_1, V_2) in the various air gap widths (W_1, W_2).

The same equation can be used for the heat transfer in solids and provided that u = 0 the convective term is set to zero.

In the case of study the external side of the PV panel gains heat from solar radiation and loses heat 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. Finally at the external wall boundary heat is lost to the environment.

For the numerical solution set up, COMSOL Multiphysics 4.3b software has been used in 3D geometry. COMSOL offers the possibility to create the geometry, the grid, the pre-processing and post-processing solution under one software package. It is also characterized by its compatibility with other design and solution software packages and most importantly its adaptability where the user can manually import a required formula.

Numerical solution software COMSOL [2], can also adapt a physics controlled mesh where it is an automatic generated mesh according to the physics pre-selected by the user with the option to modify it according to the user needs. On the time dependent solver solution operation, COMSOL software can freely choose time steps, according to the calculated error, which can reduce computational memory and time.

3. Results and Discussion

As shown before in Figure 1 the structure consists of a PV panel, air gap and wall. To run the program, various properties of the materials must be adjusted according to a real case scenario. The actual values used, are shown in Table 1.

Table 1: Properties of the various construction components.

Property	PV panel	Air gap	Wall
ρ (kg/m^3)	1500	1.2	2000
c_p (J/kg·K)	1760	1000	1500
k (W/m·K)	0.36	0.026*	1.46
h (W/m^2·K)	15 (external surfaces)	3-3.5* (internal surfaces)	15

*Evaluated at every time step

Additionally, equations describing the solar radiation falling on the PV panel for a typical day in June in Cyprus were derived. The equations were used for three vertical surfaces facing east, south and west. In the simulations, 85% of the falling radiation was assumed to be converted into heat, whereas the other 15%, which is the usual efficiency of polycrystalline silicon solar cells, was assumed to be converted into electricity. The graphical presentation of the solar radiation on the three orientations during the day and the temperature variation are shown in Figure 3.

The internal heat transfer coefficient, between the air and the boundary surfaces was calculated using the following method: The air is considered as flowing between two parallel plates under uniform heat flux either in natural convection or flowing under forced convection with a fan.

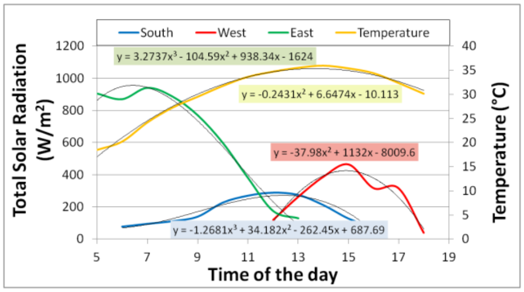

Figure 3. Equations presenting the Solar radiation on vertical surfaces orientated east, south and west and the temperature variation during a typical June day in Cyprus.

In the first case the Bar-Cohen and Rohsenow [3] analysis is employed, where the Nusselt number is given by:

$$\mathrm{Nu_L} = \frac{\mathrm{h_L S}}{\mathrm{k}} = \left[\frac{48}{\left(\frac{\mathrm{Ra_S S}}{\mathrm{L}}\right)} + \frac{2.51}{\left(\frac{\mathrm{Ra_S S}}{\mathrm{L}}\right)^{0.4}}\right]^{0.5}, \tag{2}$$

where L is the gap height and $\mathrm{Ra_S}$ is the Raleigh number for the gap opening S, given by:

$$\mathrm{Ra_S} = \frac{\mathrm{g\beta \dot{q}_S S^4}}{\mathrm{k\nu^2}}\mathrm{Pr}, \tag{3}$$

where:

$\mathrm{h_L}$: convective heat transfer coefficient
g: Acceleration due to gravity (= 9.81 $\mathrm{m/s^2}$),
k: Thermal conductivity of the air (W/m·K),
ν: Kinematic viscosity of the fluid ($\mathrm{m^2/s}$),
β: Volumetric coefficient of expansion of the fluid (1/K),
S: Air gap (m),
Pr: The Prandtl number,
$\dot{q}_S$: Heat flux ($\mathrm{W/m^2}$),

Using the data extracted from the calculations, the simulation for a reference structure of 3 m height, with air gaps of W_1= 0.07 m, W_2 = 0.02 m and a steady flow velocity of V_1 = 0.02 m/s and V_2 = 0.04 m/s, showed that the greatest temperature is experienced on an east facing surface and reaches to a maximum of 77°C early in the morning. However, the maximum temperature for a south facing panel reaches to a maximum 50°C and that for a west facing surface reaches 58°C. The maximum resulting temperatures on the external surface of the PV panel facing east, west and south are shown in Figure 4.

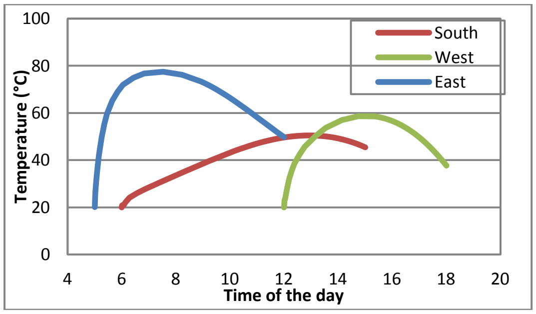

Figure 4. Mean resulting temperatures on the external surface of a PV-panel orientated east, south and west during a typical June day in Cyprus.

At this point it is very important to observe the heat flow through the structure. Figure 5 shows the temperature through the structure facing east where there is a gradual fall of the temperature in the width of the PV-panel, reaching a maximum of 72°C at the inside surface when the outside temperature is 77°C.

The flow of air drops the temperature in such a way that the wall temperature is only slightly affected after several hours (due to time lag), reaching a maximum of 28.5°C at the air-wall boundary and 20°C at its external surface. This shows that the air flow through the cavity causes sufficient cooling and the thermal load increase of the building is avoided.

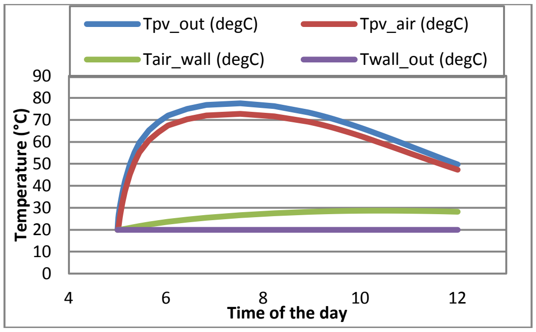

Figure 5. Mean resulting temperatures on the external and internal surface of the PV panel and the wall, orientated east, during a typical June day in Cyprus.

COMSOL can present pictorially the temperature variation in the structure facing east for the reference structure. It is clearly seen (Figure 6) that the lower part of the structure is cooler than the top part since the air is cooler at the entry (always equal to the ambient air) than the top. The same condition occurs also on the wall where we observe that the heat penetrates deeper on the top side of the wall causing a higher temperature than the lower side.

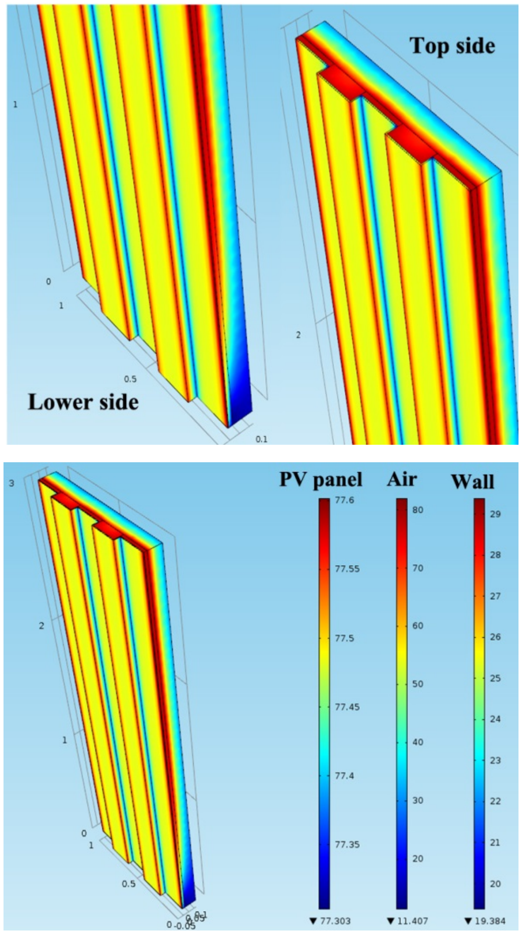

Figure 6. Temperature variation in the reference structure.

The two main variables that are of importance to the PV-panel temperature are the air gap width between the PV-panel and the wall and the air velocity. These two parameters are further examined in the following section.

Firstly, the system is simulated with different air gap widths and a constant air velocity. The results are shown in Figure 7. For the simulations a steady air velocity of V_1 = 0.25 m/s and V_2 = 0.5 m/s was used. The graph shows the variation in the average temperature at the boundary between the PV panel and the air gap in respect to the time. As it is shown, the larger the air gap width the less the average PV-panel temperature at the boundary between the PV-panel and air gap.

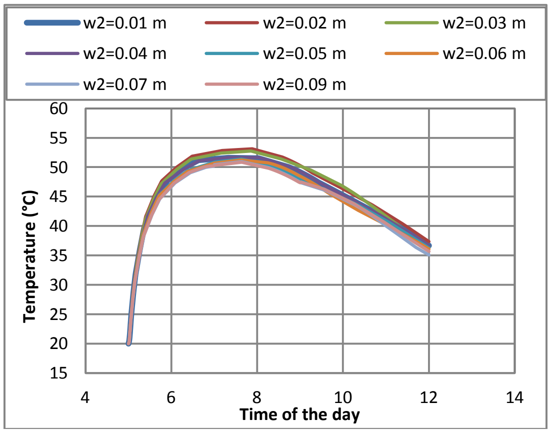

Figure 7. Effect of the air gap width (W_2), on the average temperature at the boundary between the PV panel and the air gap in respect to the time, for a constant air velocity and an east facing structure.

Additionally, the temperature at the same boundary for an east facing structure was plotted against the air gap width, at two different hours: at 7 am and 11 am (see Figure 8). As it is observed, the temperature at 7 am is higher than the temperature at 11 am because of the higher solar radiation falling on the structure. Also, it can be concluded that the lowest temperature at each time is reached with a width of W_2 = 7 cm. Larger widths have no additional effect on lowering the temperature.

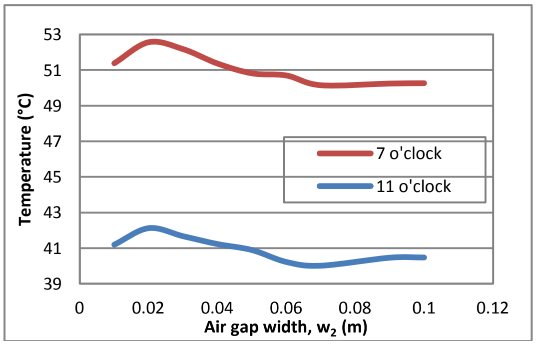

Figure 8. Average temperature at the boundary between the PV panel and the air gap against air gap width for an east facing structure and at a constant air velocity V_1 = 0.25 and V_2 = 0.5 m/s, at 7 and 11 am.

As already mentioned, the air velocity is another important factor. The results from the simulations to see the effect of the air velocity at the temperature at the boundary between the PV panel and the air gap are shown in Figure 9. The graphs are plotted for a constant air gap width of $W_1 = 0.07$ m and $W_2 = 0.02$ m. It can be observed that the higher the air velocity, the lower the temperature. An air velocity of $V_1 = 0.6$ m/s and $V_2 = 1.2$ m/s can lower the mean temperature of the panel from 77°C to 42°C allowing for a significant increase in its efficiency. Figure 10 shows the relation between air velocity V_2 and the temperature at the boundary between the PV panel and the air gap.

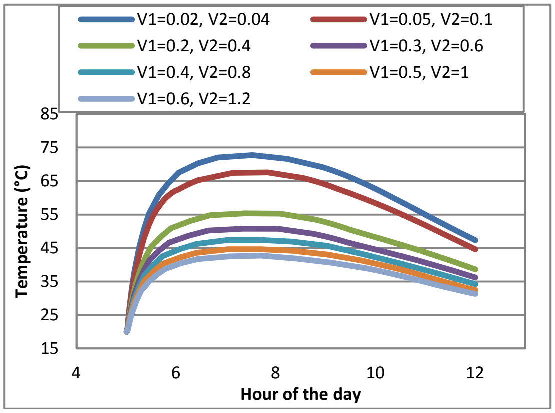

Figure 9. Effect of the air velocity on the average temperature at the boundary between the PV panel and the air gap in respect to time, for an air gap width of $W_2 = 0.02$ m.

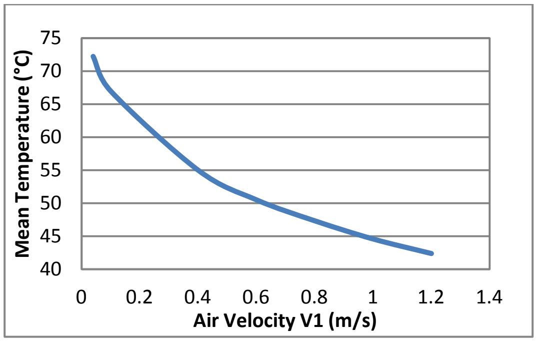

Figure 10. Mean temperature at the boundary between the PV panel and the air gap against air velocity V_1 for an east facing structure at a constant air gap width of $W_2 = 0.02$ m.

4. Conclusions

This study focuses on the BIPVs and the effect of the air flow on a building integrated PV panel facing east, south and west. Two important parameters affect the temperature of the PV panel, the air gap width and the air velocity and their effect is examined.

The results showed that the maximum temperature of a PV-panel of 3 m in height facing east, in summer reaches 77°C early in the morning. However, the maximum temperature for a south facing panel is 50°C and that for a west facing surface is 58°C.

The air-gap width is varied for a steady velocity of $V_1 = 0.25$ m/s and $V_2 = 0.5$ m/s and it is shown that the temperature of the building wall remains constant for an air gap width W_2 bigger than 0.07 m while the highest temperature occurs when the air gap width W_2 is 0.02 m.

Finally it is shown that for an air gap width of $W_2 = 0.02$ m, an air velocity of $V_1 = 0.6$ m/s and $V_2 = 1.2$ m/s can lower the mean temperature of the panel from 77°C to 42°C allowing for a significant increase in its efficiency.

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6. References

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