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Nonlinear Interfacial Wave Phenomena from the Micro- to the Macro-Scale

The effect of air flow on a building integrated PV-panel

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Abstract

Photovoltaic (PV) materials are increasingly being incorporated into the construction of new buildings for generating electrical power 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 advantage of integrated photovoltaic systems over the non-integrated systems is that their initial cost can be offset by reducing the cost of the materials and labour that would normally be spent to construct the part of the building that is replaced.

This study examines the effect of air flow on a building integrated PV-panel. It is shown that in summer, the maximum temperature of a PV-panel of 3 m in height is experienced for an east facing surface and reaches 77°C early in the morning. The maximum temperature for a south facing panel is 51°C and that for a west facing surface is 58°C. The air velocity in the air-gap between the PV-panel and the building wall is an important factor. It is shown that for an air-gap width of 0.02 m, an air velocity of 0.5 m s^{-1} can lower the mean temperature of the panel from 77°C to 39°C, allowing for a significant increase in its efficiency. Finally the air-gap width is varied for a steady velocity of 0.2 m s^{-1}, and it is shown that the temperature of the building wall varies from 23.7°C for a width of 0.01 m to 20°C for a width of 0.05 m.

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Keyword: Photovoltaics, building integration, convection heat transfer, thermal modeling

1. Introduction

The Renewable Energy Framework Directive sets a 20% target for renewable energy utilisation 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 Renewable Energy Sources (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

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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. Photovoltaic systems are expected to take a leading role in providing the electrical energy needs, as they can contribute directly to the building electricity.

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 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.

The advantages of building integration of RES are that more space is available on the building for the installation of the required area of the RES systems and that the traditional building component is replaced by the RES one, which increases the economic viability of the systems.

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 system. Originally, one of the best typical applications considered to integrate PV 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 improves the cost effectiveness by having the PV panels provide additional functions that involve active solar heating and daylighting. The following are some recognized methods of beneficial integration:

A. *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.

B. *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 increases with lower panel temperature. This strategy can be adopted in either an open-loop or a closed-loop configuration. In an 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 that fall into the above two categories are the PV roof and the PV façade. It should be noted that in these cases 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: protection from rain penetration and increase of temperature of the building component and consequent addition of thermal load to the building during summertime. For this purpose an air gap is left between the back of the PV panel and the basic building component through which usually fresh air is allowed to flow. This air-flow 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.

C. *Integrating Light Transmission Functions into the PV Panel (BIPV/L)*. This strategy uses special PV panels (semi-transparent PVs) that transmit sunlight. As was the case for the previous approach, this strategy utilises the fact that only a fraction of the incident solar energy is converted into electricity, and the remainder can be used for other purposes - in this case for useful lighting, thereby saving energy that electrical lights would otherwise use. Thin-film PV cells that let some sunlight through are commercially available for this purpose. A major challenge is to limit the temperature rise of the windows, and control 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

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

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

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

where t (s) is time, T (K) is fluid temperature, c_p (J kg^{-1} K^{-1}) is the specific heat at constant pressure, ρ (kg/m^3) is the fluid density, u is the flow velocity (m s^{-1}), k (W m^{-1} K^{-1}) 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).

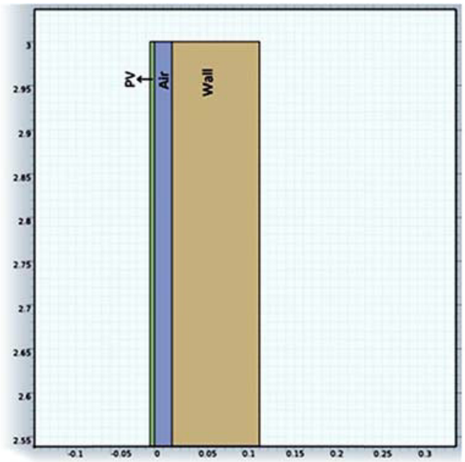

Fig. 1. Side view of the air gap between the PV panel and the wall (dimensions in m).

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, while 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 4.3a software[2] has been used in 2D 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, 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

To run the program the various parameters were adjusted according to a real case scenario. The actual values used are shown in Table 1.

Table 1. Physical properties.

Property	ρ kg m^{-3}	c_p J kg^{-1} K^{-1}	k W m^{-1} K^{-1}	h W m^{-2} K^{-1}
PV-panel	1500	1760	0.360	16 (external surfaces)
Air-gap	1.2	1000	0.026*	3–3.5* (internal surfaces)
Wall	2000	1500	1.460	15

Note: *Evaluated at every time-step

Also equations describing the solar radiation falling on the PV panel were derived for a typical day in June in Cyprus and used for three vertical surfaces facing east, south and west. In the simulations it was assumed that 85% of the falling radiation is converted to heat, whereas the other 15% is converted into electricity that is the usual efficiency of polycrystalline silicon solar cells. The graphical presentation of the solar radiation on the three orientations during the day and the temperature variation are shown in Fig. 2.

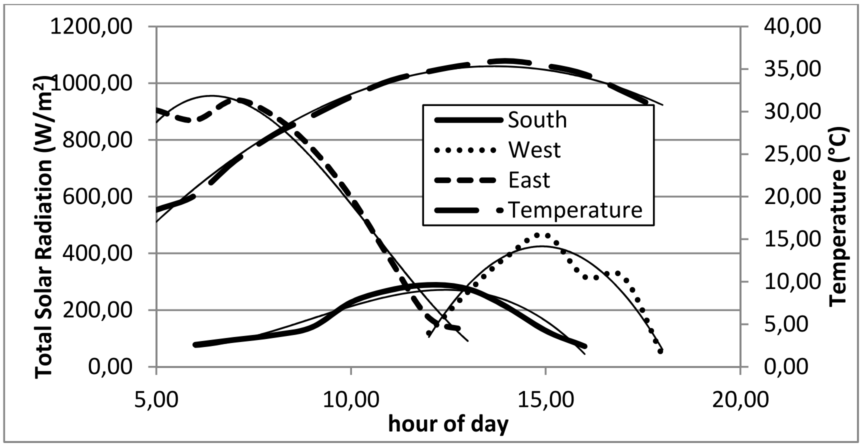

Fig. 2. Solar radiation on vertical surfaces orientated east, south and west and the temperature variation during a typical June day in Cyprus.

The internal heat transfer coefficient between the air and the boundary surfaces was calculated using the following method. The flow is considered to occur between two parallel plates under uniform heat flux. There are two cases here; the first is when the system operates under natural convection and the second when operating under forced convection where a fan is used to create a flow of air in the gap between the PV and the wall element. In the first case the Bar-Cohen and Rohsenow[3] analysis is employed with the Nusselt number (Nu_L) being given by

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

where L is the gap height and Ra_S is the Raleigh number for the gap opening S, given by

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

where g is the acceleration due to gravity (= 9.81 m s^{-1}), β is the volumetric coefficient of expansion, $\dot{q}_S$ is the heat flux, S is the air-gap, k is the thermal conductivity of the air, ν is the dynamic viscosity and Pr is the Prandtl number.

By following the above analysis for the gap of 0.05 m the heat transfer coefficient h obtained is 3.909 W m^{-2} K^{-1}. The values for the various air-gap sizes are shown in Table 2. By assuming that the system is operating under forced convection in the laminar flow range the velocities that correspond to these heat transfer coefficients can be calculated. This assumption is not absolutely correct but gives an indication of the velocities needed as input to the program to solve Eq. (1). Under this condition, for a large aspect ratio of the air channel the Nusselt number is fixed and equal to 8.24 (for a constant heat flux). This gives a heat transfer coefficient equal to 2.253 W m^{-2} K^{-1}, which - although differring from the above value - is of the same order of magnitude. The maximum air velocity to achieve laminar flow so as this analysis is valid gives a velocity of 0.395 m s^{-1}.

By following this analysis the velocity obtained for the various air gaps is shown in Table 2.

Table 2. Heat transfer coefficient and maximum air velocity in the gap.

Gap size (m)	h W m^{-2} K^{-1}	Maximum velocity m s^{-1}
0.02	3.627	0.959
0.04	3.889	0.489
0.06	3.919	0.332
0.09	3.927	0.228

Using the above data, the simulation for a 3 m PV-panel, with an air gap of 0.02 m and a steady flow velocity of 0.05 m s^{-1}, showed that the greatest temperature is experienced on an east facing surface that reaches a maximum of 77°C early in the morning (Fig. 3). The maximum temperature on a south facing panel is 51°C, while that on a west facing surface is 58°C.

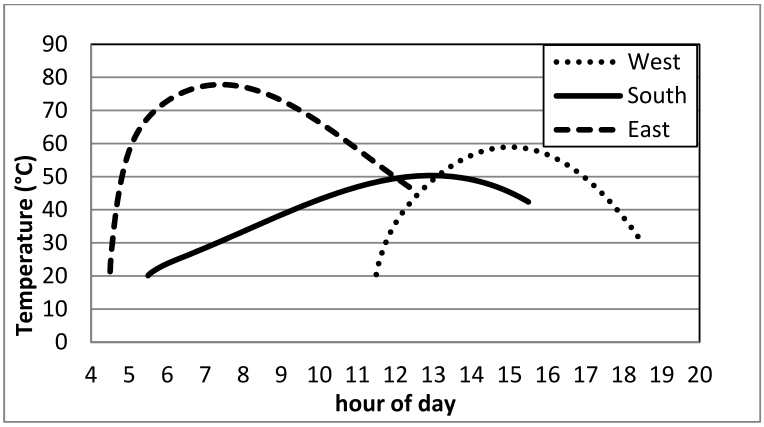

Fig. 3. Mean resulting temperatures on the external surface of a PV-panel orientated east, south and west during a typical June day in Cyprus.

At this point it is of interest to observe the heat flow through the structure. Fig. 4 shows that there is a gradual fall of the temperature in the width of the PV-panel, reaching a maximum of 71°C at the inside surface when the outside temperature is 77°C. Then the flow of air causes a drop of the temperature in such a way that after several hours, the wall temperature is only slightly affected, reaching a maximum of 27.5°C at the air-wall boundary and 23.5°C at its outer surface. This shows that the air flow through the cavity causes sufficient cooling and the thermal load increase of the building is avoided.

Next we observe the temperature variation in the structure (Fig. 5) for an air gap of 0.02 m and a steady air flow velocity of 0.05 m s^{-1}. It is clearly seen that the lower part of the structure is cooled more 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 increasing its temperature more than the lower side.

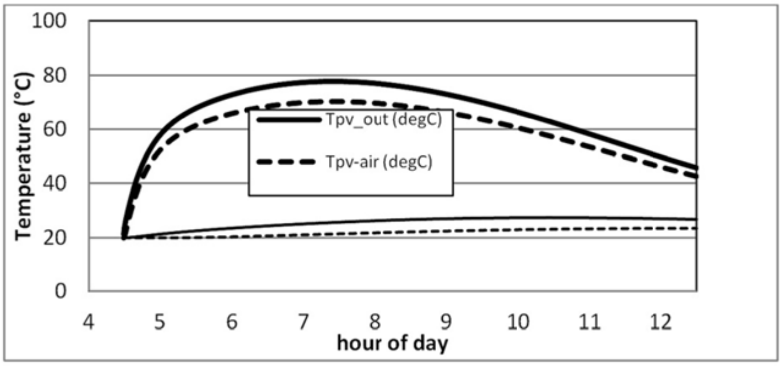

Fig. 4. Mean resulting temperatures on the external and internal surface of the PV-panel and the wall, orientated east during a typical June day in Cyprus.

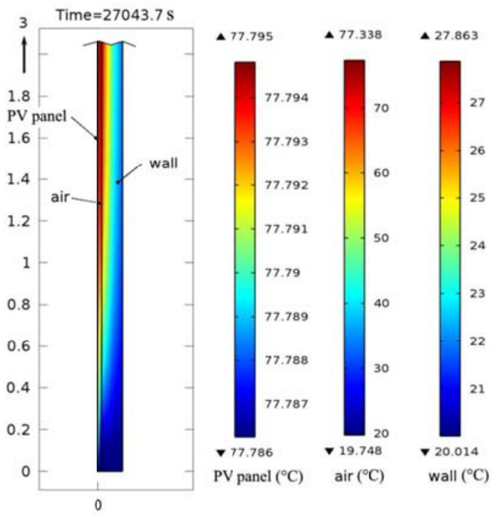

Fig. 5. Temperature variation in the structure for an air gap of 0.02 m and a steady flow velocity of 0.05 m s^{-1}.

The two main variables that are of importance to the PV-panel temperature are the air-gap width and the air velocity. Fig. 6 shows the effect of the air-gap width w for a steady air velocity of 0.2 m s^{-1}. As it is shown, the bigger the gap the less the average PV-panel temperature is at the boundary between the PV-panel and the air gap. By plotting the temperature against the air-gap width, shown in Fig. 7, it can be concluded that a width greater than 0.05 m has no additional effect on the temperature.

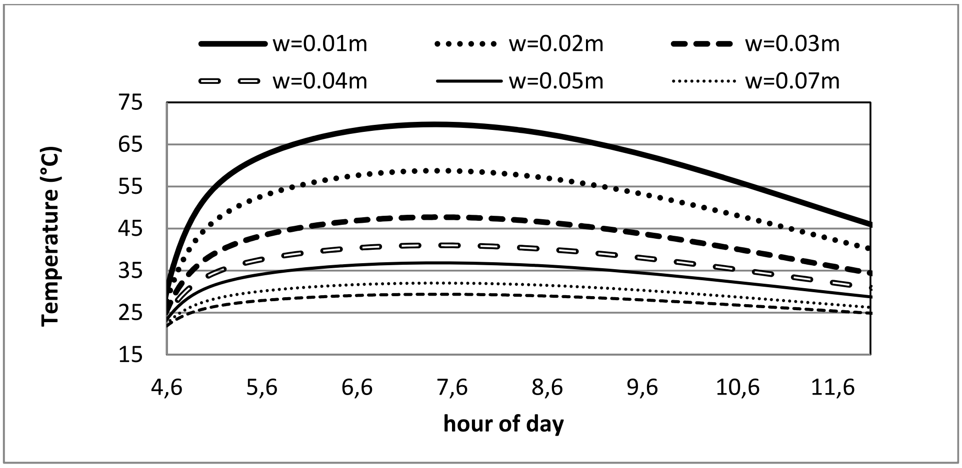

Fig. 6. Effect of the air-gap width w on the average temperature at the boundary between the PV-panel and the air-gap with respect to time, for an air velocity of 0.2 m s^{-1}.

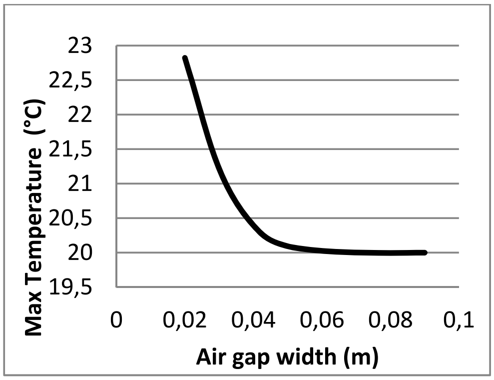

Fig. 7. Maximum temperature at the boundary between the PV-panel and the air gap against the air-gap width, for an air velocity of 0.2 m s^{-1}.

Finally, it is shown that the air velocity is another important factor. Its increase has a similar effect as the increase of the air-gap length. As it is shown in Fig. 8, drawn for an air-gap length of 0.02 m, an air velocity of 0.6 m s^{-1} can lower the mean temperature of the panel from 77°C to 39°C and a velocity of 1.2 m s^{-1} to 31.7°C, allowing for a significant increase in its efficiency. Fig. 9 shows that an increase of the air velocity will have additional cooling effect on the panel.

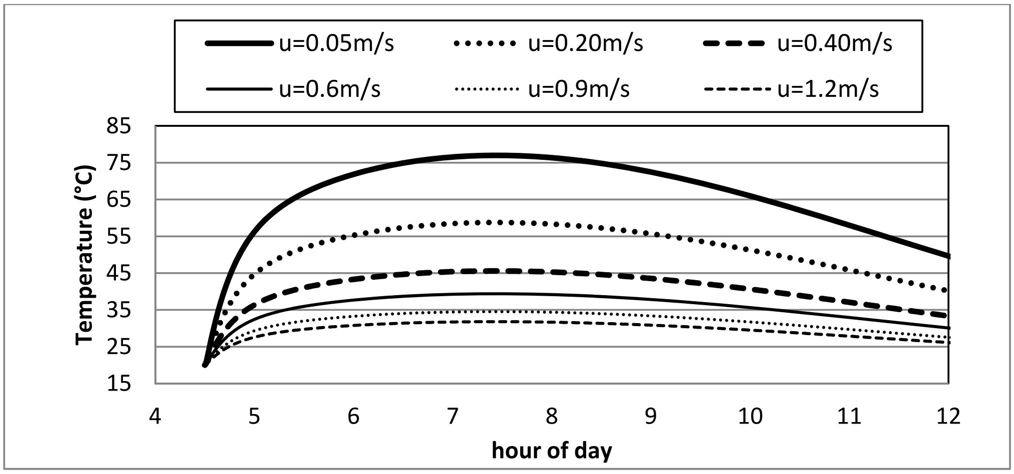

Fig. 8. Effect of air velocity on the average PV-panel temperature at the boundary between the PV-panel and the air gap with respect to time, for an air gap length of 0.02 m.

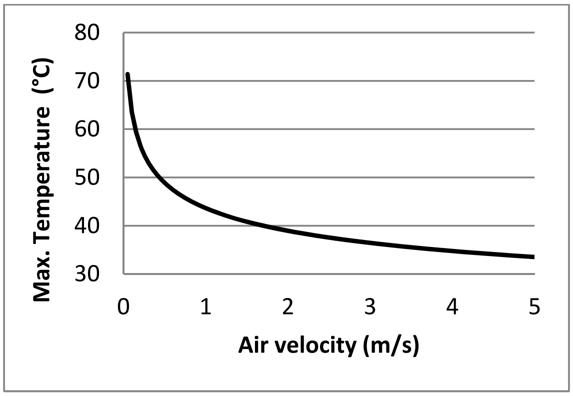

Fig. 9. Average PV-panel temperature against air velocity, for an air-gap length of 0.02 m.

4. Discussion

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 PV and STS integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. This uptake in RES in buildings is expected to rise dramatically in the next few years. This is further augmented by a recast of the Directive, which specifies that the buildings in EU should have nearly zero energy consumption (residential and commercial buildings by the year 2020 and public buildings by 2018). Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good insulation or advanced glazing systems. Both PV and STS are expected to take a leading role in providing the electrical and thermal energy needs, as they can contribute directly to the building electricity, heating, cooling and domestic hot water requirements.

As can be seen from the solutions presented in this paper a number of ideas have been tried and others are just at the concept stage and generally more R&D effort is needed. It is believed that in the coming years more and more of these solutions/ideas will find their way in the market in view of the implementation of the directives imposed by the EU.

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