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Topic n°2: Passive heating, passive cooling and renewable energy for buildings

Integrated thermal modelling of photovoltaic panels for the solar protection of buildings in tropical and humid conditions

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SUMMARY

This paper deals with the integrated thermal modelling of photovoltaic panels for the solar protection of buildings under strong solar radiation as encountered in tropical and humid conditions. The thermal model is integrated in a building simulation code and is able to predict the thermal impact of PV panels installed on buildings in several configurations and also their electric production. Basically, the PV panel is considered as a complex wall within which coupled heat transfer occur. Conduction, convection and radiation heat transfer equations are solved to simulate the global thermal behaviour of the building envelope including the PV panels. The model is first detailed, with a focus on the radiation modelling within the semi-transparent layers of the panels and then preliminary results are presented in terms of verification. Conclusions are finally drawn regarding the impact of the panels in terms of thermal insulation for summer tropical conditions.

INTRODUCTION

Renewable solar energy is an important alternative to the use of fossil energy and therefore constitutes a convenient part of the solution for the problem of global warming. With the decreasing potential of fossil materials for use with the existing means of electricity production, and also the increasing rate of pollution of human origin, it is necessary to study new solutions for the electricity needs of human activities as well as human comfort.

Photovoltaic panels, constituted with assemblies of several photovoltaic cells, are more and more used to produce electricity and are installed on buildings in several configurations.

In addition to their ability to convert solar energy, and considering their installation on well exposed building walls to solar radiation, photovoltaic panels also play the role of an insulation system for the corresponding wall, which in some case, like the one considered here, is an important point when dealing with problems like solar protection of buildings.

In La Reunion Island for example, where solar radiation is strong and coupled with a high level of humidity (tropical and humid climate), it is more and more important to have a good solar protection of the exposed walls (especially the roof), in order to reach thermal comfort conditions and thus reduce the need for active cooling during summer.

In this article, we thus focus on a thermal model for the behaviour of photovoltaic panels, with the objective of characterising the solar protection they offer, and consequently their impact on the comfort conditions on a typical building of La Reunion Island. The thermal model is integrated in an existing building simulation code, named ISOLAB (Miranville, 2002), which is a dynamic simulation tool used to predict the thermal field of building envelopes. The PV thermal model is more precisely derived using the existing structural architecture of the code, and that's the reason why the implementation of the model is qualified as an "integrated" one. This approach is linked to the topic concerned by this paper, but more generally, to existence of strong energy couplings between building envelope and PV panel. This approach is the one choose in major codes as ESP (Clarke 2001).

After a brief description of the building simulation code, a focus is proposed on the PV thermal model, and especially the radiation relations. Then two cases are presented, the first one proposing a preliminary verification step and the second showing the thermal impact of a PV panel installed as a roof on a typical well known building (case 600 from the BESTEST procedure, (Judkoff 1995)).

DESCRIPTION OF THE BUILDING SIMULATION CODE ISOLAB

The thermal PV model is integrated in a typical building simulation code, developed for research purposes, named ISOLAB. Implemented with MATLAB platform, the code is actually dedicated to models testing before integration in the CODYRUN software, developed and distributed at the Building Physics and Systems Laboratory of the University of La Réunion Island (Boyer 1996). This simulation code is able to predict the heat and mass transfer in buildings according to a nodal 1D description of the building and its corresponding thermophysical and geometrical parameters. Other aspects are linked to pollutants and daylighting calculations. For the thermal model, the resolution is based on a finite difference numerical scheme and the system of differential equations, written in a matrix form, is solved numerically for each time step.

The initial point for the physical description of the whole building is a typical wall, within which the heat balance equation for the conduction mode of heat transfer is solved, considering a dynamic evolution of the thermal temperatures and a volumic production of energy. The discretisation of the differential equations for each node of the physical description leads to a system of algebraic equations, specific to the wall, which is written in a matrix form. When assembling every matrix corresponding to the several walls of the building, it is possible to generate the matrix for the whole building and from a thermo-convective balance equation of the air volume surrounded by the walls (supposed isothermal and homogenous), this approach allows calculation of the thermal field.

INTEGRATED THERMAL MODELLING OF PV PANELS

The thermal modelling of the PV panels is done through ISOLAB with the addition of new types of wall, corresponding to the most used configurations. Quite similar as PVSYST (Mermoud 1994), a reference dedicated PV simulation software, the various configurations of PV panels considered are the following (*Figure 1*) :

- Non integrated (to the wall)
- Integrated
- Window

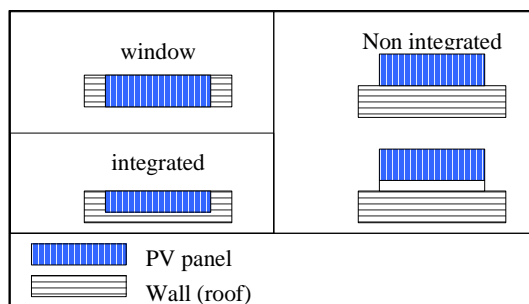


Figure 1: Typical configurations of PV panel installation

These descriptions allow the modelling of all types of typical existing panels.

The hypotheses for the conduction heat transfer within each layer of the PV wall are identical to the classical walls. For the convection heat transfer, the wall is subject to forced convection at the exterior face and natural or forced convection (depending on the considered configuration) at the interior face. Actually, the boundary convection conditions, whether forced or natural, are inherited from the existing convection models of the code. These are well described in (Miranville, 2002) and are quite common to all building simulation codes. The correlation from Sturrock is for example widely used in simulations when comparing the predictions to measured values. For the radiation heat transfer through the PV walls, the model is specific and has been developed according to the following assumptions:

- Silicium layers are thin enough to admit that the whole radiation is transformed in electricity,
- The PV wall is considered to be divided in two parts : the first is a semi-transparent multilayer system, and the second is an opaque multilayer when not of “window” type,
- Temperatures are lower than 300°C, and semi-transparent materials used in PV panels are totally opaque for the infrared radiation for these temperatures,
- The temperature influence on the absorption coefficient is taken into account due to an efficiency coefficient. This coefficient is given by the panel constructor.

The equations of the thermal model are written such that they can be integrated in the whole matrix system given for the considered building; this last one can be, in a numeric form, expressed in the following well known form:

$$[A]_i \cdot [T]^t = [A]_e \cdot [T]^{t+1} + [B]$$

Matrixes $[A]_i$ and $[A]_e$ describe the composition of the various materials constituting the building, while matrix $[B]$ corresponds to outside or internal sollicitations of the system. Matrixes $[T]^t$ and $[T]^{t+1}$ contain all nodes temperatures of all walls.

In this case, it has been necessary to create a PV panel model which is based on the same level of discretisation of the existing equations of the code; hence the conduction problem is defined by the heat balance equation:

$$\Delta T + \frac{P}{\lambda} = \frac{1}{a} \cdot \frac{\partial T}{\partial t}, \text{ with } \begin{cases} a = \frac{\lambda}{\rho \cdot C_p} \\ T = T(x, t) \end{cases}$$

To integrate convective exchanges as boundary conditions for the heat transfer equation, it is necessary to affect convenient values to the convection coefficients h_c for fluid / solid interfaces. It is so necessary to define the various types of convection:

- Natural Convection in an isolated air layer
- Natural Convection in an air or water layer between two flat plates,
- Forced convection in an air or water layer circulating between two flat plates.

These configurations are for fluid (air or water) layers between two boundaries, and thus are likely to be applied into the PV wall. For the exterior surfaces, as indicated previously, typical well known correlations are used.

Like convection heat transfer, radiation is integrated in the heat transfer equation as an additional sollicitation. In a panel constituted with several different layers of semi-transparent materials, the radiative transfer can be defined schematically as indicated on **Figure 2**.

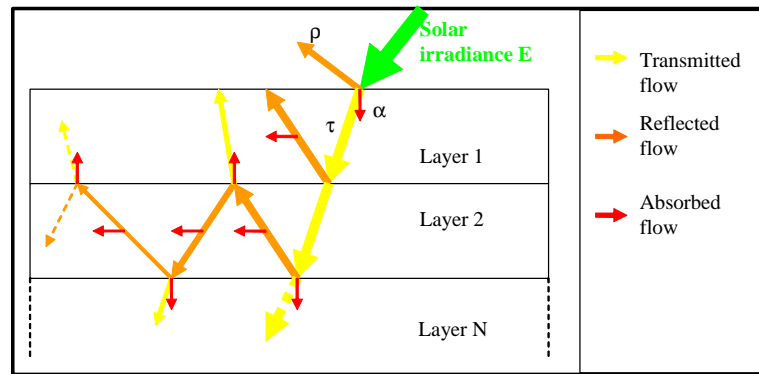


Figure 2 : section view of the multiple reflections phenomena in a semi-transparent multilayer material (Siegel, 1992).

The layer N corresponds to the last layer ($\tau > 0$, if not an opaque layer).

A system describing radiative flux exchanges can be defined for such a configuration:

$\Phi_{\text{abs}}(i,1,j)$ is the flow absorbed by the layer I at the iteration j on its exterior face ($\Phi_{\text{abs}}(i,2,j)$ corresponds to the inside); $\Phi_{\text{trans}}(i \rightarrow k,j)$ is the flux transmitted to the layer k by the layer i in the iteration j, and $\Phi_{\text{ref}}(i \rightarrow k,j)$ is the reflected flux by the layer i on the layer k for the iteration j. In the below relations, the indicated physical parameters are the following:

- α_i : absorption coefficient of the layer i
- τ_i : transmission coefficient of the layer i
- ρ_i : reflectivity coefficient of the layer i
- ε_i : emissivity coefficient of the layer i
- F_{pe} : view factor between the panel and the environment
- F_{pi} : view factor between layers i and j

E: incident shortwave radiation
 Ti: temperature of the layer i
 Φ_{abs} : absorbed radiation flux
 Φ_{trans} : transmitted radiation flux
 Φ_{ref} : reflected radiation flux

In terms of equations, the physical phenomenon can be described as indicated below:

- Initial condition :

$$\begin{aligned}\Phi_{abs}(1,1,1) &= E \cdot S \cdot \alpha_1 \cdot F_{pe} \\ \Phi_{trans}(1 \rightarrow 2,1) &= E \cdot S \cdot \tau_1 \cdot F_{12} \\ \Phi_{trans}(N+1 \rightarrow N,1) &= \varepsilon_{N+1} \cdot \sigma \cdot S \cdot T_{N+1}^4 \cdot F_{N+1,N}\end{aligned}$$

- boundary conditions : for $2 \leq j \leq I$:

$$\begin{aligned}\Phi_{abs}(1,2,j) &= \Phi_{abs}(1,j-1,2) + (\Phi_{ref}(2 \rightarrow 1,j-1) + \Phi_{trans}(2 \rightarrow 1,j-1)) \cdot \alpha_1 \cdot F_{21} \\ \Phi_{trans}(N+1 \rightarrow N,j) &= 0; \quad \Phi_{trans}(1 \rightarrow 2,j) = 0; \quad \Phi_{ref}(1 \rightarrow 2,j) = 0 \\ \Phi_{ref}(N+1 \rightarrow N,j) &= (\Phi_{trans}(N \rightarrow N+1,j-1) + \Phi_{ref}(N \rightarrow N+1,j-1)) \cdot \rho_{N+1} \cdot F_{N+1,N}\end{aligned}$$

- System description : for $2 \leq j \leq I$ et $2 \leq i \leq N$:

$$\begin{aligned}\Phi_{abs}(i,1,j) &= \Phi_{abs}(i,j-1,1) + (\Phi_{ref}(i-1 \rightarrow i,j-1) + \Phi_{trans}(i-1 \rightarrow i,j-1)) \cdot \alpha_i \cdot F_{i-1,i} \\ \Phi_{abs}(i,2,j) &= \Phi_{abs}(i,j-1,2) + (\Phi_{ref}(i+1 \rightarrow i,j-1) + \Phi_{trans}(i+1 \rightarrow i,j-1)) \cdot \alpha_i \cdot F_{i+1,i} \\ \Phi_{ref}(i \rightarrow i-1,j) &= (\Phi_{trans}(i-1 \rightarrow i,j-1)) \cdot \rho_i \cdot F_{i-1,i} \\ \Phi_{ref}(i \rightarrow i+1,j) &= (\Phi_{trans}(i+1 \rightarrow i,j-1)) \cdot \rho_i \cdot F_{i+1,i} \\ \Phi_{trans}(i \rightarrow i-1,j) &= (\Phi_{trans}(i+1 \rightarrow i,j-1) + \Phi_{ref}(i+1 \rightarrow i,j-1)) \cdot \tau_i \cdot F_{i,i-1} \\ \Phi_{trans}(i \rightarrow i+1,j) &= (\Phi_{trans}(i-1 \rightarrow i,j-1) + \Phi_{ref}(i-1 \rightarrow i,j-1)) \cdot \tau_i \cdot F_{i,i+1}\end{aligned}$$

The absorbed flux by the layer situated after the PV system and the absorbed flow by each layer are known:

$$\begin{aligned}\Phi_{abs}(N+1,1) &= \alpha_{N+1} \cdot F_{N,N+1} \cdot \sum_{j=1}^{j=I} \Phi_{trans}(N \rightarrow N+1,j) \\ \Phi_{abs}(i,1) &= \sum_{j=1}^{j=I} \Phi_{abs}(i,j,1) \quad \Phi_{abs}(i,2) = \sum_{j=1}^{j=I} \Phi_{abs}(i,j,2)\end{aligned}$$

Iterations can be stopped when the residual energy of the system is lower than a threshold value (*error*):

$$\sum_{i=1}^N (\Phi_{trans}(i,j) + \Phi_{ref}(i,j)) - \sum_{i=1}^N (\Phi_{trans}(i,j-1) + \Phi_{ref}(i,j-1)) \leq error$$

The integration of the PV module to the building simulation is done according to the synoptic of **Figure 3**. Once the thermal model of the considered building without PV panels is

generated, a test is done in order to detect the inclusion of PV panels; if PV panels are detected, the PV module generates the corresponding system of equations and solves the whole model. Results can then be analysed.

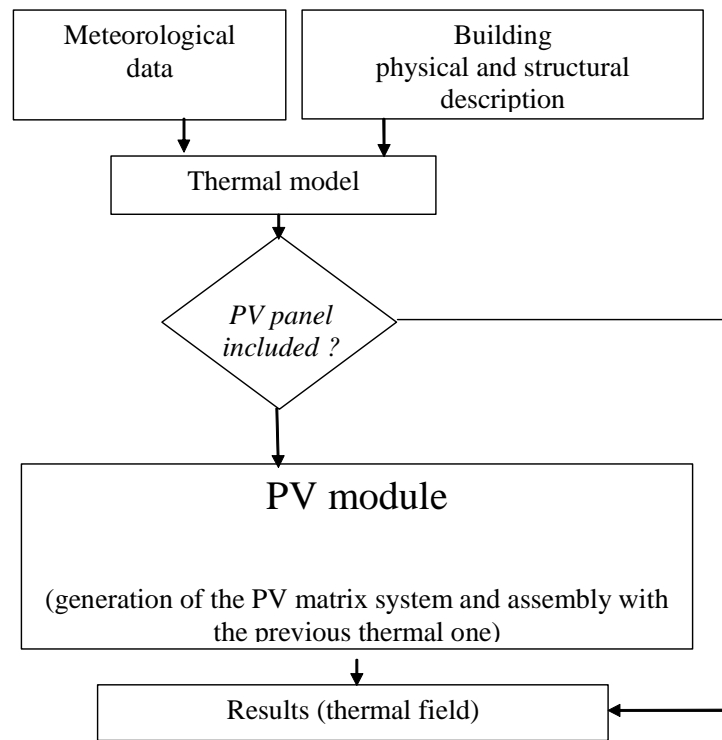


Figure 3 : Integration of the PV calculation module to the existing Isolab code.

RESULTS AND DISCUSSION

In order to verify the correct implementation of the PV module, a comparison is proposed between two thermal models of the same building, the first one using ISOLAB in a previous version (not integrating the PV model) and the second one with the PV module included. Since the PV module is based on the thermal model initially included in ISOLAB, a simple opaque wall can thus be modeled as well as complex PV panels. Hence, using a simple test case building, it is possible, in addition to the several verifications of the implementation, to indirectly put in evidence the correct inclusion of the PV module.

To illustrate the approach, a well known building description has been used, the case 600 included in the BESTEST procedure (Judkoff 1995). As ISOLAB has passed these tests before its modification, if the new results of the same building are accurately reproduced, then we can conclude that the implementation is valid.

A comparison with the BESTEST case (600) has thus been conducted and shows a very good agreement (the curve are actually superposed), as indicated on **Figure 4**, where air temperatures for each models are drawn for a period of 5 summer days (from day 179 to day 183).

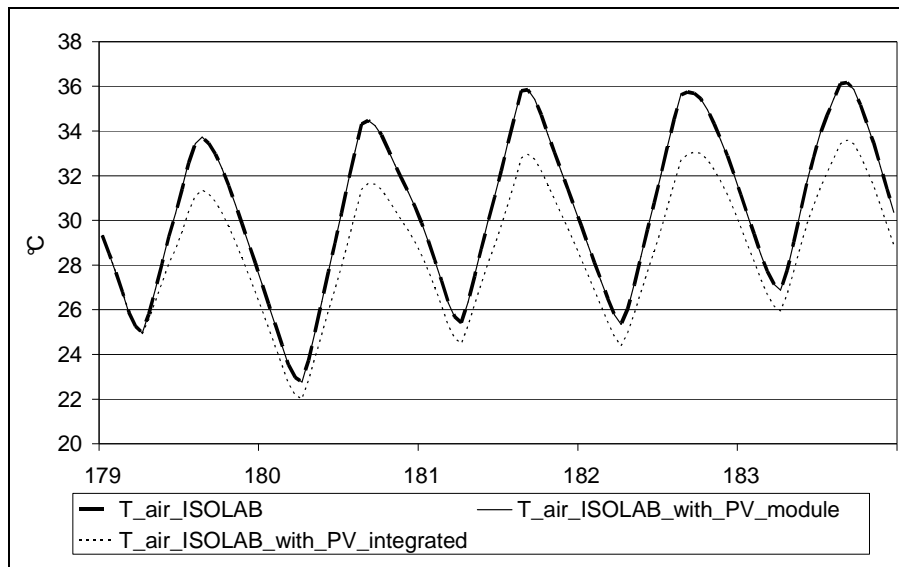


Figure 4: Air temperatures comparison between three thermal models : case 600 described with ($T_{air_ISOLAB_with_PV_module}$) an without (T_{air_ISOLAB}) the PV module and case 600 modified with the inclusion of a PV integrated roof ($T_{air_ISOLAB_with_PV_integrated}$)

The residual between the two evolutions of air temperatures of the descriptions of the same case 600 building is lower than 0.05°C , which can be due to numerical calculations.

Once this validation obtained, it is interesting to put in evidence, as a first use of the model for practical applications, the insulation effect produced by the installation on the existing roof of the building (from interior to exterior, plasterboard/glass fiber/roofdeck) a typical PV panel (from interior to exterior, aluminium/EVA/silicium/EVA/glass). The corresponding air temperature is also indicated on *Figure 4*, where a significant difference can be seen. Just by adding the PV panel on the roof, the air temperature is decreased with a maximum of 3°C . This simple case illustrates the insulation potential of PV panels which should be taken into account when dealing with the design of new sustainable buildings.

As in fact PV panels are primarily installed to produce electricity for energy needs, our thermal model is also able to predict the electrical production, assuming that it can be considered as the solar radiation absorbed by the silicium layer of the PV panel. Due to the radiation model, which takes into account the several multi-reflections within each semi-transparent layer, the several radiative losses are taken into account; the convective losses are also included as boundary conditions for the panel.

The electrical production is indicated on *Figure 5*, as well as the incident radiation on the panel. The efficiency of the panel can thus be calculated and a value of approximately 6,5% has been obtained. This last one is closed to the one given by the constructor, and is in the range of the known values (Lu, 2006).

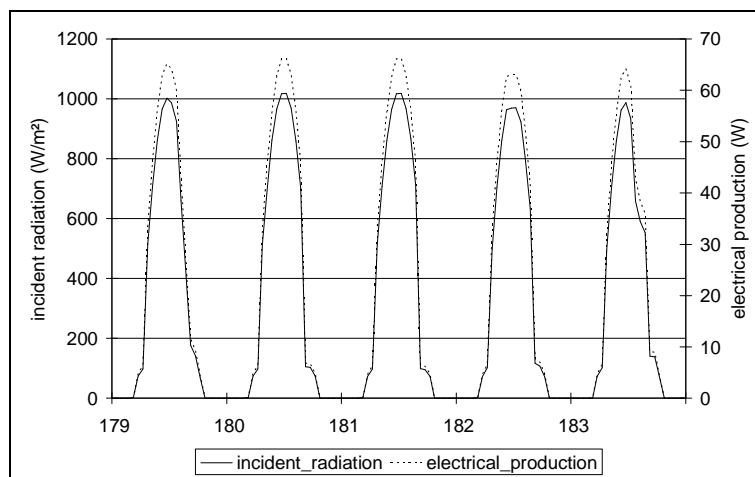


Figure 5: Electrical production of the PV panel installed on the roof of the building

CONCLUSIONS

This paper shows the integration of a PV thermal (and electrical) model within the simulation code ISOLAB, which is part of the building energetic simulation tools. The implementation has been done according to an existing architecture of development and organized in order to use the existing models. As shown, this coupled approach of building and PV allows quantifying indirect effect of insulation of PV roof installation. Other models are also used for practical applications, with specific assumptions regarding radiation models, quite different from our approach (Mattei, 2005) (Notton, 2005). In our case, preliminary results insuring confidence have been presented and will be completed by intermodel comparisons and confrontation with experimental data.

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