582. A Photovoltaic panel coupled with a phase changing material heat storage system in hot climates

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Abstract

Nowadays, there is a great impulse in the field of photovoltaic cell systems (PV) to develop new devices with better energy conversion performances and higher cost effectiveness. This paper is focused on the design and development of a modified PV system, consisting of a normal PV panel coupled with a Phase Change Material (PCM). PCMs are "latent" energy storage materials, using chemical bonds to store and release heat. The system is based on the idea that decreasing the operating temperature of the panel causes an increase in its energy conversion efficiency.

A theoretical analysis of the system was accomplished by using COMSOL MULTIPHYSICS, a partial differential equations (PDEs) solver. By using this software, the thermal behaviour of the PV-PCM system was simulated, thus allowing a better identification of the suitable thermo-physical parameters for the optimization of the panel efficiency.

The numerical simulations accomplished showed that a PCM with a melting temperature between 28°C and 32°C in a typical summer day in Sicily induces a significant variation in the energy conversion efficiency. The experimental set-up realized to validate these results is also described in the paper, but the experimental tests have still not been run.

Furthermore, the exploitation of this simple technology could permit to reduce CO_2 emissions because the increasing of the energy conversion efficiency means more energy production and consequently less emission of greenhouse gases to produce energy by fossil fuel or normal PV panel.

Keywords: Phase Change Material; PV; heat storage; energy conversion efficiency.

1. Introduction

The exploitation of solar energy is a good option for electric power generation. Photovoltaic technology is founded on the photovoltaic effect, which is based on the properties of certain semiconducting materials able to convert solar radiation into electric energy by an excitation of electrons from asymmetric impurity potentials.

When sun light enters the PV cell, a part of the energy of the photons is absorbed by the semiconductor's atoms, which release electrons from the negative layer of the cell. By flowing through an external circuit, these electrons reach the positive layer and produce electricity.

The photovoltaic module or panel is the converter device which exploits the photovoltaic effect to produce electric energy.

The efficiency of a PV cell depends on:

- the kind of semiconductor material used (generally silicon);
- the intensity of the solar radiation;
- the operating temperature of the cell.

The power efficiency of PV is computed as its "peak power", which is the power that the PV module is able to generate in its maximum power point. The peak power of a PV cell is conventionally evaluated in the following "standard conditions": irradiation of 1000 W/m^2 and cell temperature of 25 °C.

The real power output of a Solar PV module changes as a function of the direction of the sun, the solar insulation level and the ambient temperature. The typical power curve of a PV module has always a single maximum and, in the above defined standard conditions, only about 15% of the solar energy incident on a photovoltaic panel is converted into electricity; while the remaining part of the solar radiation is transformed into heat.

The operating temperature is the most important factor to determine the energy conversion efficiency of a PV panel. In particular, the efficiency of a PV device is a decreasing function of the operating temperature.

This paper describes a methodology to maximize the energy conversion efficiency of a PV panel by using a phase change material (PCM) layer to limit temperature rises.

PCMs are able to store large amounts of heat during their change from solid to liquid phase. Thanks to this property PCMs work as a thermal flywheel in solar heating systems. When a peak temperature occurs, PCM absorbs the excessive energy by undergoing a phase transition. It will release the absorbed energy later, when the temperature peak will be over. The PCM layer can be dimensioned so that its temperature is kept under a fixed value, defined by the designer [1].

In this paper the authors describe the numerical simulations accomplished to model the thermal behaviour of a coupled PV/PCM system that was assembled in the laboratory.

2. The Phase Change Materials

The *internal energy* is defined as the sum of all the microscopic forms of energy of a system. It is related to the molecular structure and the degree of molecular activity and can be viewed as the sum of the kinetic and potential energies of all the molecules constituting the system. The portion of the internal energy of a system associated with the kinetic energy of the molecules is called the *sensible energy*. The average velocity and the degree of activity of the molecules are proportional to the temperature. Therefore, at higher temperatures, the molecules possess higher kinetic energy, and as a consequence the system is characterized by higher internal energy.

The energy required to raise the temperature of a unit mass of a substance by one degree is defined as the *specific heat.* The internal energy is also associated with various binding forces between the molecules of a substance. If enough energy is added to the molecules of a solid or a liquid, the molecules overcome these molecular forces and break away, turning the substance into a gas: this is a phase-change process. The internal energy associated with the phase of a system is called the *latent energy* [2].

There are different substances, with high latent heat, which allow the storage of big amounts of heat during a solid-liquid phase transition and the consequent release of the same heat amount during the inverse process. For pure substances this phase change takes place at constant temperature and for certain materials the process of melting and solidifying can be repeated over a very high number of cycles with no change in their physical or chemical properties [3].

However, commercial PCMs used in building applications are not pure materials. As a consequence, their phase transition temperature is not constant but varies within a certain range.

Many substances have been studied as potential PCMs, but only a few of them are commercialised for the moment. In particular, it is possible to identify two different families of PCMs: inorganic and organic materials.

Inorganic materials are characterized by the following main features:

- large latent heat for a unit mass or volume;
- low price;
- no flammability;
- possibility of a property loss (due to chemical dissociation) after an elevated number of phase transitions.

The main features of organic materials are:

- availability in different forms and with different ranges of solidification temperature;
- higher price with respect to inorganic materials;
- no corrosive effect in general;
- chemical stability;
- compatibility with building materials;
- large latent heat for a unit weight.

Materials with different properties (especially fusion latent heat) have been studied to find the best ones in terms of utilization as a thermal flywheel in building applications.

At this aim, the most widely used PCMs are paraffin [4]. Paraffin is the common name for the alkane hydrocarbons with the generic formula C_nH_{2n+2}. Melting point of pure paraffin depends on the number of carbon atoms, this number is between 14 and 40 and melting temperature range is between 6°C and 80°C.

In the experimental application that will be accomplished by the authors, three kinds of paraffin will be tested. A paraffin (PCM$_1$) with relatively low phase transition starting temperature (26°C), that could be interesting for the typical Sicilian winter and autumn thermal regimes; a paraffin (PCM$_2$) with a range of phase transition temperature of negligible width and a paraffin (PCM$_3$) whose phase transition occurs at a temperature close to the typical Sicilian summer average temperature.

The main features of these materials during the phase transition are:

- ✓ high heat energy storage capacity;
- ✓ no performance decay;
- ✓ no toxicity;
- ✓ chemical neutrality.

In Table 1 the most important physical properties of these three paraffin are showed.

Table 1: Physical properties of the used paraffin

	PCM$_1$	**PCM$_2$**	**PCM$_3$**
Transition temperature [°C]	26 ÷ 28	31	28 ÷ 32
Solid density [kg l^{-1}]	0.87	0.87	0.88
Liquid density [kg l^{-1}]	0.75	0.76	0.76
Heat Capacity [kJ kg^{-1}]	179	169	157
Specific heat Capacity [kJ kg^{-1}K^{-1}]	1.8 ÷ 2.4	1.8-÷ 2.4	1.8 ÷ 2.4
Conducibility [W m^{-1}K^{-1}]	0.2	0.2	0.2
Volumetric change [%]	10	10	10

The specific heat of a PCM varies as a function of its temperature, reaching its maximum value during the phase transition.

For example, in Fig. 1 it is showed the variation of the c_p of a paraffin (PCM$_3$) as a function of the temperature.

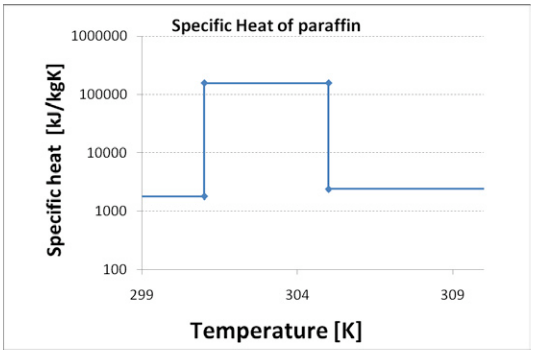

Fig. 1. Specific heat of the paraffin vs temperature.

The constant-pressure specific heat of a substance is defined as:

$$c_p = \left(\frac{\partial h}{\partial T}\right)_{p=\cos t} \quad (1)$$

Where h is the enthalpy and T is the temperature. In the discrete form eq. (1) can be written as:

$$c_p = \frac{\Delta H}{\Delta T} \quad (2)$$

As a consequence, if one represents the temperature variation curve as a function of the enthalpy, the qualitative trend represented in Fig. 2 is obtained.

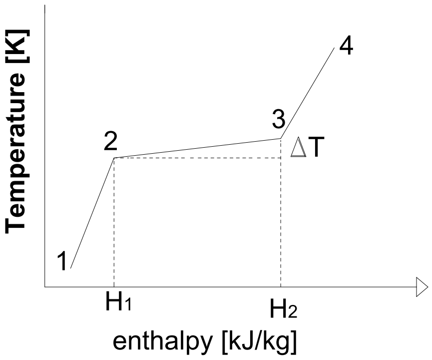

Fig. 2. PCM phase transition

As it is possible to observe, the curve has a piecewise linear trend. In its first part (1-2) the PCM is still in its solid phase and is characterized by the lowest value of c_p. This condition determines an high slope of the part 1-2 of the curve in Fig. 2 (see eq. (2)). Analogously, the part 2-3 is characterized by the highest value of c_p, and consequently the lowest slope. Finally, part 3-4 is characterized by an intermediate slope.

3. PV-PCM System

The coupling of a PCM to a PV panel allows a limitation in temperature peaks on the rear part of the panel with a consequent increase in its energy conversion efficiency.

In Fig. 3 the heat transfer process occurring in a PV/PCM system is schematized.

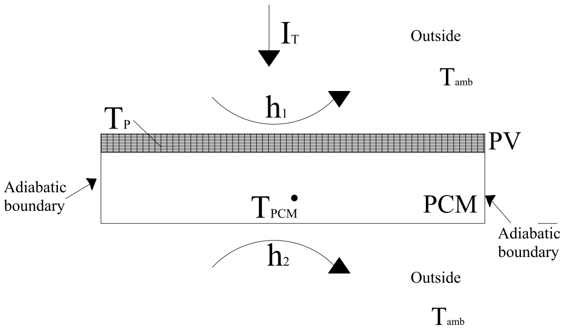

Fig. 3. Heat exchange in a PV/PCM system

For simplicity's sake the thermal flux can be assumed mono-dimensional and orthogonal to the surface of the panel and we can take into consideration a pure PCM (it has a unique melting temperature that remains constant during the melting process). Therefore the lateral surfaces of the system depicted in Fig. 3 are to be considered adiabatic. However, it has to be noticed that the commercial PCMs are generally eutectic mixtures of different substances and their melting temperature consequently varies within a certain range.

In particular Fig. 3 describes heat exchange in a PV/PCM system in stationary conditions where:

- ✓ T_p is the average temperature of the PV panel [K];
- ✓ T_{PCM} is the average temperature of the PCM at time t [K];
- ✓ I_t is the incident power [W m^{-2}];
- ✓ Δt is the time step [s];
- ✓ h_1 and h_2 are the heat transfer coefficients related to the upside and downside surface of the system respectively [W m^{-2} K^{-1}];
- ✓ T_{amb} is the ambient temperature [K];

Assuming that the main contribution to the energy stored by the system is due only to the PCM, the energy stored by the system Q_s in the time interval Δt can be written as [5]:

$$Q_s = \begin{cases} mc_s\left(T_{PCM} - T_{amb}\right) & \text{if } T_{amb} < T_{PCM} < T_m \\ mc_s\left(T_m - T_{amb}\right) + H & \text{if } T_{PCM} = T_m \\ mc_s\left(T_m - T_{amb}\right) + H + mc_l\left(T_{PCM} - T_m\right) & \text{if } T_{PCM} > T_m \end{cases} \quad (3)$$

where:

- m is the mass of the PCM [kg];
- c_s is the specific heat of the solid PCM [J kg^{-1} K^{-1}];
- c_l is the specific heat of the liquid PCM [J kg^{-1} K^{-1}]
- T_m is the melting temperature of the PCM [K];
- H is the latent heat of fusion of PCM [J].

Taking into account also the energy conversion by the PV panel, the complete energy balance of the PV/PCM system can be written as:

$$\tau\alpha I_t \Delta t = \eta_c I_T \Delta t + U_l\left(T_P - T_{amb}\right)\Delta t + Q_s \quad (4)$$

where:

- τ is the trasmissivity of the glass layer;
- α is absorbitivity of the silicon cell;
- η_c is the energy conversion efficiency;
- U_l is the overall heat transfer coefficient between the PV cell and the external environment (including conduction and radiation) [W m^{-2} K^{-1}];
- T_p is the average temperature of the PV cell in the time interval Δt [K].

Comparing the values of η_c obtained with the same value of the ratio $\left(T_p - T_{amb}\right)/\left(I_t \Delta t\right)$, it is possible to compare systems with different characteristics without taking into account time.

In a traditional PV system, the air flow licking the bottom part of the panel contributes to reduce its temperature. The allocation of a PCM under the PV panels optimizes this effect, because during the phase transition the PCM removes heat from the silicon panel reducing temperature fluctuations.

In this case the efficiency of the PV/PCM system depends on Q_s. During the phase change $(T_{PCM} = T_m \simeq T_p)$, by combining equation (3) and (4) and dividing by the time interval Δt, it is possible to express the energy conversion efficiency of a PV panel as:

$$\eta_c = \left(\tau\alpha - \frac{H}{\Delta I_t}\right) - \left(U_L + \frac{mc_s}{\Delta t}\right)\left(T_p - T_{amb}\right) I_t^{-1} \qquad (5)$$

From equation (5) it is possible to observe that the energy conversion efficiency of the PV panel is a decreasing function of the difference between the temperature of the PV panel and the ambient temperature. For this reason it is possible to understand the importance of controlling the temperature of a PV panel and, in particular, of maintaining its value close to that of the ambient temperature.

4. Case Study

4.1 Numerical Simulation

The theoretical thermal behaviour of the system was studied by solving the energy balance equations through a partial differential equations (PDEs) solver called COMSOL MULTIPHYSICS. It is a powerful interactive environment for modelling and solving all kinds of scientific and engineering problems based on PDEs.

In this way it was possible to compute the mean temperature of the cell in the two different cases: with and without the use of PCM.

The overall process of heat transfer throughout the system can be schematized as depicted in Fig. 4:

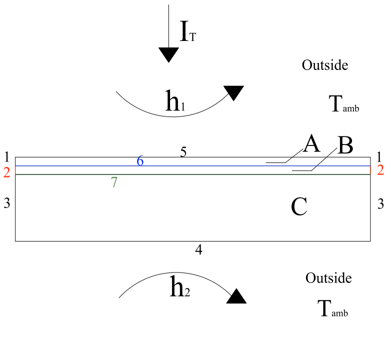

Fig. 4. Schematization of the heat transfer process throughout the PV/PCM system

where:

- A: is the glass layer of the PV panel;
- B: is the plastic layer of the PV panel;
- C is the PCM layer.

Every number in the figure (from 1 to 7) represents a single surface of the calculation domain, with a particular boundary condition for the solution of the PDEs. In this case the following conditions were defined:

- Surface 1: Adiabatic;
- Surface 2: Adiabatic;
- Surface 3: Adiabatic;
- Surface 4: Convective Flux;
- Surface 5: Heat Flux;
- Surface 6: Continuity;
- Surface 7: Continuity.

Silicon cells have a negligible thickness compared to the dimensions of the remaining elements of the system; in fact they were represented in the model as a simple separation surface between layer A and layer B (Surface 6).

In Table 2 the thermo-physical properties of the materials present in the PV/PCM system are listed.

Table 2: Thermo-physical properties of the materials present in the PV/PCM system

Sub-domains	Thermal conductivity [W m^{-1} K^{-1}]	Density [kg m^{-3}]	Specific heat [J kg^{-1} K^{-1}]
Plastic	0.1	1760	1255
Glass	1.3	2200	840
PCM	see Table 1	see Table 1	See Table 1

Once fixed the boundary conditions, a mesh with triangular elements was created. The mesh was refined in the proximity of the edges constituting physical discontinuities.

In Fig. 5 an excerpt of the used mesh is showed.

When we use a PCM, it is very important to define the heat capacity as a function of the temperature, which strongly depends on the external weather parameters. In order to simulate the effect of the external energy input, it was thus necessary to supply COMSOL MULTIPHYSICS with a file containing the hourly values of air temperature and solar radiation in Palermo.

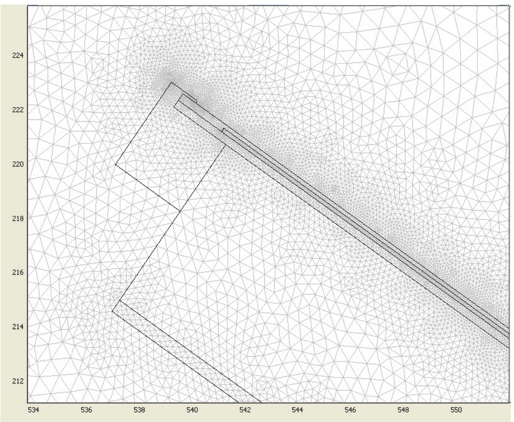

Fig. 5. A particular of the calculation mesh

With the real heat capacity it is also possible to describe the non-isothermal phase change in the PCM. The real heat capacity of the PCM mass is an increasing function of the energy stored and released during the phase change and of the specific heat.

In the application described in this paper the authors simulated the thermal behaviour of the system during two typical summer days (july 2007).

Figure 6 shows the evolution of the temperature of the PV panel both with and without the presence of the PCM. In particular, it was used a PCM$_3$ paraffin, whose heat capacity varies with the following law [6]:

Melting process

$$c_l = \begin{cases} 1800 & \left[\mathrm{J\,kg^{-1}\,K^{-1}}\right] & \text{if } T_{PCM} < 28°C \\ 157000 & \left[\mathrm{J\,kg^{-1}\,K^{-1}}\right] & \text{if } 28°C \le T_{PCM} \le 32°C \\ 2400 & \left[\mathrm{J\,kg^{-1}\,K^{-1}}\right] & \text{if } T_{PCM} > 32°C \end{cases} \qquad (6)$$

4.2 Results

To define the photovoltaic efficiency of a traditional PV panel it is possible to use the solar collector efficiency equation with electric power as the output power.

The photovoltaic efficiency can thus be expressed as:

$$\eta_c = \tau\alpha - U_L\left(\frac{T_p - T_{amb}}{I_T}\right) \qquad (7)$$

If one wants to take into account the effect of the PCM material allocated under the PV system, this equation becomes the equation (5), that, as previously observed, is a decreasing function of the difference between the temperature of the PV panel and the ambient temperature.

By comparison of the traditional PV system with the PV/PCM system it is possible to observe that the peak temperature values are lower in the latter case (Fig.6).

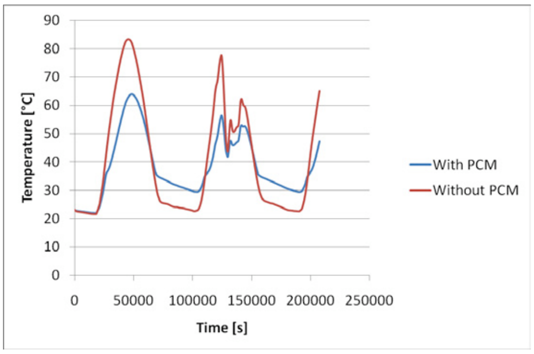

Fig. 6. Temperature trends of PV and PV/PCM systems

Figure 6 shows the result of the simulation related to days of July in Palermo. It is possible to observe that the peak temperature (blue curve) is lower in the PV/PCM system than in the traditional PV panel (red curve). One can observe that during the night the temperature of PV/PCM system is higher than simple PV system due to the presence of PCM mass that is releasing the heat adsorbed during the day.

The lower temperature of the PV/PCM systems leads to a rise in the value of h$_c$.

In particular, the average energy conversion efficiency (computed in two days) for the simple PV system is close to 12% and in the PV/PCM system is 26%.

5. Design of the experimental test set

At the aim of validating the results of the numerical analysis, the authors realized an experimental equipment.

A supporting frame for the PV/PCM system was designed and built up. It is constituted by an aluminium parallelepiped in whose upper part is possible to allocate a PV panel (1.2x1.9 m^2) and whose lower part can contain the PCM (Fig. 7). During the application a guard ring made from polyurethane foam will thermally insulate the whole perimeter.

The dimensions of this structure are:

- ✓ Depth: 1.3 m
- ✓ Width: 0.93 m

The main components of the frame are:

- ✓ an aluminium drawer with PCM;
- ✓ two crank gears, one on each side of the drawer, that can move the drawer thus allowing a regulation of the thickness of the PCM layer;
- ✓ an inspection window to monitor the experiment;
- ✓ a tilting framework, allowing the inclination of the PV/PCM system between 20° and 45°.

Fig. 7. Supporting frame of the PV/PCM system

When the experiment will be run, thermocouples of type T (Copper-Constantan), will be used to monitor the temperatures of:

- ✓ the bottom part of the PV panel;
- ✓ the PCM;
- ✓ the external surface of the system;
- ✓ the ambient temperature.

The experimental measurements that will be accomplished with the above described laboratory equipment will allow the assessment of the results of the numerical simulations. Furthermore, several experiments will be realized by varying the type of PCM and its thickness in order to find the optimal type of paraffin for the weather conditions typical of Mediterranean climate. By varying the position of the drawer in the support frame, it will be possible to investigate the effect of the thickness of the PCM layer on the energy conversion efficiency of the system. Detailed investigations will also address the duration of the constant-temperature phase change and the consequent time delay caused in the thermal wave which hits the panel.

6. Conclusion

The allocation of a proper mass of PCM on the rear part of a traditional PV panel contributes to lower its operative temperature, thus improving the overall energy conversion efficiency of the system.

This work presents the first results of a numerical simulation of the thermal behaviour of an integrated PV/PCM system.

The numerical analyses were accomplished by using the commercial package COMSOL MULTIPHYSICS to solve the heat transfer differential equations taking into account the thermal exchanges of the system with the external environment for conduction, radiation and convection.

The simulations accomplished by using the weather data related to a typical summer day in the town of Palermo (Italy) revealed a significant average increase in the energy conversion efficiency of the system

Results obtained from numerical simulations have to be considered *"cum grano salis"* due to the numerous simplifications introduced in the heat balance and in the COMSOL MULTIPHYSICS model definition.

In order to validate the results of the numerical analysis, an experimental equipment was set up.

Furthermore, several researches show that the massive exploitation of PV technology to produce energy, could strongly influence the emission of GHG and in particular CO_2 emissions respect the use of fossil fuels. In this field, increasing the energy conversion efficiency of PV by using a PCM could play an important role.

7. Acknowledgements

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