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Finite difference thermal model of a latent heat storage system coupled with a photovoltaic device: Description and experimental validation

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ABSTRACT

The use of photovoltaic (PV) systems has been showing a significant growth trend but for a more effective development of this technology it is essential to have higher energy conversion performances. Producers of PV often declare an higher efficiency respect to real conditions and this deviation is mainly due to the difference between nominal and real temperature conditions of the PV. To improve the solar cell energy conversion efficiency many authors have proposed a methodology to keep lower the temperature of a PV system: a modified PV system built with a normal PV panel coupled with a Phase Change Material (PCM) heat storage device. In this paper is described a thermal model analysis of the PV–PCM system based on a theoretical study using finite difference approach. The authors developed an algorithm based on an explicit finite difference formulation of energy balance of the PV–PCM system. To this aim, a forward difference at time t and a first-order central difference for the space derivative at position *x* was used. Two sets of recursive equations were developed for two types of spatial domains: a boundary domain and an internal domain .The reliability of the developed model is tested by a comparison with data coming from a test facility. Results of this experience confirm the performed numerical simulations and show that the proposed model is valid and can be used to determine the thermal behaviour of a solar cell coupled with a PCM heat storage device.

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1. Introduction

The intense exploitation of fossil fuels has caused an increase in the concentration of carbon dioxide from 280 ppm to 370 ppm and a consequent estimated global warming of 0.4–0.8 °C. The global effort to fight the effects of global climate change has been oriented at reducing energy consumptions through new technologies [1] and ensuring a more efficient exploitation of RES (Renewable Energy Sources) [2].

Among RES, solar energy is the most important and available natural resource. During the last decade there was a widespread use of photovoltaic (PV) systems not only for decentralized production in advanced countries but also in developing countries, where the most likely alternative to produce electricity is related with the use of poor fuels (coal and lignite, peat, etc. which are very polluting) and biomass.

A key element of a wider dissemination of PV systems is represented by a high power conversion efficiency. Concerning this point, the energy produced by a PV cell depends, apart materials, also on other two important parameters: the amount of the incident radiation and the temperature of the PV cell.

The performances of a PV panel in fact are defined by manufactures according to the "peak power", which identifies the maximum electric power supplied by the PV panel when it receives an insolation of 1 kW/m^2 and the cell temperature is maintained at 25 °C. These parameters are only observed under reference conditions, because solar radiation has a variable intensity and the panel is subjected to significant temperature changes, with temperature values much higher than 25 °C. In real conditions performances of a PV panel are different from those declared under the nominal conditions and the conversion efficiency decreases when temperature of the cell increases [3].

For given values of insolation, cell temperature and electric load the operating point can be identified by drawing lines of the different loads on the *P*–*V* characteristic (Fig. 1); the maximum

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power points are indicated by red circles (colour in the web version).

The cell temperature thus is a key parameter that affects the energy conversion efficiency of a PV panel: increasing the temperature decreases the delivered power.

The wind speed greatly influences the heat exchange between the PV panel and the external environment mitigating its temperature; however, especially in densely populated urban areas often the wind is too weak [4–6] to determine a desirable cooling of the solar cell.

Among other measures aimed to increase the energy conversion, PCMs have been receiving increased attention, due to their capacity to store large amounts of thermal energy in narrow temperature range. PCMs represent a possible solution that may reduce peak loads and thermal energy consumption in buildings due to their good insulation properties and thermal inertia effect related to the phase change phenomenon [7–9]. Indeed this property makes them ideal for passive heat storage in different building application as: in the envelope of the building, in radiant floor systems heating, in free cooling system, in the photovoltaic element and in building integrated PV [10–18].

The idea to couple the PCMs with the photovoltaic technology arises from features of these materials to absorb large amounts of heat (keeping almost constant the temperature) when the heat is not required and overheating would cause a drop in the efficiency of photovoltaic cells. The absorbed heat should be then released to the surrounding air during the night when the panel does not produce electrical power. The application of PCM coupled to a PV panel may represent an innovative technological solution to smooth daily temperature fluctuations and improve the energy efficiency of the panel. However, PCMs are generally characterized by low thermal conductivity.

To better understand how PCM ensures a thermal regulation for a PV system, it is necessary to examine in detail the heat transfer process across a multi-layered system in which one of the layers is composed by a material that changes phase during the day.

In this paper a finite difference model is described, capable to forecast the variable temperature profile of a PV-PCM system; the adopted numerical scheme is presented in detail, also discussing the equations of the model and the resolution system using the FDM approach (finite difference method).

To validate the numerical model, we performed a comparison with data derived by a real-time monitoring apparatus.

2. PV–PCM model

Considering a PV panel coupled with PCM system, the energy balance must take into account the presence of the phase-change material. Schematically, the energy exchanges in a PV–PCM system can be exemplified as shown in Fig. 1. Due to the presence of a simple geometry, it was possible to adopt a one-dimensional approach, considering only a heat flow orthogonal to the PV plane. The simplification of the thermal problem giving up a more accurate representation in 2D or 3D [19] does not lead to unacceptable errors in the evaluation of the temperature field. The hypothesis of mono-dimensionality of the heat flow is in fact justified by the ratio thickness/surface, which in the case of the PV–PCM system is close to 0.02 m^{-1}. The thermo-physical characteristics of each component are also constant with respect to the other two directions and neglecting the effects relative to the edges of the panel the overall energy balance remains practically unchanged. Furthermore, with regard to the PCM, it is confined in small vacuum plastic bags about 250 ml. This configuration, also thanks to the high viscosity of the material in liquid phase allows to completely exclude the establishment of natural neither buoyant convection.

In Fig. 2h_{rad} and h_{conv}, respectively, represent the external radiative and convective coefficients.

Let us refer to a particular geometry, assuming the system composed by:

- a tempered glass sheet with a thickness of 3.2 mm (glass layer);
- 1 mm of PET plastic panel on which are “printed” the silicon cells; the silicon cells are considered having negligible thickness (plastic layer);
- an optional layer of air interposed between the panel and the heat storage system representing a possible imperfect contact (air layer);

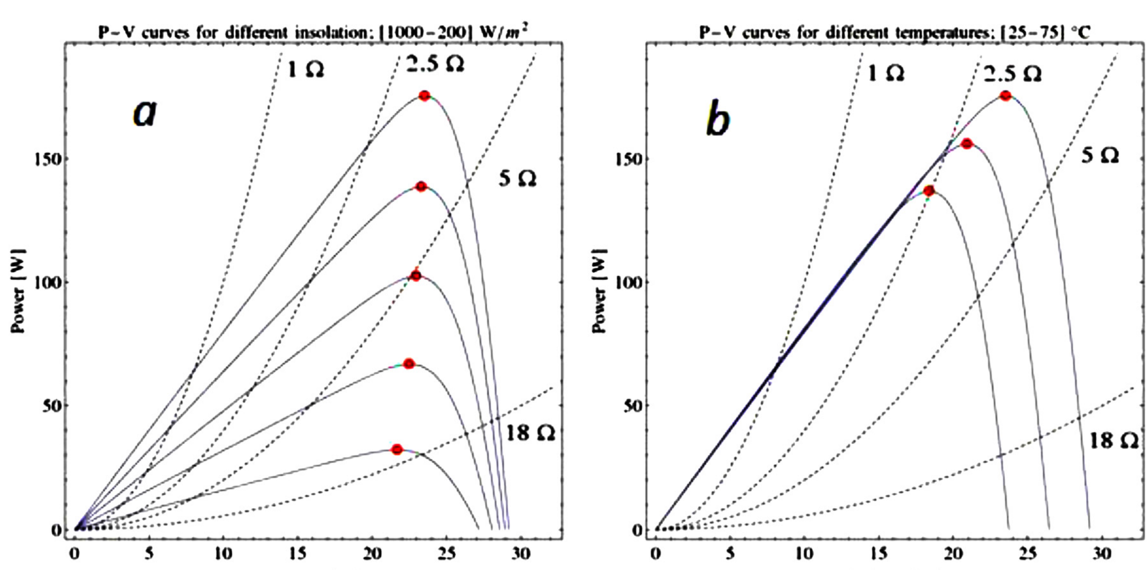

Fig. 1. Working point of the examined Kyocera PV panel at constant temperature (25 °C) and varying solar irradiance (1000–200 W/m^2) and electric load (a) and at constant irradiance (1000 W/m^2) varying temperature (25–75 °C) and electric load (b).

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