18èmes Journées Internationales de Thermique (JITH 2017)
Monastir (Tunisie), 25 - 27 Octobre 2017

Modeling of thermal response of photovoltaic-phase change material panels

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Abstract

In this study, a numerical model which integrates the thermal aspect has been developed. The thermal model is based on the energy balance of the PV panel in which the different heat transfer modes between the panel and ambient are taken into account. In order to analyze a PV panel with and without PCM, two different cases were studied; in case 1, PV cell without PCM was simulated while in case 2, a rectangular cavity containing PCM mounted to the backside of the panel was modeled. A two-dimensional transient conjugate heat transfer model was performed using COMSOL Multiphysics to study the performance of the proposed system. Since the developed model is able to take into account the environmental variation such as outside temperature, solar radiation. Additionally, the effect of different PCMs on the performance of PV panel is investigated. The results clearly show its ability to predict the hourly average variation of PV panel temperature and testing the performance of the PV/PCM system in different environmental conditions. Thus, the model could be useful to realistically simulate the thermal behavior of PV panel and ultimately to determine the electric thermal efficiency of the PV/PCM system.

keywords:

PV panel, Phase change material, Thermal model, Efficiency

1. Introduction

During the last decade, photovoltaic devices appear to be one of the potential solutions to reduce energy consumption, mitigate climate change and increase the security of our global energy supply system [1]. As it is known, a small part of the solar radiation incident on photovoltaic (PV) panel is converted into electricity while the remaining absorbed part is transformed into heat [2]. The produced heat contributes to the increase of the photovoltaic panel operating temperature, which affects adversely its electrical conversion efficiency [3-5]. Since the control of operating temperature is the most important factor to enhance the output efficiency, the cooling of PV panels is become increasingly challenging. Therefore, the development of this technology highlights the need for effective thermal management which is usually done by cooling the PV panel. Until present, various cooling methods have been investigated and recently the phase change material (PCM) has been proposed as a novel passive strategy to ensure a better thermal management of PV panels [6-7]. A special focus on the use of PCM thanks to its high latent heat of melting, which during its phase change keep the module temperature at a fairly constant temperature and therefore maintain its temperature as low as possible.

This approach involves integrating the phase change materials into PV panel in order to keep its operating temperature close to its nominal value by absorbing the excess of heat during the melting. Several thermal behaviour investigations of a PV panel have been performed in order to predict the thermal response under given environmental conditions. Jones et al [8] proposed an energy balance model in which all aspect of heat transfer between the panel and its environment are modeled. The different energy exchange at the panel was theoretically evaluated with considering heat losses by radiation, convection and the power generated. A similar thermal analysis carried out by Armstrong et al [9] for the study of PV module operating temperature, integrating the varying atmospheric conditions, the material properties of the PV panel and the mounting structure. The reliability of the developed model is tested by a comparison with experimental data obtained from a test facility. The initial studies based on the use of PCM for the thermal regulation were performed by Huang et al [10-12], they investigated numerically and experimentally the integration of a suitable PCM to delay the temperature rise of the panel, examined the performance of PCM with different configurations, dimensions and fin forms. Cellular et al [13] built a numerical model using Comsol Multiphysics and the simulated results showed that the average conversion efficiency for a PV system without PCM was close to 12% while in PV-PCM system this value was as high as 26%.Stropnik et al [11] simulated the PV module coupled with PCM using TRNSYS software and it was investigated that the electricity production increases up to 7.3% annually. Park et al [12] performed numerical and experimental investigation on the effectiveness of PCM to shave peak temperature of PV panel. From the comparative study outcomes, the amount of electric power generation of PV-PCM was increased by 1.5% compared to that of the conventional PV panel and efficiency of the PV-PCM system was increased by about 3.1%. Kibria et al [13] established a mathematical model to simulate the thermal response of BIPV coupled with PCM. However, in their study, the outcome of wind velocity, convection effect in melted PCM, and the consequence on power output was not considered. By against a computational fluid dynamic study carried out by Kant et al [14] in which different heat transfer mechanisms have been accounted for. Additionally, they highlighted the importance of considering the impact of convection during melting of PCM, the velocity of wind and the PV panel's tilt angle on its operating temperature. Therefore, the results of simulation demonstrate that PCM offers an effective way of regulating the temperature increase of PV panel.

This paper presents a thermodynamic model of PV panel coupled with PCM in which different factors are included such as heat losses by natural convection, heat losses by radiation and variable meteorological conditions of a Tunisian climate. PCMs with different latent heat of fusion and transition temperature are selected in order to evaluate the performance of each PCM on the PV panel operating temperature.

2. Physical model

The PV panel under investigation is composed of five different layers such the glass covering, PV cells, ethylene vinyl acetate (EVA) layer and a Tedlar layer. The properties of layers are listed in **table 1**. A rectangular aluminum container filled with PCM is mounted to the back side of PV panel as shown in **Figure 1.** The height of PV/PCM system is h=0.132m, the thickness of the PCM cavity is 0.02m and the thickness of the aluminum on each side is 0.004m.

The PV/PCM system was installed at an angle of inclination 35° from vertical. The PCMs used for this study are RT25, RT28 and RT35.The effect of PCMs with different melting temperature on the operating temperature of PV panel are investigated. The initial temperature of the panel and the PCM is equal to the ambient temperature. The numerical simulation was performed for the atmospheric condition for 25 July 2012, for the city of Monastir, Tunisia. **Figure 2** represents the data of ambient temperature and solar radiation. Natural convection and radiation heat transfer from both the front and back surface to surrounding are considered.

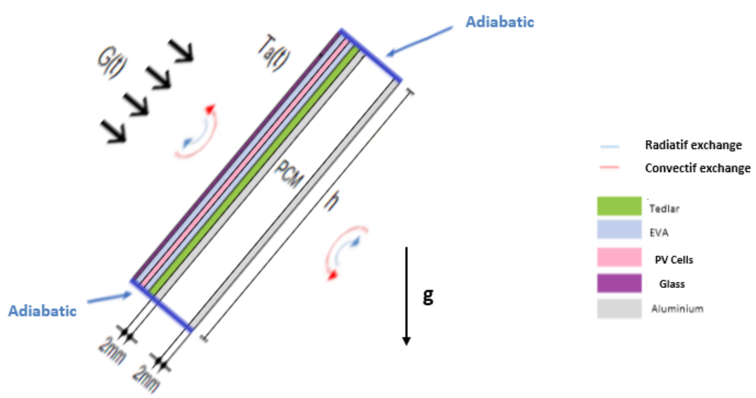

Figure1: Problem geometry and boundary conditions

3. Numerical simulation

A two-dimensional transient model was built using the finite element modeling software COMSOL Multiphysics. The thermo-physical properties of the simulated materials are listed in table 1 and 2. In order to perform the thermal modeling of PV panel coupled with PCM, the conjugate heat transfer and the laminar heat flow physics module were used.

3.1. Mathematical formulation

A model of module temperature based on environmental condition is proposed by considering the various thermal energy exchanges at the module. The thermal model is based on the energy balance of the PV module in which the different heat transfer mechanisms between the module to the environment.
Therefore, the energy heat balance equation can be written as:

$$\rho C_P \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + q_s - q_{conv} - q_{rad} - P_{out} - q_{PCM} \quad (1)$$

3.1.1. Irradiance modeling

The radiation absorbed by PV panel can be calculated as:

$$q_s = \alpha G(t) A \quad (2)$$

where α is the absorptivity of covering glass assumed 0.95 and G(t) is the incident solar radiation on the front of the PV panel.
Since the proposed thermal model takes into account the different meteorological conditions (solar radiation flux, ambient temperature) the heat exchanges with the thermal environment must be expressed with care. These boundary conditions are described in terms of two physical phenomena, convection and radiation.

3.1.2. Convective heat transfer modeling

The heat loss due to convection with the air is modeled as:

$$q_{conv} = Ah(T_{pv} - T_{amb}) \quad (3)$$

$$h = {Nuk_{air}}/{L} \quad (4)$$

where k_{air} is the thermal conductivity of air, L is the length of the PV panel and Nu is the Nusselt number which is calculated from the empirical equation for inclined flat plate [18]:

$$Nu = \left\{ 0.68 + \frac{0.67(\cos\varphi)Ra_L^{1/4}}{\left(1+\left(0.492/\Pr\right)^{9/16}\right)^{4/9}} \right\} \quad (5)$$

where Ra_L is the Raleigh number and Pr is the Prandtl number of air which are defined as:

$$Ra_L = \frac{g\beta\rho^2 C_p |T_{PV} - T_{amb}| L^3}{k\mu} \quad (6)$$

$$\Pr = \frac{C_p \mu}{k_{air}} \quad (7)$$

3.1.3. Radiative heat transfer modeling

The expression to calculate the radiation heat loss is based on the Stefan-Boltzmann law.

$$q_{rad} = A\sigma\varepsilon_{front/rear} F_{front/rear} (T^4_{PV-front/rear} - T^4_{sky/ground}) \quad (8)$$

where ε is the emissivity of PV panel on the front surface (glass covering) and on its rear surface (aluminum)and F is the view factor on PV/PCM system.
The expression of the sky temperature defined by Swinbank equation is used and is given by [19]:

$$T_{sky} = 0.037539 T_{amb}^{1.5} + 0.32 T_{amb} \quad (9)$$

and the ground temperature was simply assumed equal to the ambient temperature.

Table 1: Photovoltaic panel materials properties

PV layers	PV layers properties			
	Density (kg/m^3)	Thermal conductivity*(W/mK)*	Specific heat *J/(kg K)*	Thickness (m)
Glass	3000	1.8	500	0.003
EVA	960	0.35	2090	0.0005
PV Cells	2330	148	677	0.0003
Tedlar Trilaminate	1200	0.2	1250	0.0005

3.1.4. Phase change modeling

The conduction-convection equation applied to the PCM domain, is shown in Eq.10

$$\rho Cp\frac{\partial \mathrm{T}}{\partial t}+\nabla\cdot\left(-k\nabla \mathrm{T}\right)+\rho Cp\vec{u}\cdot\nabla \mathrm{T}=0 \tag{10}$$

The velocity field is given by Navier-Stokes equations for incompressible fluids.
The phase change from solid to liquid, and vice versa, occurs over a finite temperature range ΔT generating the apparition of an artificial mushy region at the solid-liquid interface. The fluid velocity within the mushy region varies from zero (PCM in solid state) to the natural convection velocity (PCM in liquid state) as the melt fraction varies from 0 to 1.
So to model the changes in PCM thermo-physical properties during the phase transition, the function B is defined as the liquid fraction of PCM which can be given as:

$$\mathrm{B}(T)=\begin{cases}0 & ,T<T_m-\Delta T\\ \dfrac{T-(T_m-\Delta T)}{2\Delta T} & ,T_m-\Delta T<\mathrm{T}<T_m+\Delta T\\ 1 & ,T>T_m+\Delta T\end{cases} \tag{11}$$

where T_m is the melting temperature and ΔT is the transition temperature. According to the Eq.11, B is zero when the PCM is in solid state and 1when it is melted and it linearly grows from 0 to 1 between the two states.
The change in the thermo-physical properties of the PCM during the phase transition is modeled as follows:

$$\rho(\mathrm{T})=\rho_s+(\rho_l-\rho_s).B(\mathrm{T}) \tag{12}$$

$$k(\mathrm{T})=k_s+(k_l-k_s).B(\mathrm{T}) \tag{13}$$

$$\mathrm{C}_P(\mathrm{T})=C_{Ps}+(C_{Pl}-C_{Ps}).B(\mathrm{T})+\mathrm{L}_F\,.\mathrm{D}(\mathrm{T}) \tag{14}$$

The modeling of the specific heat includes an additional term to account for the latent heat of fusion required for phase change once the melting point is reached. This latent heat contribution is modeled using the following Gaussian function centered about Tm:

$$D(\mathrm{T})=e^{\frac{-(T-T_m)^2}{\Delta\mathrm{T}^2}}\Big/\sqrt{\pi\Delta\mathrm{T}^2} \tag{15}$$

It is supposed that the PCM in the liquid state is a Newtonian fluid. The mass and momentum equations are modified to model the phase change process which can be given as:

$$\rho\frac{\partial\vec{u}}{\partial t}+\rho\left(\vec{u}\cdot\nabla\right)\vec{u}-\mu\cdot\nabla^2\vec{u}=-\nabla P+\vec{\mathrm{F}_b}+\vec{\mathrm{F}_a} \tag{16}$$

where $\overrightarrow{F_b}$ is the buoyancy force which gives rise to natural convection in the liquid PCM. It is modeled through the Boussinesq approximation as follows:

$$\overrightarrow{F_a} = -\rho_l (1 - \beta(T - T_m))\vec{g} \quad (17)$$

and a modified viscosity is used to distinguish between solid and liquid regions. This viscosity takes the measured liquid viscosity value μ_l when the PCM is in liquid state but forces the solid PCM to behave as a solid by providing an extremely large viscosity.

$$\mu(T) = \mu_l (1 + A(T)) \quad (18)$$

A(T) is the Carmen-Koseny equation which appears in the source term within the momentum conservation equations:

$$A(T) = C \frac{(1-B)^2}{(B^3 + q)} \quad (19)$$

where C is a constant which has a large value varying between 10^4 and 10^7 depending on the morphology of the PCM and q simply takes a small value (10^{-3}) to avoid division by 0 when B has a value of 0 in the solid region. Using $A(T)$, a second volumetric force $\overrightarrow{F_a}$ is defined to provide a way to more easily handle the Navier-Stokes equation when applied to the solid PCM.

$$\overrightarrow{F_a} = -A(T) \cdot \vec{u} \quad (20)$$

Table 2: Thermo-physical properties of PCMs

		RT 25	RT28	RT 35
Latent heat of fusion*(J/kg)*		232000	245000	157000
Melting temperature*(°C)*		26.6	28	35
Density *(Kg/m^3)*	solid	785	880	880
	liquid	749	770	760
Thermal conductivity*(W/mK)*		0.2	0.2	0.2
Specific heat *J/(kg K)*	solid	1800	2000	1584
	liquid	2400	2000	1824
Kinematic viscosity*(mm²/s)*		2.4	2.4	3.3

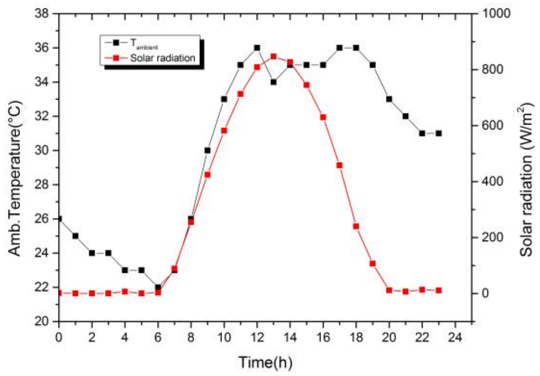

Figure 2: Data of ambient temperature and solar radiation.

3.2. Mesh and model validation

Simple linear free triangular elements are used to create the overall mesh. A mesh independence study was done in order to provide an accurate mesh independent solution and improve the calculation time of the model. To determine the appropriate size of elements to use, different mesh sizes were initially studied and the obtained results were quite similar. So the simulations were then carried out using the finer mesh.

The developed thermal model with and without PCM is validated with a previous experimental study taken from literature. The comparative Figure of the experimental and the predicted results obtained with the numerical model shows a good accuracy of the model.

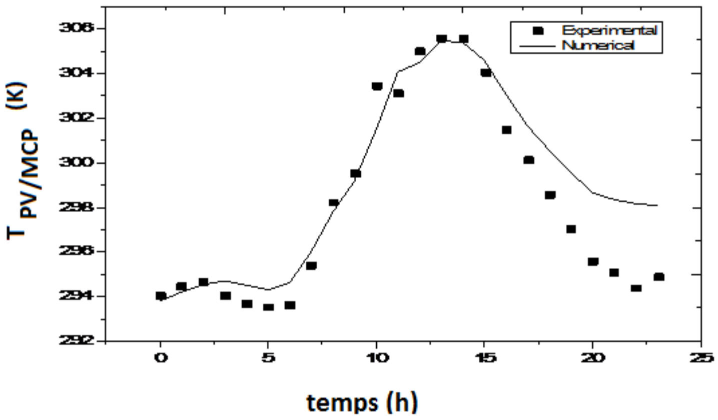

Figure 3: The temperature variation of the experimental and numerical model

4. Results and discussion

The results of the performed simulations are presented and discussed in this section.

4.1. Comparison between the conventional PV and the PV/PCM system

Figure 3 presents the result comparison of the PV module temperature between the conventional PV system and the PV/PCM system, as measured in July 25, 2012, the day the highest level of solar radiation and temperature was recorded. The ambient temperature ranged from 22 to 36°C, and the incident solar radiation reached a maximum value of 847W/m^2.

The PV module temperature in the conventional PV and the PV/PCM system reached maximum levels of 82.8 and 79.4°C, respectively, as the air temperature and the amount of solar radiation increased. The PV module temperature of the PV/PCM system was determined to be 3.4°C lower than that of the conventional PV system.

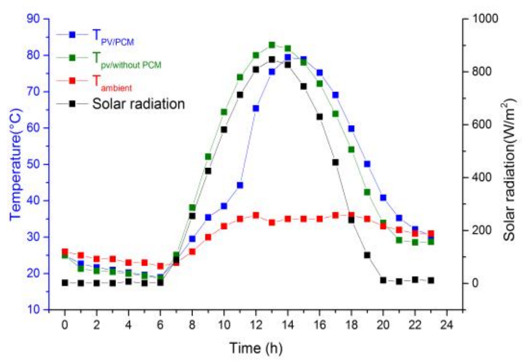

Figure 4: Temperature variation of PV panel over the daytime

4.2. Comparison between PCMs on PV panel operating temperature

The simulation is then carried out for four different PCMs with different melting points and heats of fusion. Depending on the thermo-physical properties listed in table 2; the PV panel temperature exhibits differently for the same time of operation. Figure 4 presents the temperature on the PV front surface for all PCMs.

The maximum level reached by the PV temperature is used to quantify the thermal regulation improvement provided by each PCM. At peak solar radiation intensity of 847W/m^2 at 14:00 PM, the maximum temperature for RT25, RT28 and RT35 are 72°C, 79.45°C and 80°C respectively. RT25 shows the lowest peak temperature thanks to its high latent heat of fusion and its low melting temperature. Therefore, PCM RT25 proves its better thermal regulation performance.

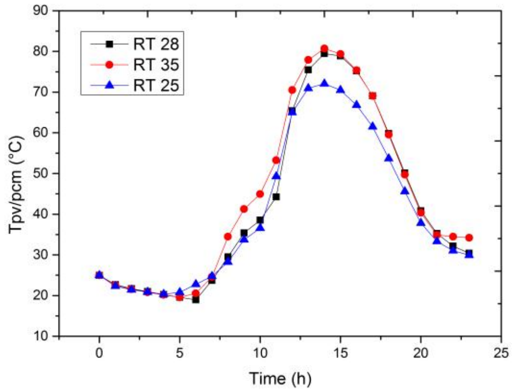

Figure 5: Evaluation of PV panel temperature with different PCMs

4.3. PV panel conversion efficiency

The efficiency of PV panel can be represented by a relation as following:

$$\eta = \eta_{ref}\left[1 - \beta_{ref}(T_{pv} - T_{ref})\right] \tag{21}$$

where η_{ref} , β_{ref} and T_{ref} are the panel's conversion efficiency, temperature coefficient and temperature at standard operating conditions. The value of β_{ref} is 0.0045[1/K] for crystalline PV panels and T_{ref} is 25°C.

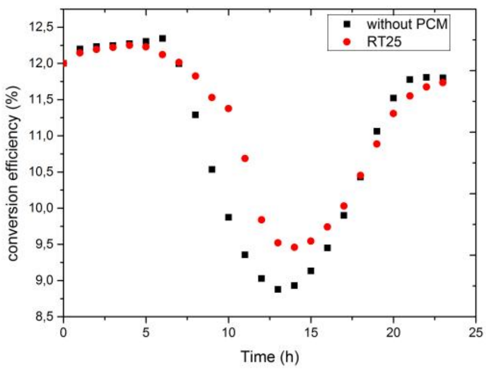

Figure 6: Evaluation of PV panel's conversion efficiency

Figure 5 represents the effect of operating temperature on the PV conversion efficiency. From this figure, the effect of PCM RT25 is clearly observed during its melting by absorbing the excess of heat out of the panel and maintains its operating temperature lower than when there is no PCM. The electric power generation, between 06:00h and 16:00h, is improved by about 0.5-1.5% compared to the system without PCM.

Conclusion

In the recent years, the thermal regulation of PV panels has received a lot of attention from researchers in order to effectively use this technology. As the performance of PV panel coupled with PCM depends on the prevailing conditions, the developed model takes into account the varying ambient temperature and solar radiation to better forecast the thermal behaviour of the panel. As it was seen, in hot and arid climates, the PV temperature frequently exceeds its nominal operating value. So it is recommended to consider the speed of wind in order to simulate the heat losses by forced convection. Additionally, in order to better enhancing the heat transfer exchanges between the panel to the environment, a heat sink mounted to the back side of PV panel can be effective as solution.

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