EFFICIENCY ENHANCEMENT OF PHOTOVOLTAIC SOLAR CELL SYSTEM USING PHASE CHANGE MATERIAL (PCM)

Vu Quoc Huy*

School of Technology, Van Lang University, Ho Chi Minh City, Vietnam

*Corresponding author: huy.vu@vlu.edu.vn

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Abstract – Electrical efficiency of photovoltaic (PV) solar cell is reduced significantly with the increase of its temperature. Cooling down the PV solar cell is essential to maintain the electrical performance and lifetime of the PV module. In the present study, cooling of PV module using a paraffin-based phase change material (PCM) in hot climate of Vietnam is investigated. Thermal modelling is first validated against experimental data reported in literature and then transient thermal simulations are carried out for a duration of 24 hours to assess the effect of PCM itself and PCM with internal fins. Results indicate that the peak temperature of the PV cell can be reduced by 4.3 K thanks to the PV-PCM system with PCM of 40 mm thickness and up to 10 K if the system is integrated with two cooling internal fins.

Key words – Solar energy; Photovoltaic cell; Phase change material (PCM); PV cooling; Electrical efficiency

1. Introduction

Solar energy is largely considered as a natural sustainable source to replace fossil fuels as well to reduce carbon dioxide emission. It is well known that only a small percentage (15 - 20%) of incident solar energy on a photovoltaic (PV) solar cell can be converted to electricity while the remaining solar energy generates heat and raises the temperature of the PV cell that affects to its efficiency [1]. In average, the efficiency of PV solar cell reduces by 0.45% for each degree of temperature rise compared to the ideal reference working temperature of 25°C. Furthermore, overheating results in thermal stress which is harmful to the lifetime of PV systems. To reduce the PV module temperature, several cooling methods are reported in literature which can be classified as active cooling, passive cooling and phase change material (PCM) cooling [12]. Phase change material cooling has received a great interest of researchers in recent years thanks to its easy installation (no fluids or extra power systems are required) and thus it is convenient for various engineering applications (solar energy, electronic cooling, building cooling…) [15]. Huang et al. [2] conducted several experiments for PCM container without and with internal fins to observe the melting process of PCM under constant insolation. The effect of inclination angle on natural convection of PCM during melting process was investigated by Kamkari et al. [6]. Dealing with a full system of PV-PCM, various thermal models have been proposed for solving concurrently the heat transfer problem and the solid – liquid phase transition of PCM [3, 4, 8]. Kaplani and Kaplanis [5] examined the dependence of PV module's temperature on its orientation and inclination, wind velocity and direction and proposed an improved thermal model describing more accurate the combined natural and forced convection. Since several factors need to be monitored to enhance overall efficiency of the PV module, numerical modelling of full thermal processes exerted on the PV module plays a pivotal role in parametric analyses.

Energy efficiency of PV system depends strongly on the weather conditions (solar irradiance, ambient temperature, wind velocity) of the location, therefore the choice of appropriate PCM type (paraffin wax RT25, RT35, RT42…) for cooling is based mainly on the local ambient temperature [9, 13, 14]. High ambient temperature conditions in tropical country as Vietnam requires more attention to the selection of PCM type, it is thus vital to conduct the study to choose the relevant PCM type in the local weather conditions. The current study presents a thermal modelling to assess the effectiveness of PCM in enhancing the PV solar cell's efficiency in the hot climate of Ho Chi Minh City, Vietnam. Thermal modelling is first validated against experimental data reported by Huang et al. [2] and then transient thermal simulations are carried out for a duration of 24 hours to monitor the full melting – solidification process of PCM as well as the temperature variation of PV-PCM systems. Effects of PCM itself and PCM with internal fins are analyzed.

2. Model of PV-PCM system

2.1. Thermal model

A standard photovoltaic (PV) panel consists of five layers: glass, ethylene-vinyl acetate (EVA) sheet, polycrystalline silicon solar cells, EVA sheet and TPT (Tedlar/PET/Tedlar) back-sheet layer. In a typical PV-PCM system, PCM material is stored in an aluminum box attached at the back of the PV module (Figure 1).

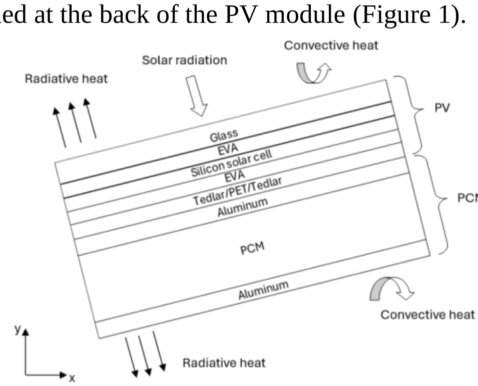


Figure 1. *Physical and thermal model of PV-PCM system*

The heat transfer through the PV-PCM system includes the solar radiation on the glass cover and silicon solar cells, the convection and radiation at the front and back surfaces with the surrounding environment, natural convection within PCM medium and the conduction among different layers of the system. At the front and back surfaces of the system, the heat transfer equations are as follows:

$$-k_{glass}\frac{\partial T}{\partial y} = h_{f,conv}(T_{amb} - T_{glass}) + \varepsilon_{glass}F_{front}\sigma(T_{amb}^4 - T_{glass}^4) + \alpha_{glass}G_{PV}(t) \quad (1)$$

$$-k_{alum}\frac{\partial T}{\partial y} = h_{b,conv}(T_{amb} - T_{alum}) + \varepsilon_{alum}F_{back}\sigma(T_{amb}^4 - T_{alum}^4) \quad (2)$$

where $h_{f,conv}$ and $h_{b,conv}$ are respectively the combined heat transfer coefficients for natural and forced convection for front glass surface and back aluminum surface, T_{amb}, T_{glass} and T_{alum} are respectively the ambient, front glass surface and back aluminum surface temperatures. Regarding the heat radiation exchange, σ is the Stefan-Boltzmann constant, $\varepsilon_{glass} = 0.91$ and $\varepsilon_{alum} = 0.85$ are the emissivity coefficients of front and back surfaces [5], F_{front} and F_{back} are the view factors of the front and back surfaces to sky and ground respectively. The sky and ground temperatures are assumed to be equal to the ambient temperature [7]. Solar radiation absorbed by the glass cover is determined from the glass absorptivity α_{glass} and the incident solar irradiation on the PV module G_{PV}.

Between the layers within the system, the heat conduction is governed by:

$$\rho C_p\frac{\partial T}{\partial t} = k\frac{\partial T}{\partial y} \quad (3)$$

in which, ρ, C_p, k are respectively the density, specific heat and thermal conductivity of each layer.

The combined natural and forced convection coefficients ($h_{conv} = h_{free} + h_{forced}$) for front ($h_{f,conv}$) and back ($h_{b,conv}$) surfaces of the PV-PCM system depend strongly on the local environment condition where the system is installed. The natural convection coefficient h_{free} may be estimated from the Rayleigh and Prandtl numbers of the air flow (laminar flow in this case $10^4 \leq Ra_L \leq 10^9$) and the characteristic length of the PV panel (L_c):

$$h_{free} = \frac{k_{air}}{L_c}\left(0.68 + \frac{0.67Ra_L^{1/4}}{\left[1+(0.492/Pr)^{9/16}\right]^{4/9}}\right) \quad (4)$$

The forced convection due to the wind velocity (normally below 6 m/s) could also be defined from the Reynolds and Prandtl numbers (formulation for laminar flow is shown):

$$h_{forced} = \frac{k_{air}}{L_c}\left(0.664Re_L^{0.5}Pr^{1/3}\right) \quad (5)$$

Naturally, forced convection is always included one part of natural convection effect. The dominance of natural or forced convection may be defined based on the parameter Gr/Re^2 of the flow [16]. Natural convection is negligible when $Gr/Re^2 < 0.1$, forced convection is negligible when $Gr/Re^2 > 10$ and both natural and forced convection must be taken into account when $0.1 < Gr/Re^2 < 10$.

2.2. Solar irradiation and power generation

Usually, the PV panel system is installed at a tilt angle (β) from the horizontal surface to maximize the amount of the receiving solar radiation. The solar irradiation on a tilted PV panel (G_{PV}) is calculated from the total horizontal (surface) irradiation ($G_{horizontal}$) as follows:

$$G_{PV} = G_{horizontal}\cos(\theta) \quad (6)$$

where θ is the solar incidence angle. For a true south-facing tilted PV panel in the northern hemisphere, θ is defined from the solar declination (δ), the hour angle (h), the local latitude (L) and the PV tilt angle (β):

$$\cos(\theta) = \sin(L-\beta)\sin(\delta) + \cos(L-\beta)\cos(\delta)\cos(h) \quad (7)$$

The view factors F_{front} and F_{back} in the equations (1), (2) are defined from the tilt angle of the PV panel as follows [5]:

$$F_{front} = (1 + cos\beta)/2 \quad (8)$$

$$F_{back} = (1 - \cos(\pi - \beta))/2 \quad (9)$$

The electrical power generated by the PV system (P_e) is determined from the area of the solar panel (A) and the solar irradiation on the system (G_{PV}):

$$P_e = \eta_{PV}AG_{PV} \quad (10)$$

The effect of the PV temperature (T_{PV}) on the efficiency of PV system is described through the electrical efficiency (η_{PV}) as given below [1]:

$$\eta_{PV} = \eta_{ref}[1 - 0.0045(T_{PV} - 25) + 0.1log_{10}(G_{PV}/1000)] \quad (11)$$

where $\eta_{ref} = 15.6\%$ is the reference efficiency of a solar cell at 25°C and irradiation of 1000 W/m^2. The equation of η_{PV} corresponds to the fact that the efficiency decreases of 0.45% when the PV temperature increases of 1°C.

2.3. PCM model

PCM acts as a heat sink, absorbing heat generation by the PV panel during daylight and releasing heat during night, to cool down the PV panel. During daylight, PCM receives heat from the PV panel and changes its physical state from solid to liquid (melting process). Reversely, solidification process of PCM takes place during night to bring the PCM back to the initial solid phase. The temperature dependent density of the PCM can be described by Boussinesq approximation:

$$\rho_{PCM}(T) = \rho_o\left[1 - \beta_{PCM}(T - T_{ref})\right] \quad (12)$$

where ρ_0 is the reference density (solid phase), β_{PCM} is the thermal expansion coefficient and T_{ref} is the reference temperature corresponding to the reference density. The PCM medium can be considered as a porous medium (Darcy - Forchheimer model) to model the phase transition process, in which the energy equation and momentum equations (Navier-Stokes equations) with the effect of buoyancy force are solved simultaneously.

3. Numerical models and validation

Transient thermal modelling of the PV-PCM system is carried out in Altair® SimLab® 2024. First, the numerical model of PCM melting process is validated against Huang experimental data for 250 minutes [2]. The experimental system had the front and rear walls fabricated from 4.5 mm thick aluminum plate. PCM RT25 used in the experiment was stored in a container of 40 mm width, 132 mm height and 300 mm length. The upper and lower horizontal faces of the PCM container were insulated. The constant insolation (a solar simulator) applied to the front aluminum surface was 750 W/m^2. The convection heat transfer coefficients on the front and rear surfaces were assumed to be 12.5 and 7.5 W/m^2.K. The ambient temperature is 22°C. Figure 2 shows the configuration of the experimental PCM system.

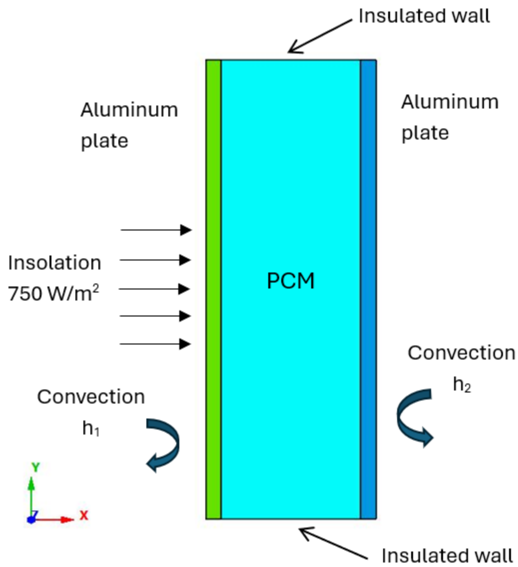


Figure 2. *Heat transfer experiment of PCM system [2]*

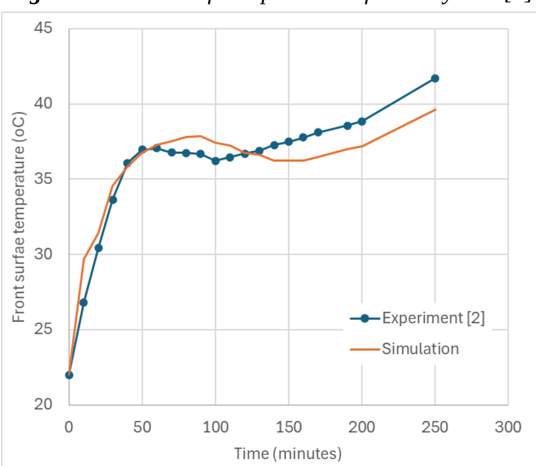
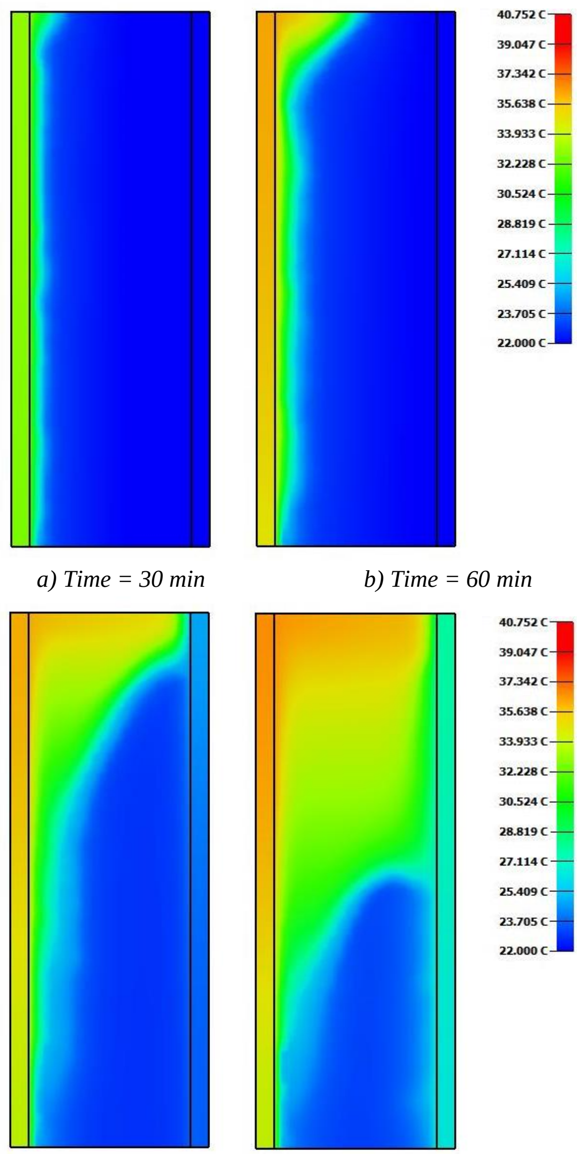


Figure 3. *Experimental and computational temperatures at the front surface of the verification PCM system*

The comparison of experimental and computational temperatures at the front surface of the system is presented in Figure 3. The numerical results are in good agreement with the experimental ones. The average difference between experimental and numerical results is 0.7°C. Figure 4 shows the temperature contours in the system during melting process at different moments (30, 60, 120, 200 minutes). At the beginning of the melting process, during first 50 minutes, the surface temperature increases linearly (Figure 3) and the solid-liquid interface inside of PCM is nearly parallel to the front hot surface (Figure 4a) illustrating that the heat conduction from the front surface to the PCM is the dominant mode (sensible heat). During the periods from 50 – 200 minutes, PCM acts to absorb heat from the front surface under the form of latent heat to maintain the temperature of the front surface while continuing receiving the constant insolation (Figure 3). During this period, the buoyant force becomes important that promotes the natural convection and thus the melting from the top wall of the container (Figures 4b, 4c). After 200 minutes, PCM approaches complete melting meaning that its capacity of heat absorption reaches the limit. Accordingly, the front surface temperature resumes to increase significantly (Figure 3).



a) Time = 30 min *b) Time = 60 min*

c) Time = 120 min *d) Time = 200 min*

Figure 4. *Temperature contour during melting process*

4. Results and discussion

4.1. Weather data and PV-PCM model

For a real local context of Ho Chi Minh city, Vietnam (10.8276 °N, 106.7 °E) weather data is collected from the website weatherspark.com and the solar irradiation data is consulted from the Global Solar Atlas of the World Bank

Group. Since both the average temperature during daytime and the solar irradiation are highest in February, the data of February 15th, 2024 is selected for study. Figure 5 represents the collected data of ambient temperature and surface solar irradiation in 24 hours (GMT +7). The wind velocity during the day varies from 2 m/s to 5.7 m/s with the average value of 3.7 m/s. It is worthy noted that since the wind velocity is instantaneous rather than quasi continuous as temperature/ solar radiation, the effective value of wind velocity should be lower than the above-mentioned value.

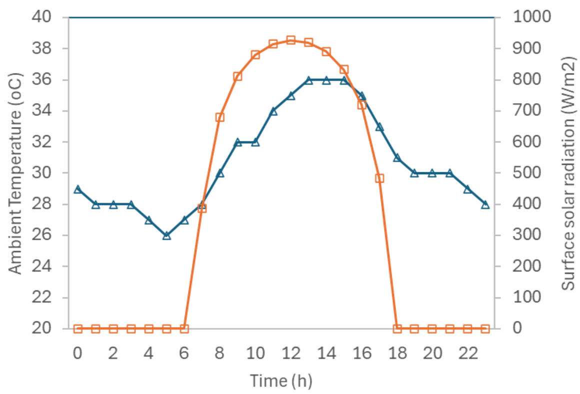


Figure 5. *Data of ambient temperature and horizontal surface solar radiation*

To assess the performance of an PV-PCM system, thermal characteristics of the system during a whole day (24 hours) need to be monitored. In the real configuration of PV-PCM presented in Figure 1, EVA layer, silicon solar cell and TPT layer have respectively thin thicknesses of 0.5 mm, 0.2 mm and 0.3 mm. The impact of EVA layer, TPT layer to the heat transfer of silicon solar cell is very small and could be negligible. Therefore, in this study, a single layer of silicon solar cell of 1 mm is used to represent concurrently the effect of EVA layer and TPT layer. The simplified five-layer PV-PCM model in this study includes the glass cover, the silicon solar cell, the front aluminium plate, the PCM and the back aluminium plate has been created (Figure 6).

The choice of PCM is based on the range of ambient temperature. As shown in the Figure 5, the nighttime where the solidification process of PCM takes place has an average temperature around 28°C. The solidification temperature of PCM should be higher than the nighttime average temperature to ensure that the PCM could release heat and come back to the initial solid phase before starting a new daytime. Therefore, RT35HC paraffin wax is selected for the PCM in this study. Table 1 shows the properties and thicknesses of layers in the studied PV-PCM system. Three cases of PCM thickness (30, 40, 50 mm) are considered to investigate the effect of PCM thickness. Regarding the length and width of the model, dimensions of a half solar cell (150 mm x 75 mm) are taken. As recommended by the Global Solar Atlas, to perform optimally, the PV-PCM panel is pointed directly to the true south and the tilt angle from the horizontal surface $\beta = 15^o$. Two different system configurations without and with internal fins are shown in Figure 6.

Table 1. *Properties and thickness of PV panel and PCM*

Layers	Density (kg/m³)	Cp (J/kg.K)	Conductivity (W/m.K)	Thickness (mm)
Glass	3000	500	1.8	3
Silicon cell	2330	677	148	1
Alumi-nium	2700	900	237	2
RT35 HC	880/770	2000	0.2	30/40/ 50

Thermal properties of RT35HC:
Latent heat of fusion (J/kg): 240 000
Phase change temperature (°C): 34 – 36

Solar radiation coming to the PV-PCM system is absorbed little by the glass cover and transmitted mostly to the silicon solar cells. The solar cell has low transmissivity, then the absorption by the layers below the solar cell could be negligible. Therefore, in this study, only the effects of solar radiation on the glass cover and on the silicon solar cell are considered. Table 2 represents the optical properties of the glass cover and the silicon solar cell used in the PV-PCM model.

Table 2. *Optical properties of PV-PCM model*

Layers	Absorptivity	Reflectivity	Transmissivity
Glass	0.05	0	0.95
Silicon cell	0.9	0.08	0.02

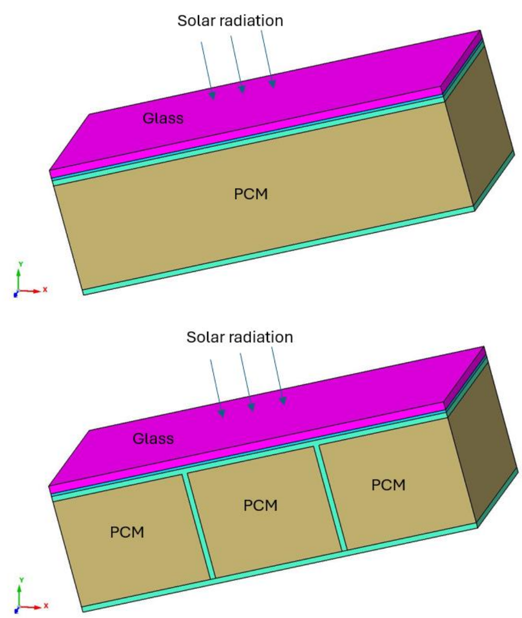


Figure 6. *Configurations of PV-PCM systems*

4.2. Result of thermal simulations with PCM

All transient thermal simulations are carried out for a duration of 24 hours, starting from 6 am corresponding to the moment having the solar radiation. The temporal values of ambient temperature and surface solar radiation shown in Figure 5 are used in simulations. To estimate the combined convection heat transfer coefficients for the front glass and back aluminum surfaces, an average constant wind velocity of 2 m/s is assumed and therefore two convection heat transfer coefficients respectively for the front and back surfaces are unchanged during the whole computation duration. The assumed wind velocity results in the Rayleigh number in the range of 10^6 – 10^7 corresponding to the regime of laminar flow. Accordingly, the natural convection coefficient h_{free} and the forced convection coefficient h_{forced} can be determined by the equations (4) and (5). Otherwise, the parameter Gr/Re^2 falls in the range of 0.01 – 0.02 and therefore the effect of the forced convection is dominant while the natural convection is negligible [16].

Figure 7 shows the variations of PV solar cell temperature during 24 hours for four different models: PV system without PCM (the reference PV system) and PV-PCM systems with different thicknesses of PCM (30, 40, 50 mm). For the reference PV system, the model includes only three layers: glass cover, silicon solar cell and the TPT back-sheet. The solar cell temperature of the reference system increases with the solar radiation and reaches a maximum value around noon. The variation of solar cell temperature is similar to the variation of solar radiation. The peak temperature of solar cell is 322.2 K. When solar radiation is not available from 18h, the solar cell temperature rapidly decreases to the ambient temperature. It is noted that although the ambient temperature maintains its maximum value from 13h to 15h (Figure 5), the solar cell temperature decreases accordingly with the solar radiation. The obtained result of solar cell temperature indicates the role of wind-induced forced convection in cooling the conventional PV module. This observation is in agreement with the experimental results reported in the studies of Hasan et al. [9] and Mohammed et al. [14] in hot climate conditions.

Regarding the three cases of PV-PCM system, the effects of PCM to the solar cell temperature are similar except the peak temperatures and the final temperatures. When the solar cell temperature rises above the PCM's melting temperature (307 K), PCM starts to absorb heat from the solar cell and thus slows down the temperature increase of the solar cell. Peak temperatures of solar cells in PV-PCM systems are lower than the peak temperature of the reference system. Furthermore, the peak temperatures in PV-PCM systems are reached later, around 14 o'clock. The advantage of PCM is proven by the significant drop of solar cell's peak temperature whereas the high temperature in the solidification phase of PCM remains its drawback. This numerical result is in accordance with the experiments conducted by Hasan et al. [9]. The peak temperatures are 319 K for the system with 30 mm PCM and 317.9 K for both cases of 40 mm and 50 mm PCM. After the daytime, PCM begins the solidification process as it releases gradually the heat to the environment to come back as close as possible to the initial solid state. However, as shown in Figure 7, the PCM's thickness has an important effect on the final temperature of the solar cell. The final temperatures are respectively 299.2 K, 300.5 K and 302.2 K for the cases of 30 mm, 40 mm and 50 mm PCM. Greater thickness needs longer time to release the heat. Among the three considered PV-PCM systems, the case with 40 mm PCM brings the best effect to the peak temperature (drop of 4.3 K) and the final temperature of the solar cell.

4.3. Enhancement of PCM effectiveness with fins

Main limitation of PCM is the low thermal conductivity and thus the PV-PCM system requires long duration to recover its initial solid state. To improve the PCM thermal performance, internal fins added inside the PCM container is a widely adopted solution. As reported in several studies [10, 11], numerous parameters of the internal fins (length, thickness, distance…) need to be considered to achieve the best effectiveness. In this study, due to the small dimension of the studied model, only two cases with one and two fins are considered. The PV-PCM system with 40 mm PCM has been selected for further study with fins. Each added fin has thickness of 2 mm and length of 40 mm (Figure 6).

Figure 8 shows the comparison of solar cell temperature during 24h between the reference PV system, the system of 40 mm PCM without fin and two systems of 40 mm PCM with one fin and two fins. The obtained results indicate the effectiveness of added fins to enhance the thermal performance of PCM in decreasing both the peak temperature and the final temperature of the solar cell. The peak temperatures are respectively 313.6 K and 312.2 K for the system with one fin and two fins. Compared to the reference system, the PV-PCM system with two fins cools down the solar cell's peak temperature by 10 K. This finding shows a great potential of using PV-PCM system with internal fins to enhance the efficiency of PV solar cell.

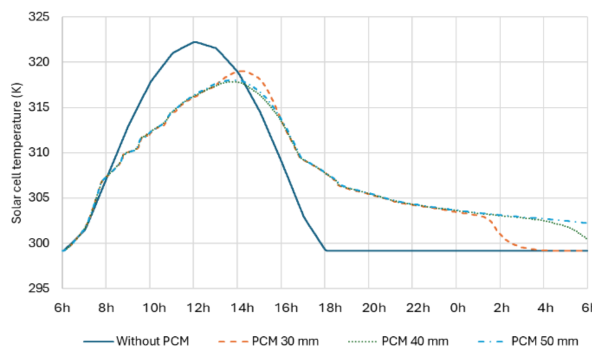


Figure 7. *Solar cell temperatures in different PV-PCM systems*

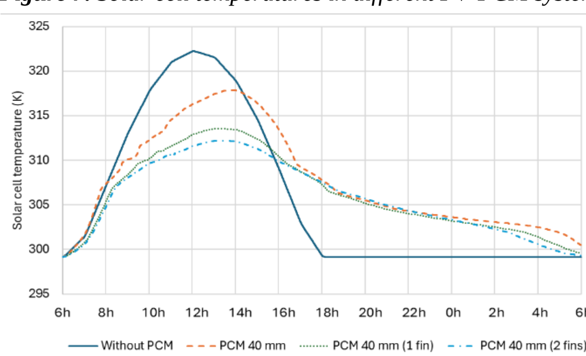


Figure 8. *Effect of internal cooling fins in PV-PCM systems*

5. Conclusion

The thermal model of the PV-PCM system including the solar radiation and three different modes of heat transfer (conduction, convection, radiation) coupling with phase change process of PCM is presented in this study. Transient thermal simulation of phase change (solid/liquid) during PCM melting process is validated against experimental results in literature. PCM itself and PCM with added fins have shown their effectiveness in cooling down the solar cell's temperature meaning enhancement of solar cell's performance. Compared to the reference PV system without PCM, the PV-PCM system with 40 mm of PCM results in a drop of 4.3 K while the system with two fins can achieve a drop of 10 K of the solar cell's peak temperature. The RT35HC paraffin wax could be a relevant choice of PCM for the weather condition in Ho Chi Minh City, Vietnam. It is shown that the PV-PCM systems with internal fins have a great potential in cooling down the solar cell temperature to enhance the thermal as well as electrical efficiency of the PV panel.

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