

Numerical Performances Study of Curved Photovoltaic Panel Integrated with Phase Change Material

Mohamed L. BENLEKKAM

*Department of Mechanical Engineering
National Polytechnic School of Oran
Oran 31000, Algeria
Laboratory of Smart Structure
Institute of Science and Technology
Centre University of AinTémouchent
AinTémouchent 46000, Algeria
mohamed_benlekkam@yahoo.fr*

Driss NEHARI

*Laboratory of Smart Structure
Institute of Science and Technology
Centre University of AinTémouchent
AinTémouchent 46000, Algeria
nehari_dr@yahoo.fr*

Habib Y. MADANI

*Department of Mechanical Engineering
National Polytechnic School of Oran
Oran 31000, Algeria
habib.yssaad@yahoo.fr*

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The temperature rise of photovoltaic's cells deteriorates its conversion efficiency. The use of a phase change material (PCM) layer linked to a curved photovoltaic PV panel so-called PV-mirror to control its temperature elevation has been numerically studied. This numerical study was carried out to explore the effect of inner fins length on the thermal and electrical improvement of curved PV panel. So a numerical model of heat transfer with solid-liquid phase change has been developed to solve the Navier–Stokes and energy equations. The predicted results are validated with an available experimental and numerical data. Results show that the use of fins improves the thermal load distribution presented on the upper front of PV/PCM system and maintained it under 42°C compared with another without fins and enhances the PV cells efficiency by more than 2%.

Keywords: phase change material, Latent heat, Thermal regulation, Photovoltaic cell, PV-mirror.

1. Introduction

The temperature rise of photovoltaic cell reduce its electrical efficiency. However, only 15–20% of the sunlight involved to in electrical conversion process. while the rest is transformed into heat [1]. Which increase the PV operating temperature. As a result affects the electrical conversion efficiency by a drop of 0.5% per 1°C; and reduce the solar cell lifetime Norton et al [2]. Therefore, maintaining the temperature of PV cells at adequate level can improve their efficiency. Several research try to control the PV cells temperature by many techniques in order to overcome it. Overall, the use of a PV panel attached by a phase change material (PCM) has been an effective solution widely used to limit the temperature rise of PV cells [3-7], which can absorb a large quantity of heat during its melting process at constant temperature.

The experimental and numerical studies of Huang et al [8-13] was conducted under the thermal regulation of building integrated photovoltaic panel BIPV by using PCM. Starting by the first research [12] which, they have succeed to maintain the temperature of the PV cells under 40 °C for 80 min, with a PCM RT25 that have a melt temperature of 32°C, then considering the low thermal conductivity of RT25 0.18 W.m-1.K-1, an internal fins in Aluminum used to transport the thermal load into the PCM in order to reduce the temperature rise on PV. In other hand Huang et al [8-11] investigated the use of inner fins in BIPV to enhance the heat transfer in PCM losing the excess heat in PCM. They have studied the effect of internal fins spacing on BIPV thermal regulation and PCM behavior, they found that the use of fins improve thermal distribution of PV/PCM system and reduce its temperature significantly. Cellura et al [14] studied a PV/PCM system numerically with a finite element method, they considered a pure PCM with a constant phase change temperature, they succeed to improve the performance of PV/PCM system by 20%, but practically the PCMs are mixtures of paraffins that have a phase change range temperature. Moreover.

Karunesh et al [15] they studied the effect of several parameters such as the heat transfer mechanisms, tilt angle and wind speed of PV/PCM system. When only conduction is considered, the operating temperature decreased by about 3°C and the solar efficiency is improved by 5%, in addition the higher wind speed and the tilt angle allow a good cooling of photovoltaic panels. Stropnik et al [7] studied both experimentally and numerically the electrical performance of PV/PCM system with the TRNSYS software, the electrical production by the photovoltaic module has been improved up to 7% for one year.

Elarga et al. [16] have developed a physical model to study the incorporation of an PCM layer on a double-facade of PV panel for three different climates, they have found that this technique can improve the conversion of solar energy into electricity independently of the climate, they concluded that the use of PCM can also increase the cooling of the building more than 20% per month. An experimental study was carried out by Nikolaos S et al [17] to evaluate the efficacy of PCM to mitigate the influence of temperature on photovoltaic module performance. The PV/PCM system was tested under Mediterranean climatic conditions. They found that the chosen PCM "RT27" succeeded in reducing the PV module temperature by an average of 11°C compared to a system without PCM, furthermore the conversion

efficiency of the PV module increases by about 8.6%. Since the phase change materials are pure and combined, Farouk et al [5] studied their influence on the performance improvement of the PV modules. They found that the use of pure PCM can reduce the PV temperature by more than 6.5°C by an average of 2.7°C, and increase the electrical efficiency by an average of 3%. on the other hand the combined PCM can reduce the PV temperature by an average of 5.6°C and improves the efficiency of the PV module by about 5.8%.

Recently, a novel technology of solar photovoltaic panel was introduced in world of solar energy, so-called PV-mirror. which combined by two types of panel: a plate one placed at the focal point of reflector mirror and the second (curved PV) behind the curved mirror [18], or several PV panels arranged rear the mirror to take the curvature form[19]. This system made with special mirror that concentrates the large part of the sunlight into a flat PV panel positioned at the reflector's focal point. On the other hand, the rest part of the sunlight is converted to electric power via curved one.

We studied previously the effect of curvature radius for several configurations on its thermal regulation. We found that the temperature distribution in curved PV/PCM system was not regulate. Therefore, in the present paper; we performed a parametric study on the effect of length of inner fins on thermal and electrical performance of a curved PV/PCM system.

2. Numerical solution

2.1. Description of the problem

The studies domain of PV/PCM considered in the present study is illustrated in Fig. 1, as shown the PV/PCM system is composed by a curved PV panel attached on a curved container filled by PCM. The PCM used is Rubitherm RT25 and its thermophysical properties which are assumed to be constant during the melting process are provided in Table 1. Natural convection was adopted over the PV panel and the back wall of the container of PCM. The PCM is in perfect contact with the PV panel and the back wall. The incident energy I_T is absorbed and dissipated into heat inside the PV/PCM system. In our case, we use the same geometry considered by Huang et al[12]. Therefore, we use the same boundary and initial conditions of the last authors, which are:

- (i) the initial temperature of the system PV/PCM is T_{PV} ;
- (ii) the front and rear surfaces of the system have respectively the values h_1 and h_2 ;
- (iii) concerning the top and bottom boundaries, the adiabatic conditions are used.

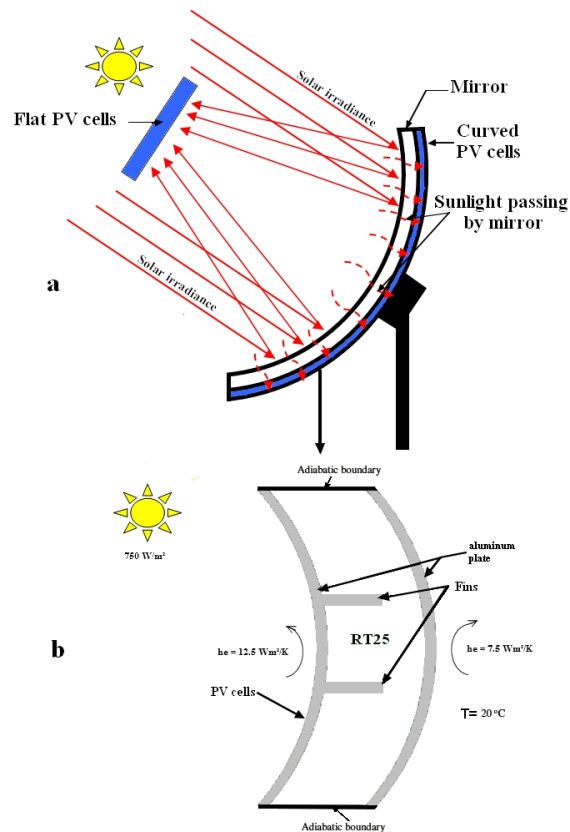
The 2D unsteady governing equations of energy and momentum heat transfer are solved by using the implicit finite volume method with the commercial code fluent 6.3.26. In addition, the Boussineq approximation was adopted to take account the change in density of the PCM in liquid phase as a function of temperature.

3. Governing equations

In the present study, 2D implicit finite volume method was used to solve the governing equations for a head transfer conjugate with phase change process. the

Table 1 Thermodynamic properties of "RT25" [20], paraffin wax[21] and Aluminum[22]

Property	"RT25" PCM	Paraffin wax	Aluminum
Density			
Solid, Kg.m^{-3}	785	830	2675
Liquid, Kg.m^{-3}	749	830	Not used
Specific heat capacity			
Solid, $\text{J.m}^{-3}.\text{K}^{-1}$	1413000	1593600	2415525
Liquid, $\text{J.m}^{-3}.\text{K}^{-1}$	1797600	2705000	Not used
Thermal conductivity			
Solid, $\text{W.m}^{-1}.\text{K}^{-1}$	0.19	0.514	211
Liquid, $\text{W.m}^{-1}.\text{K}^{-1}$	0.18	0.224	Not used
Melting temperature,	26.6	32	Not used
Latent heat of fusion, J.kg^{-1}	232000	25 000	Not used

**Figure 1** The schematic diagram boundary conditions of curved PV/PCM system for the present study

enthalpy-porosity formulation was adopted in solving phase change region in PCM. In this method the interface between the solid and the liquid phases modeled as a porous medium. The liquid fraction varies smoothly across this porous, so-called mushy region. The mushy zone is modeled via the phase fractions, which are incorporated in the source terms in the governing equations to account for the phase change phenomena.

- Equation de continuity

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \quad (1)$$

- Equation of momentum (x) axis:

$$\frac{\partial}{\partial t} (U) + \frac{\partial}{\partial X} (U^2) + \frac{\partial}{\partial Y} (UV) = -\frac{\partial P}{\partial X} + P_r \left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2} \right) + R_a P_r \sin(\alpha) + S'_x \quad (2)$$

- Equation of momentum (y) axis:

$$\frac{\partial}{\partial t} (V) + \frac{\partial}{\partial X} (UV) + \frac{\partial}{\partial Y} (V^2) = -\frac{\partial P}{\partial Y} + P_r \left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2} \right) - R_a P_r \cos(\alpha) + S'_y \quad (3)$$

- Equation energy :

$$\frac{\partial}{\partial t} (\rho h) + \frac{\partial}{\partial x} (\rho u h) + \frac{\partial}{\partial y} (\rho v h) = \frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k \frac{\partial T}{\partial y} \right) + S_h \quad (4)$$

Where ρ is the density, k denotes the thermal conductivity, μ is the dynamic viscosity, S_i and S_h are the source terms, u_i is the velocity component in the i-direction, x_i is a Cartesian coordinate, and h is the specific enthalpy. The sensible enthalpy h_s is given by:

$$h_s = h_{ref} + \int_{T_{ref}}^T C_p dT \quad (5)$$

And the total enthalpy, H is defined as

$$H = h_s + \Delta H \quad (6)$$

Where $\Delta H = \gamma L$ is the enthalpy change due to phase change, h_{ref} is the reference enthalpy at the reference temperature T_{ref} , C_p is the specific heat, L is the specific enthalpy of melting (liquid state) and γ is the liquid fraction during the phase change which occur over a range of temperatures

$T_{solidus} < T < T_{liquidus}$ defied by the following relations:

If $T < T_{solidus}$

$$\gamma = \frac{\Delta H}{L} = 0 \quad (7)$$

If $T_{solidus} < T < T_{liquidus}$

$$\gamma = \frac{\Delta H}{L} = \frac{T - T_s}{T_l - T_s} \quad (8)$$

Si $T > T_{Liquidus}$ (liquid state)

$$\gamma = \frac{\Delta H}{L} = 1 \quad (9)$$

The source terms S_i and S_h are given by:

$$S_i = -A(\gamma) u_i \frac{C(1-\gamma)^2}{\gamma^3 + \varepsilon} u_i \quad (10)$$

$$S_h = \rho L \frac{\partial \gamma}{\partial t} \quad (11)$$

Where $A(\gamma)$ is defined as the “porosity function” which governs the momentum equation based on Carman-Kozeny relationship for flow in porous media. The function reduces the velocities gradually from a finite value of 1 in fully liquid to 0 in fully solid state within the computational cells involving phase change. The epsilon $\varepsilon = 0.001$ infinity avoidance constant due to division by zero and C is a constant reflecting the morphology of the melting front where $C = 10^5$.

Boussinesq approximation was adopted to calculate the change in PCM density as a function of temperature in the liquid density given by:

$$\rho = \rho_0 [1 - \beta (T - T_0)] \quad (12)$$

And the relationship of buoyancy forces in the momentum equation is given by:

$$-\rho g = \rho_0 g [\beta (T - T_m) - 1] \quad (13)$$

where ρ_0 is the reference density at melting temperature T_m and β is the thermal expansion.

The above equations (Eq. (1), (2) and (3)) which govern a heat transfer are solved by an implicit finite volume method of the commercial code fluent 6.3.26. A fined regular grid and variable time step with a minimum value of 0.01s are used for all the simulations. The total number of grid is 132x48 for all simulation.

The temperature of the PV cell (T_{pv}) can vary depending on the weather variables such as ambient temperature (T_{am}), local wind speed (V_w), solar radiation (I_t), physical properties of the system such as glazing Skoplaki et al. [23]. The effect of temperature on the electrical efficiency of a PV cell can be obtained by using a fundamental equation: Kant et al [15]

$$\eta_c = \eta_{ref} [1 - \beta_{ref} (T_c - T_{ref})] \quad (14)$$

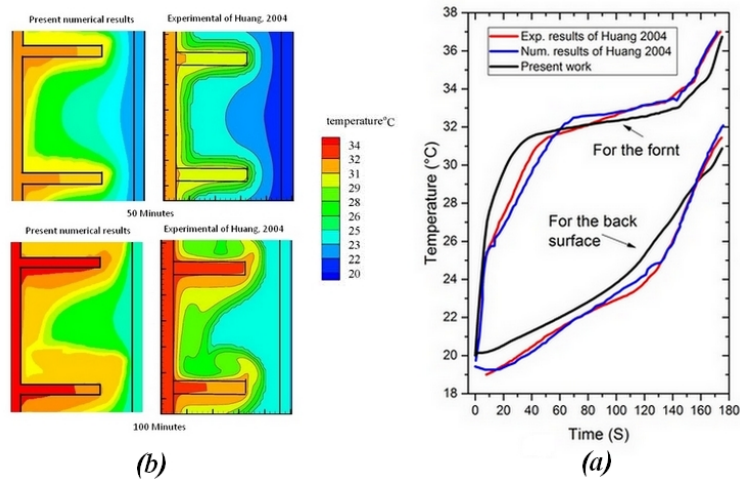
where η_{ref} and β_{ref} are the reference solar cell efficiency and the solar cell temperature coefficient at the standard operating temperature of 25°C, respectively. The reference solar irradiance, I_t , is equal to 1000 W/m². These values are provided by the manufacturer data sheet and are available for most PV cells.

Table 2 Photovoltaic Cell maximum efficiency

T_{ref} ($^{\circ}\text{C}$)	η_{ref}	β_{ref} (K^{-1})	Cell type	References
25	0.15	0.0041	Mono-Si	[24]
28	0.117	0.0038	Average of Sandia and commercial cells	[25]
25	0.11	0.003	Mono-Si	[26]
25	0.13	0.004	Mono-Si	[27]
25	0.11	0.004	Poly-Si	
25	0.12	0.0045	Mono-Si	[28]
25	0.15	0.004	Poly-Si	[15]

4. Numerical modeling

For the numerical solution, the pressure-velocity coupling is accounted for by using SIMPLE algorithm [29], whereas the Quick scheme was adopted for convective discrimination. The grid size adopted in present simulation was 48×132 and a variable time step with a minimum value of 0.01s are used for all the simulations, and the convergence was confirmed at each time step, with the convergence criterion of 10^{-6} for all variables.


Figure 2 Model validation with Huang et al 2004 [12]

4.1. Validation

All the simulations were conducted using the heat transfer coefficients on the front and rear surfaces are respectively $12.5 \text{ Wm}^{-2}\text{K}^{-1}$ and $7.5 \text{ Wm}^{-2}\text{K}^{-1}$ and the insolation was 750 Wm^{-2} .

The present model Benlekkam et al [30] was validated successfully with numerical and experimental data of [12], our validation was performed with a same initial and boundary conditions, material properties and geometry, then we compared our results with the predicted and experimental temperature evolution of front and rear surface of PV/PCM system Figure 2a, in addition we compared the isothermal contours of temperature in Figure 2b a good agreement was obtained.

5. Results and discussion

The use of PCM for passive cooling is one of the most effective technique according to many researches [5, 8-12, 14, 16, 30-36]; but it still need more development, in order to determine several influential parameters on thermal performance of PV/PCM system; such as PCM thickness, inner fins number and PCM properties. In the present study, we tried to evaluate the length of internal fins in the range of 0 mm to 40 mm in an interval of 5mm of curved PV/PCM system with curvature radius (R) equal 100mm.

5.1. Effect of internal fins length

From previous study [30], we explored the effect of curvature radius for PV/PCM system without fins. We found that this configuration have some minor effect on cooling rate, where the molten PCM layer adjacent to the rear surface of PV play as insulate material because of its low thermal conductivity ($\lambda_{PCM} \approx 0,2 \text{ Wm}^{-1} \cdot \text{K}^{-1}$). So the good solution to improve the thermal conductivity of PCM is the use of aluminum internal fins in order to transport the thermal load into the PCM.

Figure 3a and 3b shows the isothermal contours and the liquid fraction of all PV/PCM systems under investigation at the 50th; it can be seen that the temperature of PV/PCM without fins reached a maximum of 37.48°C compared with the rest; while it maintained below 33.8°C for the rest configurations. This great difference value of 4°C between just a PV/PCM system without fins and other with 5mm length fins allowed us to investigate the rest length ranges.

It's clear from Figure 3 that temperature of PV/PCM system decrease significantly to take minimum value $30,28^\circ\text{C}$ with system that length fins take 35mm. Overall, the predicted temperatures at the front surface of all PV/PCM system decrease with the increase of length fins; this is due to the large exchange surface, which allowed to lose more heat loads inside the PCM. Moreover, as time elapse the melt front extends into the PCM. to increase the molten PCM bulk; so the heat transfer dominated by convection. Therefore, the cold convective flow from upper surface of fins improve the cooling rate; moreover the heat is transferred to the solid PCM and the molten PCM cooled.

The predicted isothermal and liquid fraction at 100 minutes are presented in Fig. 4a and 4b respectively. The high temperature registered on PV/PCM system without fins rises at 38°C , contrariwise it maintained less than 31°C for all system with fins. We can see that this difference of 7°C was great compared with the previous at 50 minutes. The melt front surface becomes more large, in this moment the heat transfer generally is dominated by convection, where the cool convective flow of melt PCM takes more heat from the rear surface of PV to solid PCM, so this circulation enhances the cooling. It's clear that the increase of the fins length reduce

the temperature of PV cells, so the configurations with fine length ($L = 25, 30$ and 35 mm) allow a good thermal cooling, where the mean front temperature maintained less than 33°C . However the others not preferable, because of their small exchange surface. with the mean temperature rises up to 36°C for configuration with 5mm length fins; but still always better than a configuration without fins.

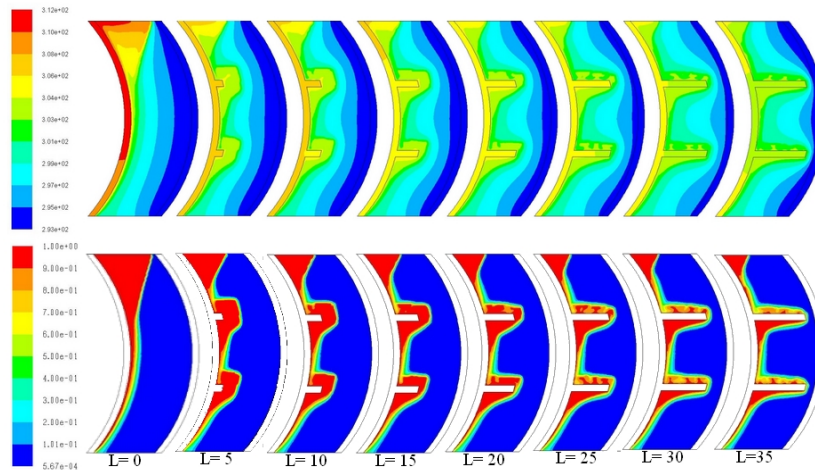


Figure 3 Predicted isothermal contours of PV/PCM system at 50^{th} : (a) isothermal temperature and (b) the liquid fraction

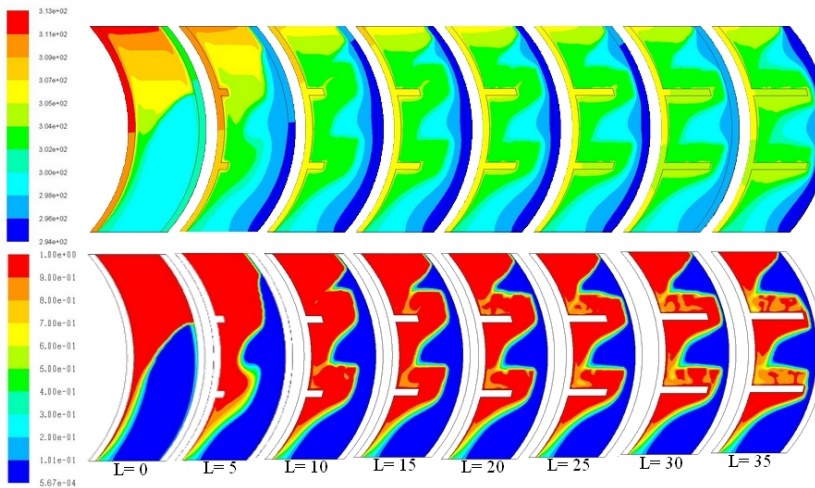


Figure 4 Predicted isothermal contours of PV/PCM system at 100^{th} : (a) isothermal temperature and (b) the liquid fraction

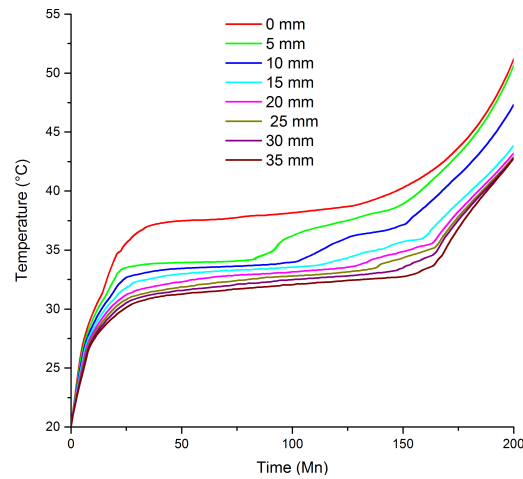


Figure 5 Predicted average temperature evolution in time of all systems

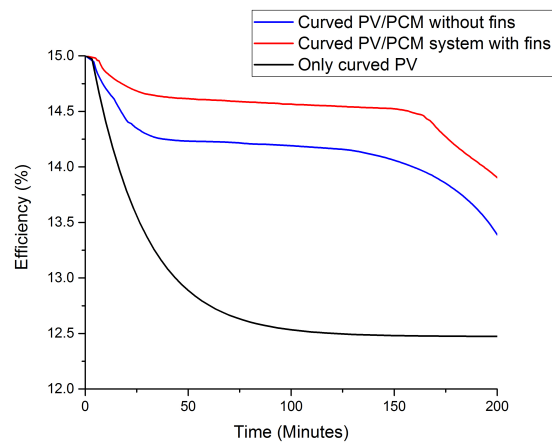


Figure 6 The PV cell electrical efficiency with and without PCM layer

The temperature evolution of the front surface of PV/PCM system in time is presented in Fig. 5. According to the figure this evolution can be divided into three parts:

1. The temperature increase rapidly and identically for 5 minutes, where the PCM retains its solid form because of the temperature of the systems is lower than that of phase change, in this part the heat transfer is dominated by the conduction in solid phase.

2. In this part the temperature of the PV increases slowly with respect to the first, because the PCM absorbs more heat and start melting; this allows to cool the PV panel by absorbing of excess heat energy us latent heat; in addition the amount of the liquid PCM increases gradually to favor the domination of convection.
3. Finally, the temperature of PV increases faster because the melting process decrease resulting the rise of temperature of molten PCM, where the sensible heat is dominated in the liquid phase.

The evolution of PV cells efficiency in time is calculated by the equation (14) and it is presented in Fig 6. As we see the addition of PCM layer without fins increase the sunlight to electrical conversion efficiency by 1.6% and maintained about 14% for more than 2 hours. This improvement due to the thermal cooling. Moreover, the use of internal fins raises this ratio to 2.1%. Overall, both of PCM and fins by L=35 mm length allowed a good thermal regulation of PV/PCM system, and they increase the PV efficiency by a mean value of 1.7% for more than 3hours.

6. Conclusion

The developed numerical model of heat transfer conjugated with a phase change was successfully performed. This model was used to study the application of PCM on the cooling of curved PV panel with inner fins.

This investigation focuses on the effect of internal fins on thermal cooling rate of the curved PV/PCM system, we tried to defeat the low thermal conductivity of PCM to improve the heat transfer through it; and on other hand, determined the best fins length which increase the thermal loss in PCM layer.

At 750 W/m² of isolation and 20°C; the temperature of curved PV/PCM system without fins was rise up to 50°C for 200 minutes, the time necessary for the melting of PCM.

This temperature affects the PV cell efficiency by a drop of 2%, in addition this configuration does not ensure an uniform temperature distribution; where the upper PV cells was always very hot compared with lowers ones.

At the same thermal conditions, the temperature of curved PV/PCM system with inner fins decrease and it was maintained under 42°C for 200 minutes by a less of 10°C compared with a system without fins. Moreover, the addition of internal fins allowed a good thermal distribution in the PV/PCM system. the natural convection was more dominating, so the cold molten PCM circulation improve the capacity of the thermal cooling effect on the PV cells, which enhance the PV cells efficiency by 2% compared with a single curved PV.

Furthermore, the configurations of L = 25, 30 and 35mm allow a better cooling of the PV panel and good PV cells efficiency.

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