Enhancement of the Thermal Regulation Performance of a Curved PV Panel

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Abstract- The aim of this work was to study the use of a phase change materials (PCM) linked to a curved photovoltaic (PV) panel in order to enhance its thermal regulation performance and to limit the temperature rise on its front surface. A two-dimensional implicit finite volume heat transfer model was used to solve an unsteady Navier–Stokes and energy equations with commercial code FLUENT 6.3.26. However, to improve the thermal performance of this curved PV panel, we varied the radius of curvature until flatting the PV panel. For the validation, an isothermals contours and time evolution of temperature are compared with literature's data. Results show that the temperature of PV cells increase for the high curvatures but the lowest ones have no more influence on this later, while the addition of PCM behind the PV panel can maintain its temperature.

Keywords Phase change material; Latent heat; Thermal regulation; Photovoltaic cell.

1. Introduction

Authors Photovoltaic solar energy comes from the conversion of a part of the sunlight into electricity by semiconductor materials such as silicon and the rest is transformed into heat [1], which causes the elevation of the temperature of the photovoltaic’s cells, therefore it reduces the efficiency of these cells. For example, we have a drop of 0.45% of solar to electrical conversion per 1°C elevation in the PV temperature for crystalline silicon cells. Hence, a cooling process will be necessary for such case in order to maintain the efficiency of the Photovoltaic Panels in an acceptable rate. Several researches were made in this domain, in particular by the use of natural or forced convection for the cooling of the PV as using a duct behind the PV which allows more heat transfer by the air circulation to decrease the PV temperature, whereas a shape of the duct can improve the cooling of PV due to wind which increase the heat transfer, so reduce the temperature of the PV according to Brinkworth [2], this later found that the ratio of 20 for the length to the hydraulic diameter of the ducts give the best cooling of the PV [3], this parameter is not influenced by the inclination of the PV module. Tripanagnostopoulos et al [4] used four hybrid PV/thermal configurations PV/WATER, PV/AIR, PV/FREE and PV/INSULATION to enhance the thermal and the efficiency of PV panel, they found that the PV temperature of the PV/WATER system increase from 55°C to 38°C and to 40°C for the PV/AIR system because the water extract more heat from the PV than the air, but they concluded that the cost of the additional unit of PV/T is more expensive than the energy obtained by cooling the PV. These techniques are expensive and require much of maintenance.

Recently, the PCM is used as passive way for cooling the PV panel; it helps to absorb the excess energy as latent heat until being completely melted. In such case the PCM is used as a layer linked to a photovoltaic (PV) panel in order to decrease its temperature by the transition temperature of PCM, which is in constant range during melting. Many researchers used a hybrid technology to control the thermal regulation in several applications as shown by Setoh et al [5] and Khateeb et al [6]. They have developed a heat transfer model to study the limitation of temperature rise for electronics devices and cooling the building walls by integrating a PCM in the brick constructive and in device packages.

Castell et al [7] found that the use of PCM integrated to a brick constructive reduced the temperature of building about 15 % then another without PCM. Similarly Setoh et al [5] found that incorporation of PCM to a phone mobile stabilize its temperature for a long time for usage. Khateeb et al [6] have investigated experimentally and numerically the cooling of electronic device by the inclusion of PCM in its heat sinks. Where, they found that this technique can improve the cooling of the electronics packaging as compared with another without PCM.

Huang et al [8] have studied both numerically and experimentally the cooling of a photovoltaic unit by using PCM in rectangular enclosure behind the PV. They have succeed to maintain the temperature of the front surface under 40 °C for 80 min, with a PCM that have a melt temperature of 32°C, for PV cells characterized at 25°C and 1000W/m2. Considering the low thermal conductivity of PCM, internal fins were used to distribute the thermal load into the PCM in order to reduce the temperature rise of PV. An experimental work for the same problem was conducted by Huang et al [9], using two PCMs (RT25, GR40) with melting temperature of 26.6°C and 43°C respectively. The RT25 was well used to control the temperature rise of the PV which its melt temperature is close to the ambient temperature comparing with the GR40.

Hasan et al [10] have experimentally investigated the thermal regulation of four different configurations of building integrated photovoltaic's (BIPV), at three insolations intensities by using five PCMs with different melt temperature. The minimum temperature obtained was 10°C for 5h under 1000W/m2, in addition they concluded that the temperature regulation depends on the quantity of PCM and thermal conductivity of both PCM and the enclosure. Moreover, the configuration of Huang et al [8] has been treated numerically by Biwole [11], using a finite element model, where a good performance was obtained.

Cellura et al [12] have studied a PV/PCM system using a finite element method, they considered the PCM as pure and its melt temperature as constant, however these properties practically are not valid because the PCMs are mixtures of paraffins which have a phase change range, they increased the performance of the PV/PCM system about 20%.

To control the temperature rise on the front surface of PV/PCM system, Huang et al [13] have used internal fins through the PCM with several spacing to decrease the excess energy of the PV/PCM system, and decrease also the cavity formation during the solidification. They found that the use of fins improve the temperature distribution and stability of the PV/PCM system. Hence, the use of RT27 PCM with internal fins have contributed to reduce the temperature elevation of the PV and maintained it under 30°C for 150 min in this case. Karunesh et al [14] carried out a study of numerical simulation of PV/PCM system by using commercial code of Comsol Multiphysics. The effect of heat transfer mechanisms (convection or conduction), the velocity of wind and angle of inclination of PV panel were investigated. When only the conduction considered, the operating temperature decreased about 3°C and the solar efficiency improved by 5%, in addition the higher wind velocity and inclination angle allows a good cooling of PV panels. Stropnik et al[15] studied a PV/PCM system numerically with TRNSYS software and experimentally, the electrical generation by the PV module was improved up to 7% for a year. Hagar Elarga et al [16] developed a physical model to simulate the incorporation of a PCM layer to a PV panel in a double skin façade at three different climate, they found that the double skin of PCM can improve the solar to electrical energy conversion efficiency and regardless of the climate, using PCM can also increase the cooling of building by more than 20% monthly.

Nowadays, in addition to solar photovoltaic panel plane type, there is a hybrid system, which combined the concentrating solar panel (CSP) with the PV panel to form a new technology known as PV-mirror. Where the PV panel placed behind the CSP reflector system as curved PV panel [17], or several PV panels arranged rear the mirror to take the curvature form[18]. This parabolic system made with special solar cells that concentrates the large part of the sunlight into a receiver positioned at the reflector's focal point. The working fluid in the receiver is heated up to high temperature to be used by an engine to generate power. On the other hand, the rest part of the sunlight is converted to electric power via the photovoltaic effect of the solar cells used. The parabolic systems provide the highest solar to electric efficiency among concentrated solar power (CSP) and photovoltaic technologies. Maintain the efficiency of such PV panel in an acceptable rate could be a challenge for the scientific community, as this technology is novel. The present investigations try to study the cooling of this type of panels.

From the above researches about the cooling of PV devices, all researchers try to control the temperature rise on a flat PV panel, but never considered the effect of curvature of the panel for the best of our knowledge. A numerical model of heat transfer was developed to treat a small prototype of PV/PCM system 132x50 (mm), by using the finite volume method.

2. Numerical Modelling

A two-dimensional configuration has been used in the present investigation as it is shown in Figure 1 and the details of the dimensions shown in the Table 1. The system is composed of a curved photovoltaic panel attached directly to a phase change material "RT25" in a curved enclosure.

In the present work, we have studied the variation of the curvature of the PV/PCM system, starting with a plane configuration (R=0), then we increase the radius (R) to take the following values: (20-40-60-80-100-300-500-700-900), an increase of 20 mm when ($0 \leq R \leq 100$) and 100 mm when ($100 \leq R \leq 900$) height (h), depth (D) and Aluminum width (X) of the PV/PCM system are kept constant as mentioned in the Table 1 and figure 1.

In the current study we use the same realistic initial and boundary conditions adopted by Huang et al [8]. A natural convection was adopted on the front and rear wall of the PV/PCM system, where the heat flux of sunlight is absorbed by the PV/PCM system in an ambient temperature, assume that:

- The PV module is perfectly connected to the aluminum front surface.
- The initial temperature of the PV/PCM system is the same as the ambient temperature.
- The front and rear surfaces of the system have respectively the values h_1 and h_2 of convection heat coefficients.
- An adiabatic condition is used for the top and the bottom boundaries.

The thermo-physical properties of the phase change materials and Aluminum used in simulations are shown in Table 2. The data of the PCM used "TR25" has been provided by the manufacturer RUBITHERM.

A two-dimensional implicit finite volume heat transfer model was used to solve the unsteady continuity, Navier–Stokes and energy equations with the commercial code FLUENT 6.3.26. On the other hand, the Boussineq approximation was adopted to calculate the change in density of the liquid as a function of temperature. For the phase change region or mushy zone, FLUENT applies the enthalpy-porosity approach.

For all simulations, the grid used is regular and uniform with finite volumes and a variable time step with a minimum value of 0.05s. The numerical predictions were performed on a PC i7 computer with 8 GB of RAM.

Table 1. The geometric configuration of PV/PCM system.

System	Radius of curvature R (mm)	Height h (mm)	Depth D (mm)	Aluminium width X (mm)
PV/PCM	0-20-40-60-80-100-200-500-700-900	132	40	4.5

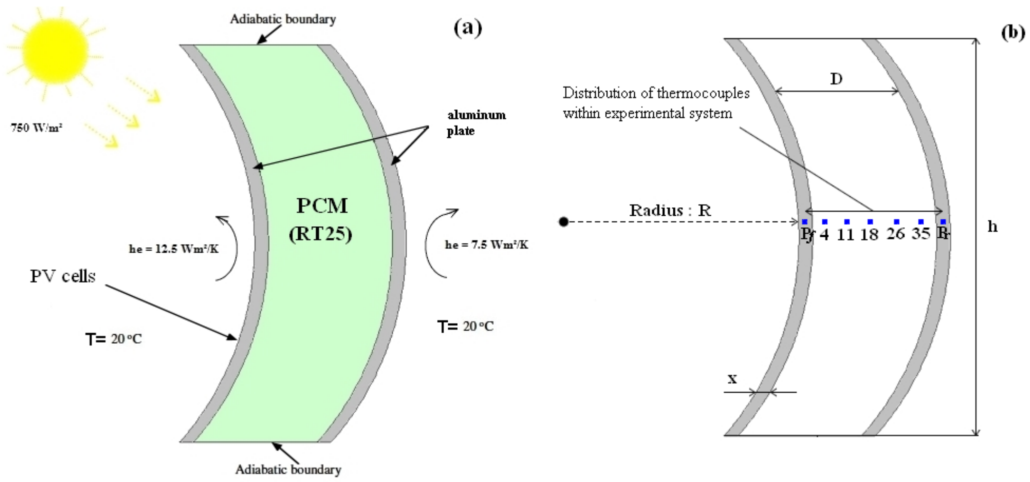

Fig .1. PV/PCM system: **a)** heat transfer and boundary conditions. **b)** Geometry of PV/PCM system.

Table 2. Thermodynamic properties of "RT25"[19], paraffin wax[20] and Aluminum[21].

Propriety	Phase Change Material "RT25"	Paraffin wax	Aluminum
Density Solid, $Kg.m^{-3}$ Liquid, $Kg.m^{-3}$	 785 749	 830 830	 2675 Not used
Specific heat capacity Solid, $J.m^{-3}.K^{-1}$ Liquid, $J.m^{-3}.K^{-1}$	 1,413,000 1,797,600	 1,593,600 2,705,000	 2,415,525 Not used
Thermal conductivity Solid, $W.m^{-1}.K^{-1}$ Liquid, $W.m^{-1}.K^{-1}$	 0.19 0.18	 0.514 0.224	 211 Not used
Melting temperature,	26.6	32	Not used
Latent heat of fusion, $J.kg^{-1}$	232,000	251,000	Not used

3. Results and Discussion

We used a heat transfer coefficients by convection of 12.5 $W.m^{-2}.K^{-1}$ and 7.5 $W.m^{-2}.K^{-1}$ on the front and rear surfaces respectively, an adiabatic condition was adopted on the top and bottom. The insolation intensity was 750 W/m^2 for all simulations.

3.1. Validation:

The numerical model used in the present work has been validated by experimental and numerical results of Huang et al [8], for isothermal contours as displayed in Fig. 2. A good agreement was obtained at both 50th and 100th minute.

As shown in Fig.3, our validation has been reinforced by comparing the time evolution of the local temperature between the present work and that of Huang as displayed in Fig.3 in seven positions, two points (P_f, P_r) are on the front and rear surfaces of the PCM enclosure respectively, while the other points (P_4, P_{11}, P_{18}, P_{26} and P_{35}) are inside the PCM. Comparing with previous studies, our results have shown a good agreement that can allow us to trust in our numerical model to contribute in this domain. We denote that our model was used with success in our recent work, Nehari, Benlekkam et al[22]

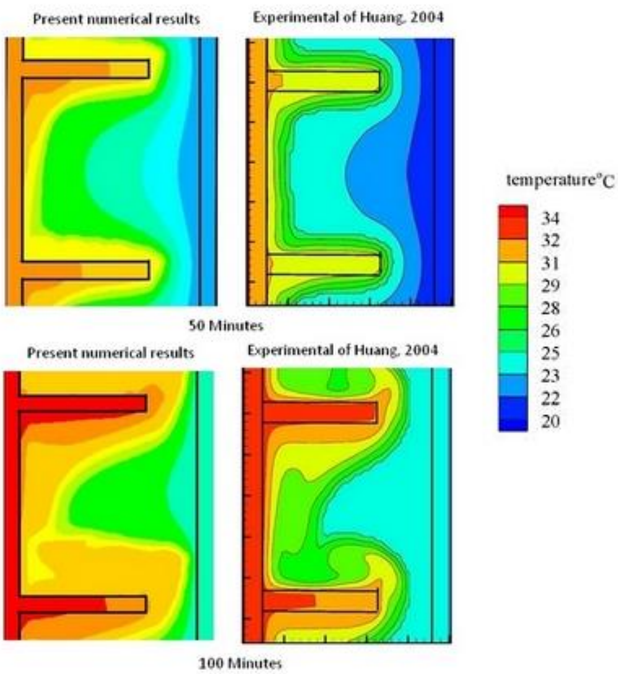

Fig .2. Comparison between the temperature contours predicted numerically and the measured temperature contours after 50 and 100 minutes.

3.2. Effect of curved PV/PCM system:

In order to study the thermal regulation on a curved PV/PCM system, we have varied the radius of the curvature as we explained above. The predicted isothermal contours are presented at the 50th minute in Fig.4, where we observed that; when the radius increase, the temperature of the front surface decreased from 39.43°C for system type S1, to 37.48°C for system type S5 and it was stabilized at 38.89°C for the rest until the flat system. The curved configuration collects more insolation than the flat one and improves the heat transfer by conduction in the PCM layer close to the front panel. Besides, when the molten PCM on the top of the system extends the convection dominate. Furthermore, the system type S1 with radius of 20 mm absorb more heat, because of the curvature degree in the panel such as thermal collector, which can take up more heat from the ambiance. Therefore, the curved container improves the liquid PCM circulation to increase the heat transfer by convection, so more phase change transition, which explains the most temperature elevation recorded. Then the heat absorption rate decreased due to the low curvature, thus the temperature decreases on front surface until the stabilization at 38.89°C for the systems (S6 to S10). We notice that the low curvature (System S6 to S9) has no more influence on front surface temperature.

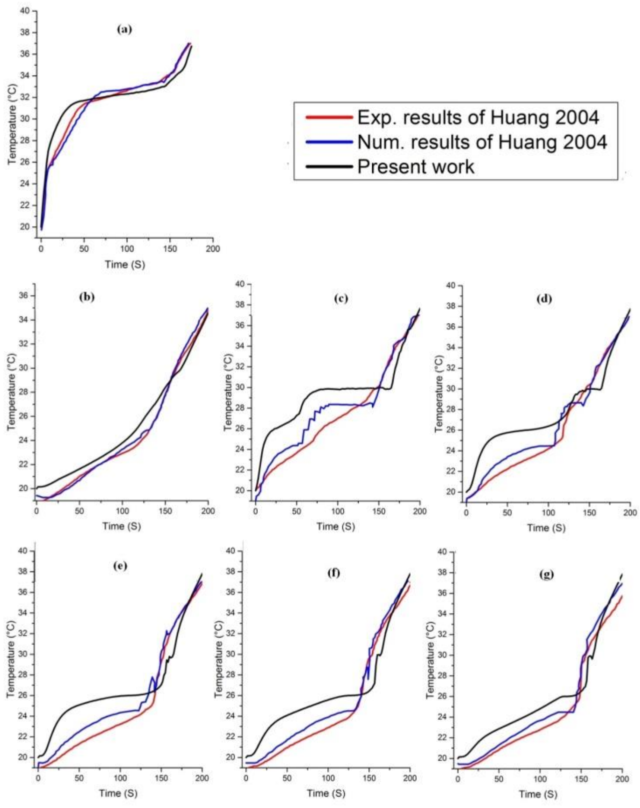

Fig .3. Comparison between present results and the experimental measurements of [8] along the time of the local temperature at different positions: (a) point f*;* (b) point r; (c) point 4; (d) point 11; (e) point 18; (f) point 26 ;and (g) point 35 .

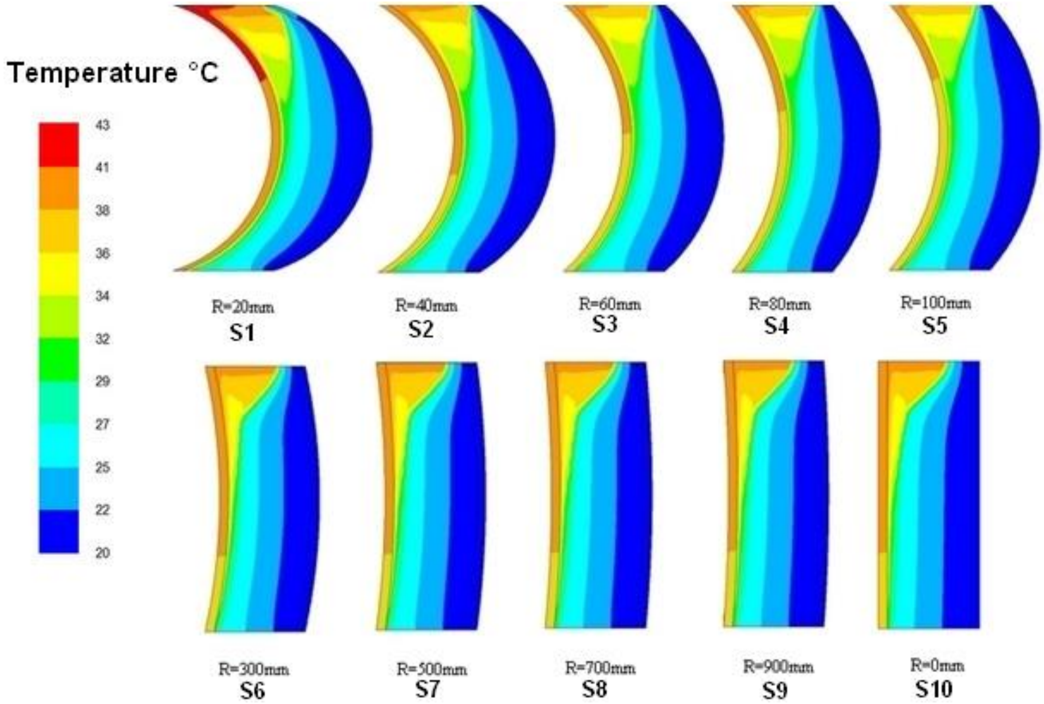

Fig .4. Isothermal contours of the cases studied of the system PV/PCM at 50th minutes.

The Fig.5 shows the thermal contours at the 100th minute for all cases under investigation, we can see that it is the same behavior of PCM and temperature distribution; moreover, the front surface temperature decreases progressively from 40.87°C for system type S1 to 37.65°C for system type S10, by a lowering of 3°C between the high temperature in system type S1 and the other type S10. Otherwise, this range was 1.5°C as observed previously at 50th minute; this change is due to the effect of curvature, which enhances the convection in the molten PCM so it extends faster, and also the circulation into the container. Therefore, more phase change transition results a better heat transfer in the high curvature system then in the lowest.

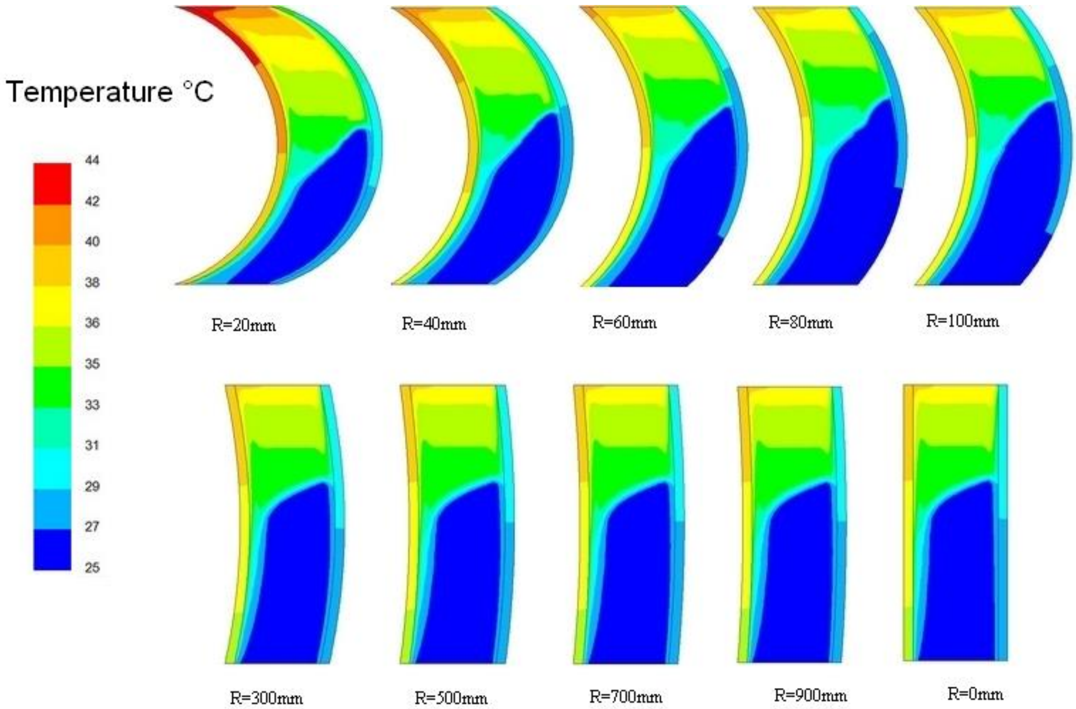

Fig .5. Isothermal contours of the cases studied of the system PV/PCM at 100th minutes.

Fig.6 presents the isothermal contours at 150th minutes, it is clear that the PCM keeps the same behavior, but we can see that the quantity of molten PCM increases with high radius because of the high insolation transfer through the front surface into the PCM which enhances the convection, therefore elevates the phase change transition. At last we found that the low curvature (S6 to S10) has no influence on the PV/PCM system thermal behavior.

Fig.7 shows the temperature evolution of the front surface along of 200 minute, the time for which the PCM is completely melted. We can see that in all cases the temperature is under 40°C for 50 minute, to keeps the same behavior at 100 minute. Afterwards the temperature increases faster for the cases (S1 to S5) because of high radius, which increase the heat transfer and the circulation of molten PCM into the container, so more phase transition. Therefore, the convection dominates in liquid PCM. It is clear that the temperature of front surface increases with the high curvature (system S1 to S5) rapidly; due to the high heat transfer by convection in the molten PCM and its higher specific heat capacity. However, for lowest system (S6 to S10), the temperature increases progressively due to the domination of conduction for a long time as compared with other configurations. So the low curvature (system S6 to S10) can maintain the temperature under 38.7°C for 1 hour. Indeed, for the same period the temperature exceeds the 60°C [8] so more than 20°C of thermal cooling.

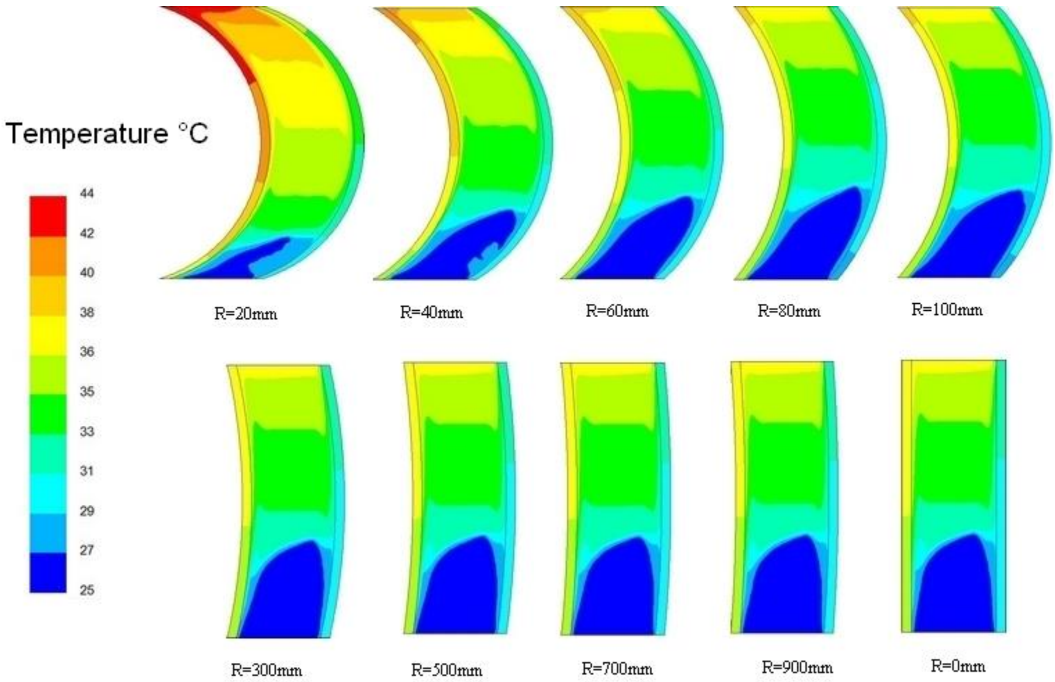

Fig .6. Isothermal contours of the cases studied of the system PV/PCM at 150th minutes.

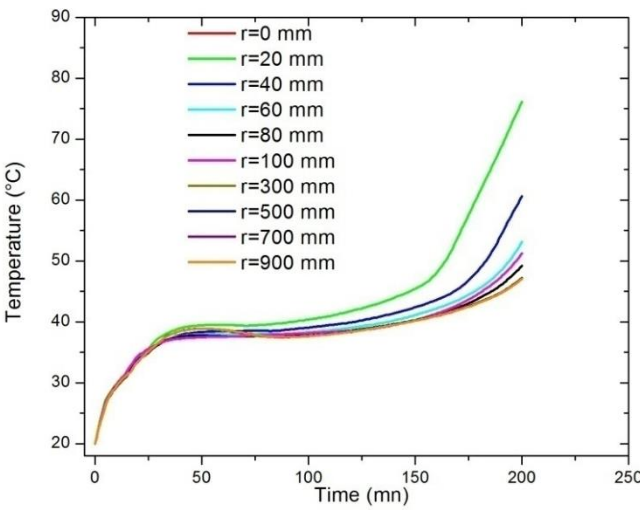

Fig .7. The effect of curvatures on the time history of the Temperature of the PV panel.

4. Conclusion:

Overall, elevation of PV cell temperature reduce the solar to electrical energy conversion efficiency, so many researches try to solve this problem by several techniques. The use of PV panel fitted with PCM is one of the among promising solutions in the future, which can maintain its temperature during the phase change and can improve its efficiency.

A two dimensional model of heat transfer was developed successfully by using the commercial code FLUENT 6.3.26 to study the effect of PCM layer on the thermal regulation of a curved PV panel under a realistic boundary conditions. The simulations are accomplished by varying the radius of the curvature of PV/PCM system as mentioned above. At the ambient temperature of 20°C and under the insolation 750 W/m^2, the temperature of the front surface of all PV/PCM systems configurations was maintained less than 40°C during 100 minutes, so it is a good agreement with experiment data. Otherwise obtained results show that the temperature of the

PV cells increases rapidly for the high curvature with a radius lower than 100 mm, because of the phase change rate, which is very large. In addition the high PV panel curvature improves the thermal absorption and the heat transfer was dominated by convection due to the high quantity of liquid PCM. Our results conduct that the low curvatures with a radius upper than 100 mm allow a good thermal regulation and maintain the temperature under 47°C for more than 3 hours. From all cases under investigation, we notice that while the PCM start to melt, the heat transfer was dominated by conduction. At the same time, the liquid PCM close to the front surface acts as insulation material because of its low thermal conductivity ($\lambda_{PCM} \approx 0, 2\ Wm^{-1}K^{-1}$).We notice that the temperature of the PV panel on the top was higher than the bottom due to the irregular distribution of temperature, therefore for a better cooling of PV panel, we must increase the heat transfer by conduction through the PCM to allow the front surface in aluminum to lose more heat, so decrease its temperature rise.

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