CHAPTER 3

Behaviour of Novel Design of Non-rectangular PCM Enclosure for PV/PCM Systems under Variable Boundary and Ambient Conditions

This chapter examines the feasibility of non-rectangular type encapsulation for PV/PCM system under variable boundary and ambient conditions (approximately similar to real conditions). The conventional design exhibits slow melting rates and degraded thermo-electric performance due to shorter regime of convective melting (ends before maximum insolation). The unsymmetrical loading of PCM in non-rectangular enclosure encourages characterization of melting according to natural convection. The proposed non-rectangular PCM enclosure for PV/PCM systems exhibits elongated quasi-steady convection regime far beyond the maximum insolation time causing increased melting rates. Compared to conventional design, the proposed design exhibits 20% more melting and PV panel works at 92% of its rated performance. The heat loss from the proposed system is approximately half compared to conventional system that explains higher insolation utilization ability of the system. Energy efficiency, exergy efficiency, economic, exergoeconomic, and enviroeconomic analysis have been done for both conventional and proposed systems. The proposed system exhibits higher exergy efficiency (13.81%) and energy efficiency (73.95%) whereas conventional system exhibits somewhat lower exergy efficiency (13.66%) and a lower energy efficiency (69.77%). The economic analysis suggests that the proposed system exhibits approximately 3% lesser cost of production of electricity compared to conventional PV/PCM system. More earned carbon credits also claims that the proposed system also helps in reducing the CO2 emissions to the environment. Hence the proposed design of PV/PCM system is beneficial and ready for domestic and industrial applications.

3.1 Introduction

The global energy demand has been continuously increasing with growth in population and progress in technology during last four decades. With this increase in energy demand, its primary source like fossil fuels are being used in excess and are on the verge of extinction. Use of fossil fuels also leads to pollution and global warming. These problems can be minimized with increase in use of renewable energy like solar energy such as photovoltaics (PV) technology in future. PV is used to convert solar energy into electrical energy. However all of incoming radiation is not converted into electricity, most of it is wasted as heat and increase the temperature of PV cell. Electrical performance of PV cell is affected by its operating temperature and PV cells shows a drop of 0.65% per degree rise of temperature according to Radzimaka and Klugmann [40]. Hence, it is imperative to extract this unwanted heat energy using solar thermal collector at the backplane of PV panel. Such photovoltaic thermal collector system (PV/T) has gained special attention by the research community in recent times [5, 10, 45]. It can improve its electrical performance and also utilize the wastes heat, so called photo-voltaic thermal collector (PV/T).

Numerous researchers have suggested that adding PCM to the back of PV panel will improve its electrical performance [6, 34, 48, 49, 66]. Phase change materials (PCM) has great potential for storing heat and using heat when required in off-light hours or during night. They have high latent heat with almost constant phase change temperature. This relatively constant phase change temperature gives an almost constant operating temperature when attached to PV system. PCM can also be used with another fluid such as air as well as water. A theoretical analysis was conducted by Esen and [66] to estimate the stored energy dependence on time in a tank containing PCM, and found that the performance of the tank is affected by the parameters like PCM properties, cylinder radius i.e. design of the storage system, the mass flow rate and inlet temperature of heat transfer fluid. Considering all these parameters PCM can be attached on the back plane of a PV/T system. Hasan et al. [6] did evaluation of different phase change materials for thermal enhancement of building integrated photovoltaics. These PCMs are RT20, C-L, C-P, CaCl2 with four different type of container materials. The highest reduction in temperature was 18°C for 30 minutes in case of C-P and CaCl2 in container A. Yang et al. [48] did an experimental investigation on performance comparison of PV/T-PCM system and PV/T system. They concluded that the largest temperature difference for PV and PV/T-PCM system during test was 15.8 °C and their electrical efficiencies were 6.98% and 8.16% respectively. Su et al. [34] performed a comparative analysis on dynamic performances of PV/T collectors integrated with PCM. Main finding was that upper PCM case is found to be more effective as temperature reduced by 7.6 °C so it has better thermal and electrical performance. Further performance of PV/T-PCM systems can be improved by doing the micro-encapsulation of PCM layer integrated with PV/T systems. Ho et al. [49] investigated a PV/T-PCM system with a microencapsulated PCM layer on its back plane and concluded that a 5 cm thick layer with a melting temperature of 30°C show the best performance.

In above discussed literature, a few researchers have considered the effect natural convection on profile of solid-liquid interface and heat transfer rate of melting PCM. Ezan et al. [36] investigated the importance of natural convection on numerical modelling of BIPVP/PCM system. They had found that with increase in PCM thickness the convection model diverge from conduction model and a difference of 50% regarding maximum PV panel temperature in convection model as compare to conduction model for a thickness of 10 cm. Further heat transfer enhancement has been achieved by researchers by using fins inside the PCM enclosure. Tao et al. [67] also concluded that natural convection significantly influence the melting rate and latent heat storage capacity of PCM. Further considering the impact of natural convection on melting it is necessary to understand the dynamics of melting under the effect of buoyancy. Janny et al. [38] describes the melting process in four different regime of melting in a rectangular enclosure. (i) Conduction regime; in this regime the melting takes place only due to conduction, (ii) Mixed regime; in this regime the heat transfer to PCM is by both conduction and convection. As time prevails the conduction starts to diminish and convection starts to prevail. (iii) Quasi-steady convection regime; in this regime heat transfer is totally dominated by convection and nearly steady with time, (iv) Solid shrinking regime; in this melting slows down due to suppression of convection current. Further Kamkari et al. [37] conducted a study on the effect of inclination angle on convection driven melting of phase change melting of PCM in a rectangular enclosure. They found that melting become slower in rectangular enclosure due to suppression of convection current. They also concluded that heat transfer by natural convection increases with inclination angle when PCM enclosure is heated from the bottom side and maximum melting is observed in horizontal enclosure. Hence to improve the electrical performance of PV module, the thermal performance of PCM enclosure must be enhanced. Many researchers suggested use of fins [50, 51] inside PCM enclosure and some proposed the use of nano-PCM [58**?**] in place of PCM. Use of fin improves the heat transfer rate by increasing the surface area as well as by disturbing the flow. While nano-PCM enhance the melting rate due to augmented thermal conductivity. Nano-PCM has the stability issues at higher temperature and generally segmented at bottom of enclosure due to gravity whereas use of fins or extrusion doesn't have such difficulties still we have to use excessive metal to make fins.

It can be observed from the above discussion that few researchers have focused on the optimization of design of enclosure to enhance the convective heat transfer in PCM. This enhancement could be achieved by decreasing the reign of solid shrinking regime during melting and augmenting the quasi-steady convection regime. Akshayveer et al. [39] proposed new non-rectangular type designs for PV/PCM sysytems to promote convection dominated melting and higher thermo-electric performance (Previous chapter). One of the linear vertical wall is changed to generic shape of non-linear profile having inclined linear, parabolic and cubic profiles as shown in Figure 3.1. Further it is proposed that parabolic profile of right wall is most suitable to get an enhanced thermo-electric performance and compact geometry design. The analysis was performed under constant boundary and ambient conditions. However, the feasibility of proposed system must be examined under variable boundary conditions as solar insolation and ambient conditions varies with progression of the day. Further the feasibilty of the system must be analyzed on the basis of the exergy production, economics and enviroeconomics criterion to know its interchangabilty with currently available convention PV and PV/PCM system. The literature for exergy, economic, and enviroeconomic analysis for modified PV/PCM system with non-rectangular type PCM enclosure is very rare, though numerous researchers have performed exergy analysis, economic analysis and enviroeconomics analysis for conventional PV and PV/PCM systems [68–70]. Therefore, in this chapter we have reported the response of various performance parameters such as PV cell temperature, electrical efficiency and heat transfer characteristics such as heat transfer coefficient, melting rate under variable boundary and ambient conditions. It has been found that the proposed PV/PCM system exhibits enhanced thermo-electric performance and most effective during maximum sunshine hours. Further it is also observed that the proposed system is more economic in electricity and exergy production and more environment friendly compared to conventional systems. Data and design investigation presented in this chapter would assist the research community in designing a better enclosure shapes that would further enhance the thermal and electrical performance of a PV/PCM module.

3.2 Methodology

3.2.1 Problem description & definition

Two-dimensional computational model of PV/PCM system is formulated (see Figure 3.1) to analyze its thermo-electric performance with conventional rectangular and modified nonrectangular PCM enclosures. Conventional PV/PCM system consists of a glass region of thickness (t_g), PV panel region of thickness (t_{pv}), and rectangular PCM enclosure region of thickness (L) with the height of the numerical domain (H_{pv}). In modified configuration of PV/PCM system, the rectangular enclosure is replaced by non-rectangular enclosure with general right wall profile of $y = (ax - b)^{(1/n)}$, (n=1 for linear, n=2 for parabolic and n=3 for cubic right wall profile). Here the constant "a" and "b" are adjusted in such a way that the volume of PCM for all investigated configuration is same as in the rectangular enclosure. Based on the findings of previous of previous chapter, parabolic (n=2) right wall profile is chosen for the proposed system to analyze its performance under variable conditions. RT27 of Rubitherm technologies GmbH (properties listed in Table 2.2) is used as PCM. RT27 exhibits very small mushy zone (very small difference between melting and crystallization temperature. Hence, it is considered to have homogenous and temperature independent thermos-physical properties for both liquid and solid phases ex-

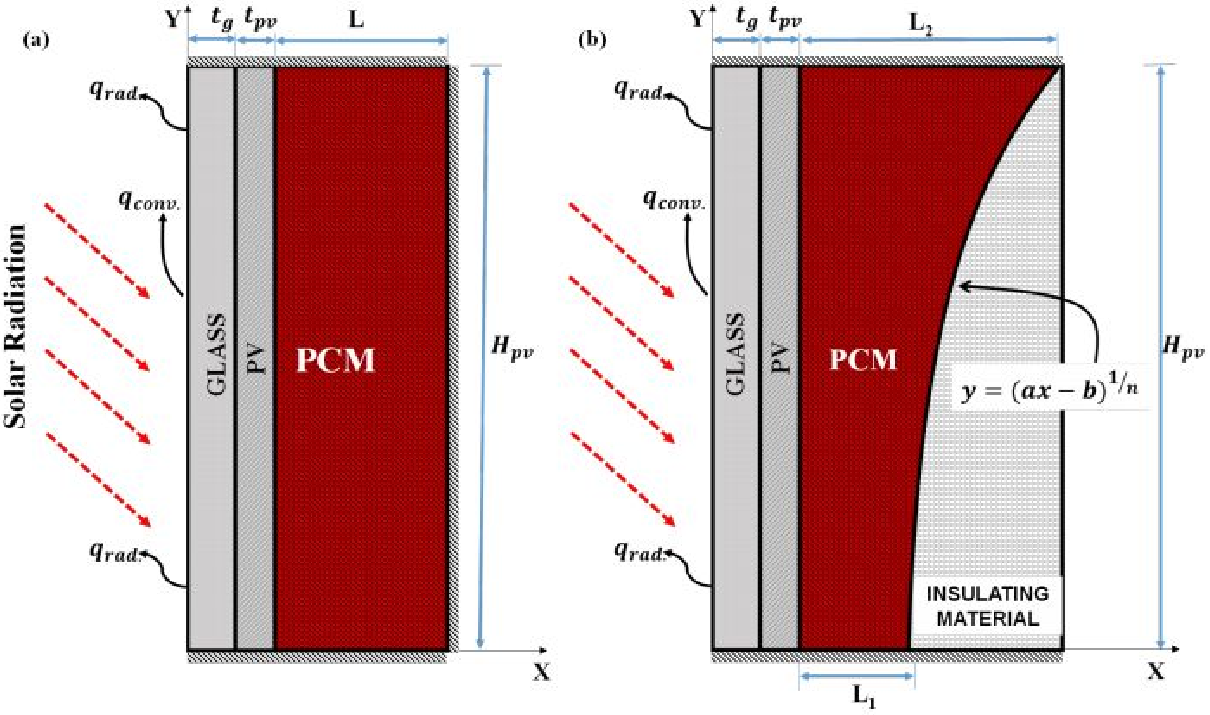

Figure 3.1: Schematic diagram showing cross-section of PV/PCM system with (a) type-A conventional rectangular PCM enclosure, (b) type-B, C, & D non-rectangular PCM enclosure with a general profile, $y = (ax - b)^{(1/n)}$, n=1 for linear, n=2 for parabolic and n=3 for cubic right wall profile.

cept density which is constant for solid phase and variable with temperature (Boussinesq approximation) for liquid phase.

3.2.2 Boundary conditions

The feasibility of the proposed PV/PCM system with non-rectangular enclosure (parabolic right wall profile) is subjected to examine under variable boundary and ambient conditions (similar to real conditions). The incident solar radiation (I_{solar}) and ambient temperature (T_a) are assumed assumed to vary from 6:00 AM to 6:00 PM as shown by Eqs. 3.1 and 3.2 and are also shown in Figure 3.2.

$$I_{solar} = I_{max} sin\left(\frac{\pi (t-6)}{12}\right), (6 \leq t \leq 18) \tag{3.1}$$

where, I_{max} is the maximum solar radiation which is assumed to be 1000 W/m^2 at 12:00 PM of the day and t is time of the day in hours [71].

$$T_a = T_{avg} + T_{amp} cos\left(\frac{\pi (t-14)}{12}\right), (6 \leq t \leq 18) \tag{3.2}$$

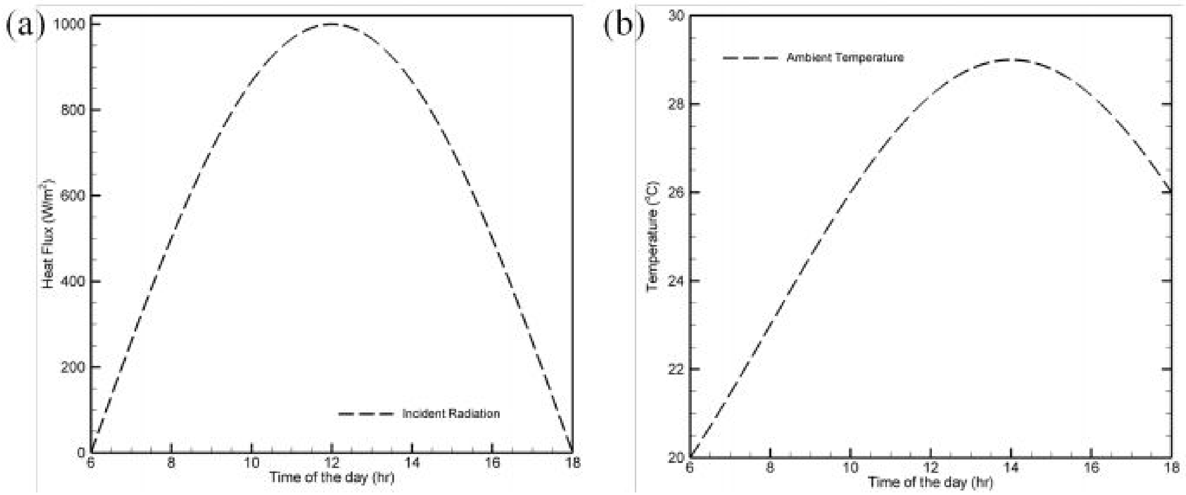

Figure 3.2: Diurnal variation of (a) incident radiation, (b) ambient temperature with time.

The average ambient temperature T_{avg} of 296.15 K and amplitudeT_{amp} of 6K is considered for present study [71]. The initial ambient temperature ($T_{initial}$ = 20°C), and wind velocity ($v_w = 2.4 m/s$) were considered for the numerical analysis. The value of wind velocity is chosen according to available average ambient conditions. Incident solar radiation (I_{solar}) on the left wall is divided into two parts, (i) conductive heat transfer into the wall and (ii) the heat flux loss from outer glass surface to surroundings, which comprises convective heat flux losses ($q''_{conv.}$) and radiative heat flux losses($q''_{rad.}$). The heat balance at the glass layer is better described in Eq. 2.1 and the related terms are shown by Eqs. 2.2-2.6 in section 2.2.1 of the previous chapter.

3.2.3 Solution method

The conservation equations with their related terms are explained by Eqs.2.7-2.14. Conservation equations are discretized and solved by adopting same assumptions and solution methodology as described in section 2.2.2 (solution method) of previous chapter. Grid independent study (see Figure 2.2) is also considered same as described in section 2.2.3 of the previous chapter. The numerical model used for the current study is validated with experimental findings of Kamkari et al.,[37] on melting of PCM inside a rectangular enclosure. The results of experimental validation of numerical model is shown by Figures 2.3 and 2.4 in section 2.2.4 of the previous chapter.The numerical model's anticipated findings are quite accurate and closely resemble the experimental arrangement. As a result, the numerical model may be utilised to further design PV/PCM systems.

3.3 Results and discussions

3.3.1 Thermal analogy of melting front propagation

Heat transfer mechanism of melting process can better unterstood by analyzing the thermal analogy of melting front propagation. The temperature distribution inside the PCM enclosure is governed by propagation of solid-liquid interface with evolution of buoyant forces in liquid PCM region. Figure 3.3 depicts the transient variation of solid-liquid interface patterns with analogous temperature distribution patterns for conventional PV/PCM and modified PV/PCM system (non-rectangular PCM enclosure) under the variable insolation and ambient conditions as per Eqs. 3.1 and 3.2. Some of the incident radiation is converted to electricity by PV panel and leftover radiation is transmitted to PCM enclosure where its is absorbed as heat. PCM stores this radiation as latent heat by changing phase from solid to liquid, and sensible heat is also absorbed in solid and liquid phase of PCM. The absorption of radiation as latent heat allows PV panel to operate at a constant lower temperature whereas sensible heating of liquid PCM increases the PV panel temperature simeltaneously which leads to various convective and radiative losses from the system to surroundings. Therefore, melting rate of PCM must be enhanced to store more latent heat compared to sensible heat which can be acheived by promoting convective heat transfer inside the PCM enclosure. Hence, characterization of melting process plays an important role in maintaining the PV panel to operate at lower temperature.

At very initial (6:00 hr), the PV/PCM system exhibits very low thermo-electric performance due to negligible insolation. However, the performance of PV panel incraeses with progression of time as solar insoaltion increases. In both type of configuration, melting starts approximately 1 hour later as solar radiation hits the glass layer and initially governed by conduction only. In conduction regime, melting proces is dominated by viscous forces only which resists the flow of liquid PCM and melting front is parallel to the adjacent PV-PCM interface. With the progression of time, melting layer thickness increases and buoyant forces starts to overcome the viscous forces. The liquid PCM starts to rise along the PV wall and a clockwise convection current develops with in the liquid region. The formation of convection current takes place approximately 1.5 hours (at 7:30 hr) after the incidence of solar radiation in all type of configuration and this give rise to mixed (conduction and convection) regime. The temperarture distribution is also similar and uniform along the height of PV panel till this time period for both type of configurations. The beginning of mixed regime erodes the solid-liquid interface in top region of enclosure but it remains parallel to PV-PCM interface in bottom region of enclosure. The temperature distribution also starts to differ in top and bottom region of enclosure. The mixed regime ends at 8:15 hr for both configurations of PCM enclosures and convective heat transfer is dominated in whole liquid region from now which gave rise to quasi-steady convection regime. Figure 3.3(a) depicts the fully developed quasi-steady convection regime at 9:00 hr via solid-liquid interface patterns for both configurations. It is visible that melting interface is no longer parallel to adajacent wall as solid-liquid interface is eroded in top region and inclined in bottom region. The temperature distribution is no longer uniform along the height of enclosure as convection current avails more heat for top region as shown in Figure 3.3(b). However, PV/PCM system exhibits very less transient variannce in temperature during quasi-convection regime as enhanced melting of PCM avails more storage of latent heat compared to sensible heat.

In conventional rectangular configuration, the quasi-steady convection regime ends at 10:54 hr which is 1:06 hr earlier than the maximum insolation time (12:00 hr). As incident radiation is still increasing with time, the liquid PCM starts to absorb sensible heat in top region of enclosure due to enhancement of buoyant forces. The temperature will rise substantially in top region of enclosure, however; bottom region of enclosure still shows lower temperature. The solid PCM starts to shrink along the right wall of the enclosure and melting becomes slower due to thermal stratification in this solid-shrinking regime of melting (see Figure 3.3(a) at 12:00 hr). The temperature of PV panel rises to 51.91°C at maximum insolation time as earlier beginning of solid-shrinking regime causes temperature rise of liquid PCM in top region of enclosure (see Figure 3.3(b) at 12:00hr). The begining of solid-shrinking regime is delayed upto 14:12 hrs in modified non-rectangular configuration by availing more PCM in top region for convection dominated melting. Therefore, more latent heat is stored compared to sensible heat during peak hours of operation and a more uniform temperature distribution is observed inside PCM enclosure during this time. The transient variation of temperature is negligible during this period that allows PV/PCM systems to work at lower temperature during peak radiation hours. Figure 3.3 at 12:00 hr depicts that melting front has not reached to the right wall of the enclosure and temperature of PV panel is 45.50°C due to less thermal stratification in liquid PCM for non-rectangular type of configuration.

After 12:00 hrs, the incident radiation to the system starts to decrease, however; input heat flux to the PCM enclosure is more than radiative and convective losses. Therefore, PCM enclosure is still storing the heat by melting process and sensible heating process. The characterization of melting in non-rectangular PCM enclosure allows uniform temperature distribution for longer time compared to conventional rectangular enclosure. The maximum temperature of PV panel in conventional PV/PCM system is 58.36°C at 14:12 hr whereas at the same time modified system exhibits only 43.63°C. However, modified PV/PCM system exhibits maximum temperature of 45.56°C at 12:42 hr while for conventional PV/PCM system it is 55.23°C which is nearly 10°C higher. At 15:00 hr the maximum temperature in conventional system approaches to 57.51°C while modified system exhibits only 43.02°C due more convection dominated melting in modified system. Higher temperature of system leads to higher convective and radiative losses and degraded performance. Further, with propagation of time, incident radiation and ambient temperature both decreases and losses from the system overcomes the heat input of the system. At this time, the system starts to release the stored heat to surroundings. The conventional

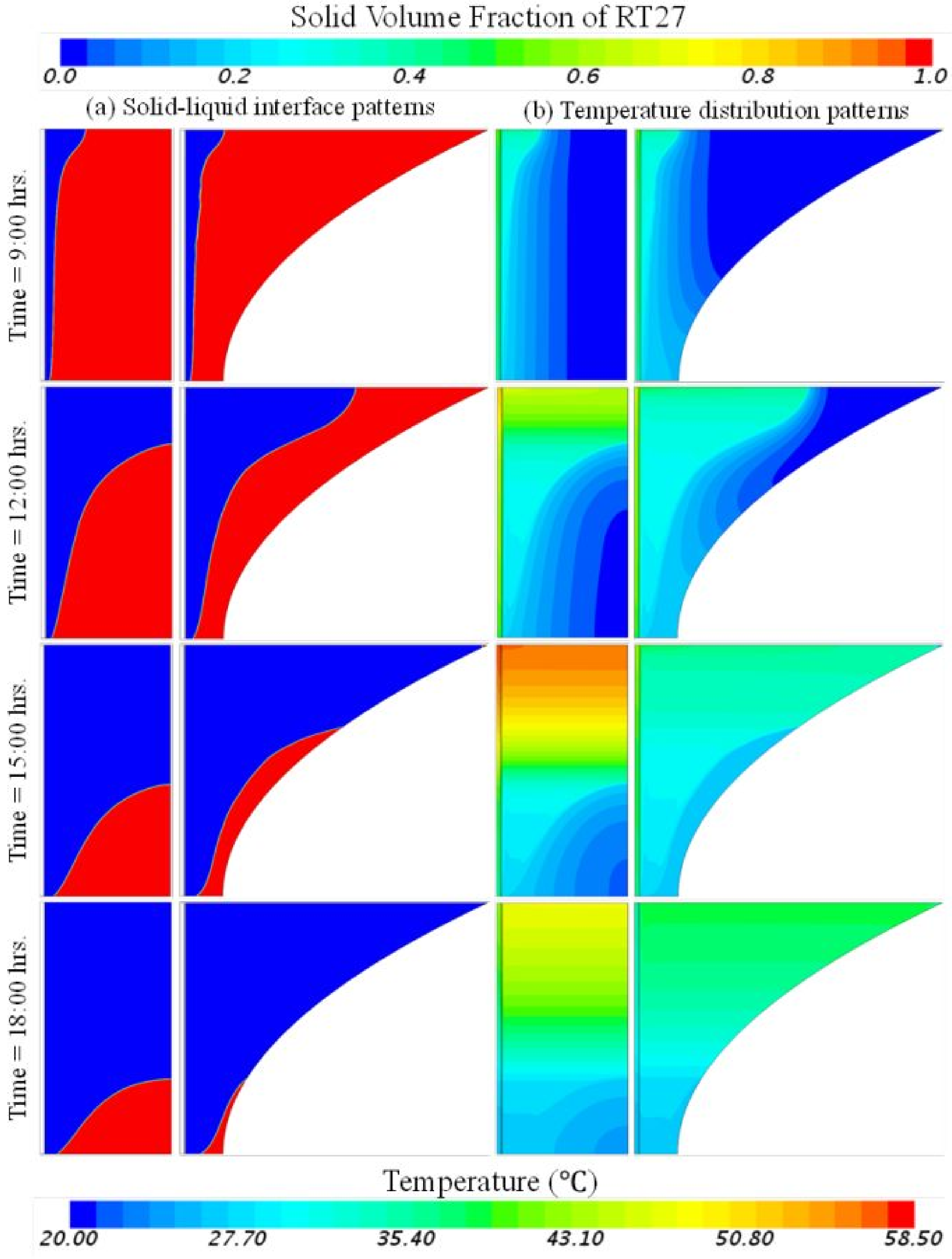

Figure 3.3: Transient history of (a) solid-liquid interface patterns, and (b) temperature distribution patterns.

system starts discharging stored heat at 16:00 hr which is 2 hours earlier than the assumed sun set. However, modified system manges to keep this stored heat intact upto 17:00 hr which is 1 hour earlier than the sun set. This delay is acheived by enhancing the quasi-convection regime of melting and lower system temperature helps in minimizing the losses from the system.

At 18:00 hr, the modified PV/PCM system with non-rectangular PCM enclosure exhibits more melting and more uniform temperature distribution compared to conventional system. The maximum temperature of the system is also lower compared to conventional PV/PCM system. The modified PV/PCM system exhibits a maximum temperature of 37.13°C while the conventional PV/PCM system exhibits a temperature of 45.72°C at the end of the day. It is observed that modified PV/PCM system not only exhibits more melting but it also exhibit more uniform and lower magnitude temperature distribution throughout the day. Therefore, modified PV/PCM system will not only exhibit better electric conversion performance bur also higher heat storage performance simeltaneously.

3.3.2 Heat transfer characteristics

3.3.2.1 Liquid fraction

The thermo-electric performance of PV/PCM system is considerably influenced by the heat storage abilty of the PCM enclosure. Heat stored by PCM at any instant of time can be written as follows:

$$Q_{stored} = mc_p\Delta T + m f_l L_{sf} \tag{3.3}$$

The heat stored consists of sensible heat due to thermal gradient and latent heat due to melting as shown first term and second term of right hand side of Eqn. 3.3. The clatent heat is considerably large compared to sensible heat in extracting the heat from PV panel and is directly proportional to liquid fraction (f_l). Hence, the augmentation in the melting rate (rate of change of liquid fraction with time) will enhance the heat stored with in the enclosure. Therefore, study of variation of liquid fraction with time is quite important.

Figure 3.4 shows the comparison of transient variation of liquid fraction for both type of configurations. The transient variation of liquid fraction is linear in both configurations for most of the time. In both configurations, melting starts 1 hour later (at 7:00 hr) the initial incident of solar radiation as solid PCM absorbs sensible heat to reach phase transition temperature. Initially, the melting is dominated by conduction only, hence; linear trend of liquid fraction with lower slope is seen till the begining of quasi-steady convection regime (8:15 hr). The slope of liquid fraction-time curve transists smoothly from a lower value to a higher value during mixed regime of melting. However, the transient variation of liquid fraction is also linear in quasi-convection regime with a higher slope that indicates higher melting rates during this regime.

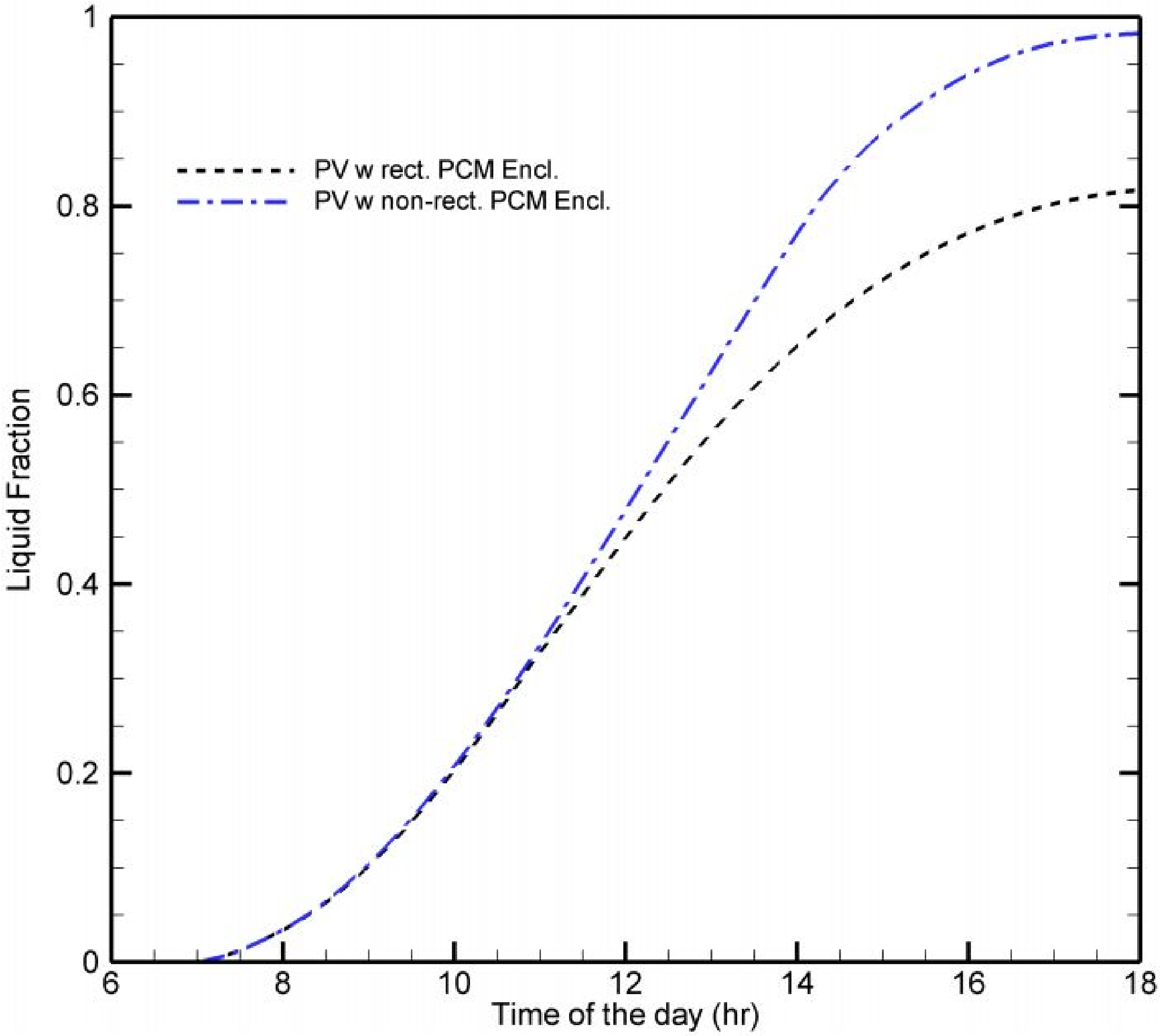

Figure 3.4: Transient variation of liquid fraction for both type of configurations. Full melting history has been shown in inset.

In conventional rectangular configuration, liquid fraction starts to the deviate from linear trend with the end of quasi- steady convection regime at 10:54 hr. With the begining of solid-shrinking regime, solid PCM starts to shrink along with the right wall and thermal stratification occurs in liquid PCM which causes the suppression of convection current in the enclosure and slower melting rates are observed. However, availability of lesser PCM in the convection dominated region of the enclosure is the main cause of smaller quasi-convection regime. Hence melting rate can be enhanced by making more PCM available in top region of the PCM enclosure.

In modified non-rectangular type configuration, the design of enclosure is such that most of the PCM is available for convection dominated melting. Therefore, an elongated quasiconvection regime (upto 14:12 hr) is observed with enhanced melting of PCM. The linear trend of liquid fraction-time curve is maintaned for longer duration and enhanced melting is seen. The begining of solid-shrinking regime is delayed by 3:18 hrs compared to conventional configuration. The liquid fraction-time curve exhibits curvulinear trend in solid-shrinking regime and nearly becomes flatter in later stages of melting. However, modified system exhibit shorter duration of solid-shrinking regime and hence better heat storage performance.

The conventional PV/PCM system exhibits 81.65% melting in full 12 hour operation, whereas modified PV/PCM system exhibit 98.25% melting in the same duration. The modified system exhibit 20.33% enhancement in melting compared to conventional configuration which is an significant enhancement. More melting leads to more uniform temperature distribution which makes it essential and efficient configuration of PV/PCM system.

3.3.2.2 Nusselt number

To understand the melting behaviour of PCM inside different type of enclosure, the investigation of heat transfer characteristics like Nusselt number is very important. Figure 3.5 compares the transient history of Nusselt number for both discussed PCM enclosures. Nusselt number (Nu) along characteristics length (H_{pv}) at any instant of time (t) is defined in Eq. 2.15.:

The height of PV-PCM interface (H_{pv}) is assumed as characteristics length for both configurations because all heat interactions to PCM enclosure is through this interface. The melting of PCM starts 1 hr later to the initial incident of solar radiation as solid PCM absorbs sensible heat to reach the phase transition temperature in this duration. At 7:00 hr, melting is initiated in PCM enclosure and a very thin layer parallel to PV-PCM interface arises due to conductive heat transfer. Nusselt number is high in this duration due to very low thermal resistance and ver small thermal boundary layer in liquid PCM region. In conduction regime, viscous forces dominates in liquid region which decraeses with increase in fluid layer and buoyant forces starts to prevail. The buoyant forces gave rise of convection current in top region of enclosure (at 7:30 hr) and then in full liquid region of PCM enclosure (at 8:15 hr). In this duration melting is dominated by convective heat trasfer in top region and conductive heat transfer in bottom region of enclosure, hence this regime is called mixed regime of melting. Nusselt number exhibits a local minimum ($Nu = 57.88$) at the end of this regime and starts to increase after this regime due to domination of convective heat transfer which gave rise to quasi-steady convection regime. The nusselt number increases first and then exhibit negligible varience with time till the end of this regime. The conventional configuration of enclosure exhibit smaller quasi-convection regime (upto 10:54 hr) and exhibit a Nusselt number of 87.97 at the end of this regime. In solid-shrinking regime, nusselt number decreases with time linearly and keep on decreasing till the end of the day. However, the non-rectangular type configuration exhibit a longer quasi-convection regime up to 14:12 hr (3:18 hr longer than conventional one). The modified PV/PCM system exhibit a Nusselt number of 92.09 at the end of this regime which is 52.02% higher than conventional configuration ($Nu = 60.57$) for this particular time. In addition to that, quasi-convection regime

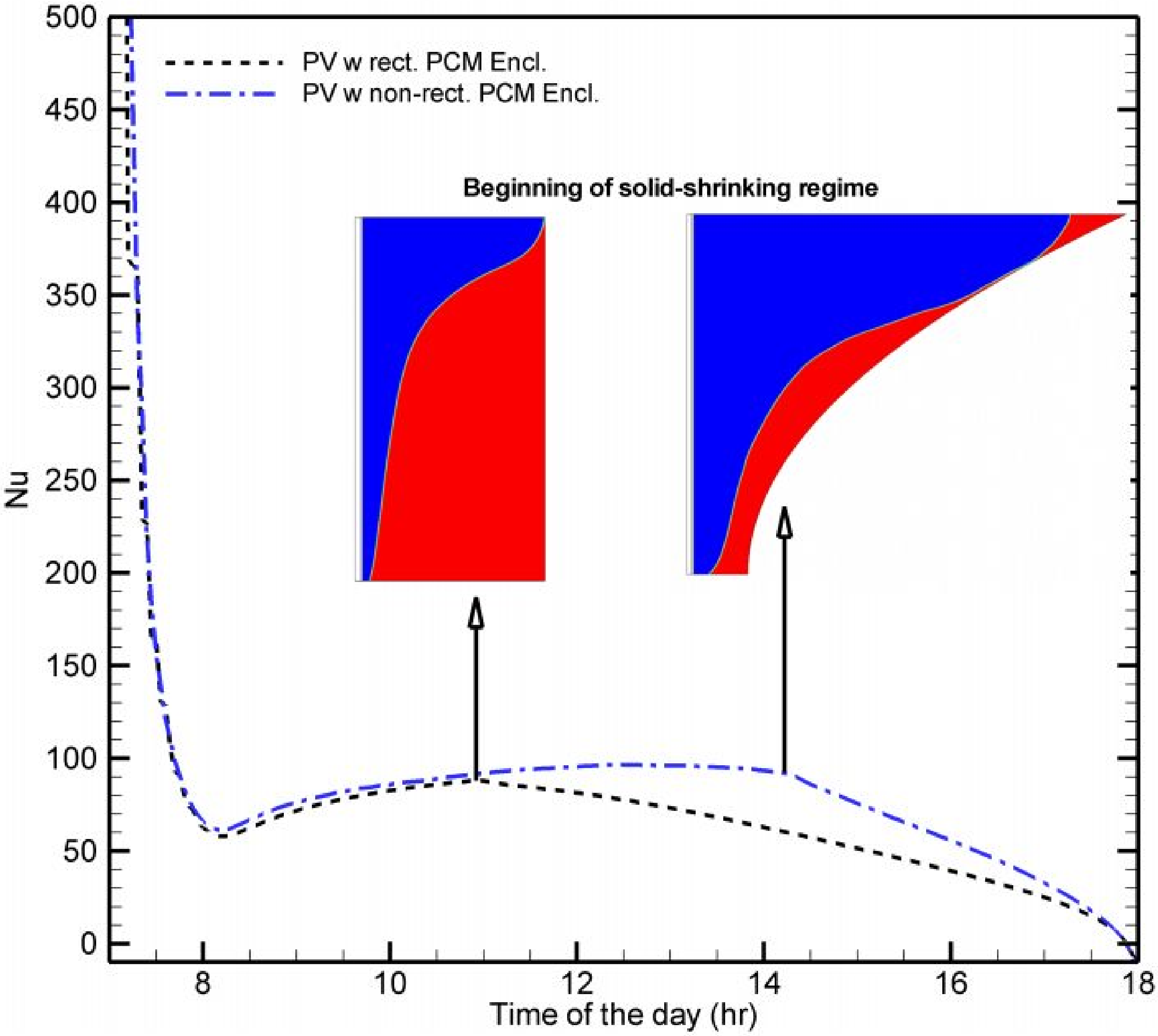

Figure 3.5: Comparison of transient history of Nusselt number for both type of configuration. Solid-liquid interface patterns for both configurations at end of quasi-steady convection regime are shown in inset.

enhanced by 2.56 times compared to conventional configuration. Hence it is best and requisite design among investigated enclosures.

3.3.2.3 Thermal energy storage performance

The maximum possible derived thermal energy from the system is termed as energy storage density (*ESD*) which is analyzed todetermine the thermal energy storage performance of PV/PCM system . *ESD* for any thermal system can be evaluated as shown in Eq. 2.16.

Figure 3.6 depicts the transient variation of *ESD* for both types of PCM encapsulation. *ESD* consists of sensible energy storage density (*SESD*) due to ΔT and latent energy storage density (*LESD*) due to melting of f_l fraction of PCM. However, *LESD* has considerably large contribution

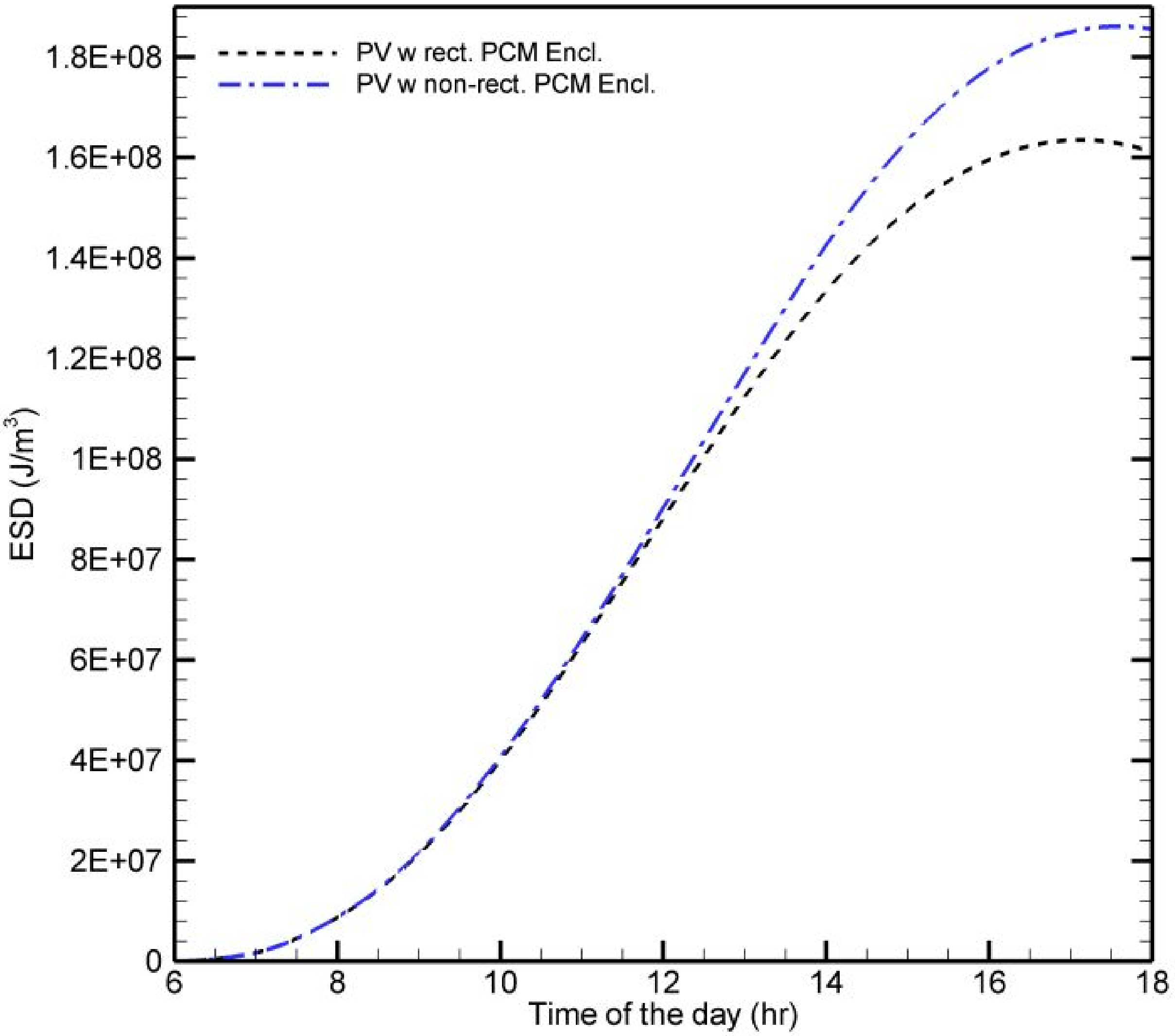

Figure 3.6: Transient variation of ESD for all configurations.

compared to *SESD* as stored latent heat is more compared to sensible heat. Initially in first hour of operation, there is no melting, hence; PCM have only *SESD*. However, with the start of melting *LESD* comes into play and soon starts to dominate *SESD*. The transient variation of *ESD* is similar to liquid fraction as *LESD* is the dominant part. However, *ESD* starts to decrease in later hours of day (last 2 hours for conventional configuration and last 1 hour for modified configuration) due to discharging of PCM. Conventional configuration exhibit an *ESD* of 161.12 MJ/m^3 at the end of the day, whereas non-rectangular type configuration possesses 185.61 MJ/m^3 of *ESD* which is 15.2% higher. Hence it can be concluded that modified non-rectangular type configuration has better thermal energy storage performance.

3.3.3 Performance characteristics

3.3.3.1 Effect of PV cell temperaure on electric conversion efficiency

Figure 3.7 and 3.8 depict the transient variation of maximum PV cell temperature and its electric conversion efficiency for both type of investigated configurations. PV cells are designed to work more efficiently at its reference temperature (25°C for c-Si PV cell) and their performance start to deteriorate with increase in temperature as shown by Eq. 2.14. The incident radiation on PV and PV/PCM system is given by Eq. 3.1 and ambient temperature is given by Eq. 3.2. Some amount of incident solar radiation is converted into electricty by PV panel, however; remaining part is wasted as heat and it increases the temperature of PV panel which decreases its electric conversion efficiency. The temperature of PV panel incraeses as global radiation incraeses with time and approaches a maximum value of 74.23°C at the time of maximum insolation due to which its efficiency decreases to 10% (rated efficiency is 12.4% for c-Si PV cell). After this stage, PV panel temperature decreases with decrease in solar inslotion and efficiency become closer to its reference value in the later hours of the day. However, this improvent is of no use as very small amount of incident radiation is available at this time. Therefore, the techniques must be applied to enhance the PV cell performance for peak insolation hours.

Attachment of rectangular PCM enclosure to PV panel (conventional PV/PCM system) is one of such common practice technique. PCM absorbs this waste heat as sensible and latent heat and thus cool down the PV panel. In conduction regime and mixed regime, the temperature of PV panel is lower compared to simple PV system, however; the temperature of PV panel increases with time as incident radiation incraeses. With establishment of convection dominated regime (8:25 hr), the variation of temperature with time becomes small and temperature of PV panel approaches to 44.77°C at the end of quasi-convection regime (10:54 hr) due to which its efficiency approaches to 11.43%. After quasi-convection regime, the temperature of PV panel starts to increase and reaches to 51.91°C at maximum insolation time (12:00 hr) and further to 58.35°C at 14:12 hr. Hence, the electric conversion efficiency decreases to 11.09% at maximum insolation time and 10.78% at 14:12 hr. After this point the temperature of PV panel decreases and its efficiency increases but it has lesser significance as insolation decreases rapidly in later hours of day. Conventional PV/PCM system exhibit a significant improvement in performance compared to PV system. However, it also exhibit degradation of performance during peak insolation hours. Hence, further modification in designs of PCM enclosure is required.

The design of PCM enclosure is modified to non-rectangular type to ensure the enhancement in quasi-convection regime to get lower PV panel temperature. The quasi-convection regime extends upto 14:12 hr by non-rectangular type enclosure as more PCM is available in convection dominated region. The modified PV/PCM system exhibits PV cell temperature of 45.50°C at peak insolation time with an electric conversion efficiency of 11.40% which is a significant improvement compared to conventional PV system (10%) and PV/PCM system (11.09%).

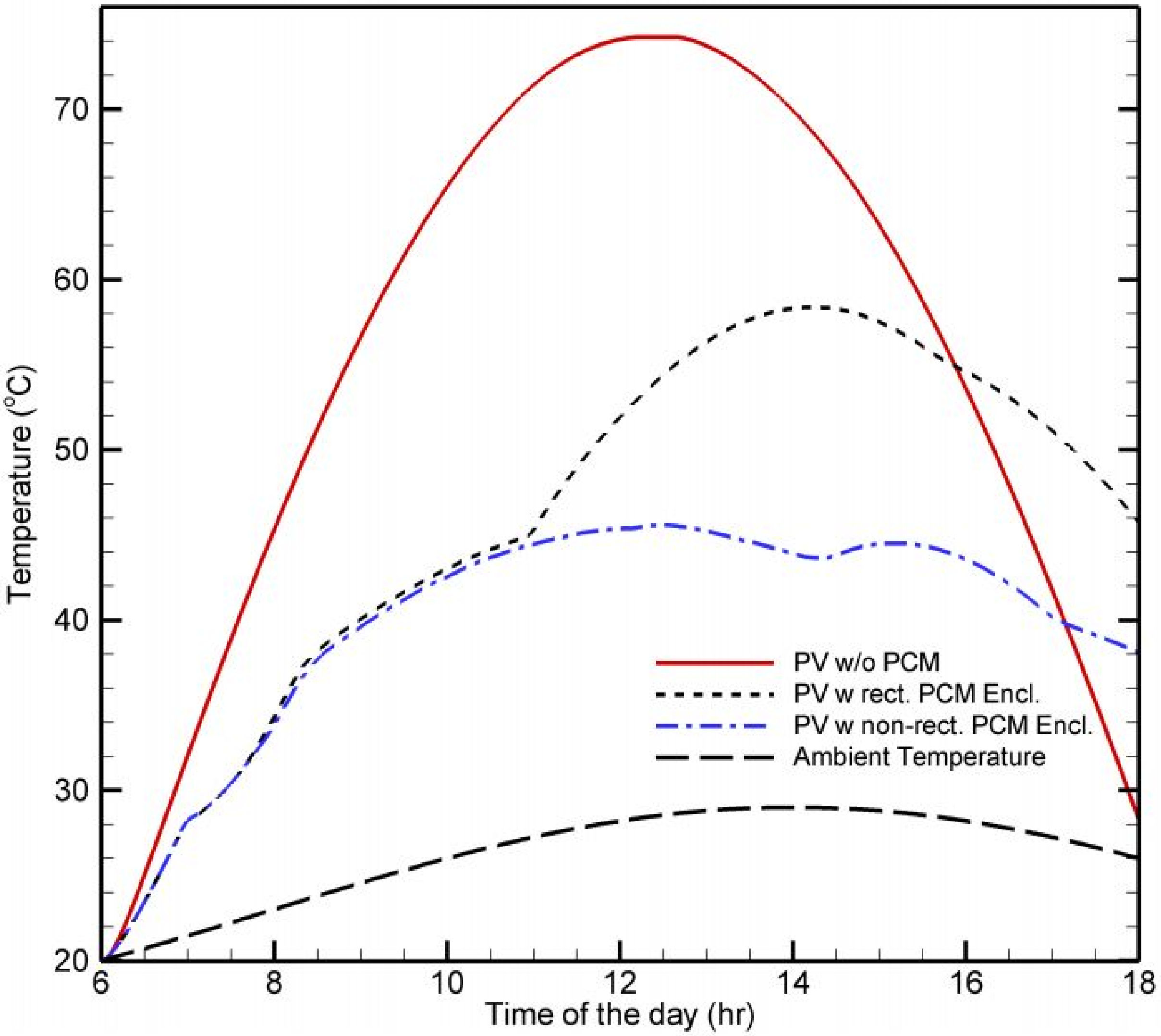

Figure 3.7: Transient variation of average PV cell temperature for all configurations of PV and PV/PCM systems.

The maximum temperature of PV panel is reported as 45.56°C at 12:42 hr with electric efficiency of 11.40% and temperature at end of quasi-convection regime is 43.63°C at 14:12 hr with an electric conversion efficiency of 11.50%. It is observed that modified system works at 11.40% efficiency in peak hours and at more than 11.40% in full day operation which was 10.78% for conventional PV/PCM system. This improvement is in peak isolation hour, hence its effect will be registered in power output of the system. Hence, modified system is well suited for enhanced thermo-electric performance.

3.3.3.2 Electric power output

Electric power output is one of the most important criterion to judge the performance of PV panel as it is directly consumable work from the system. Electric power output per unit area at

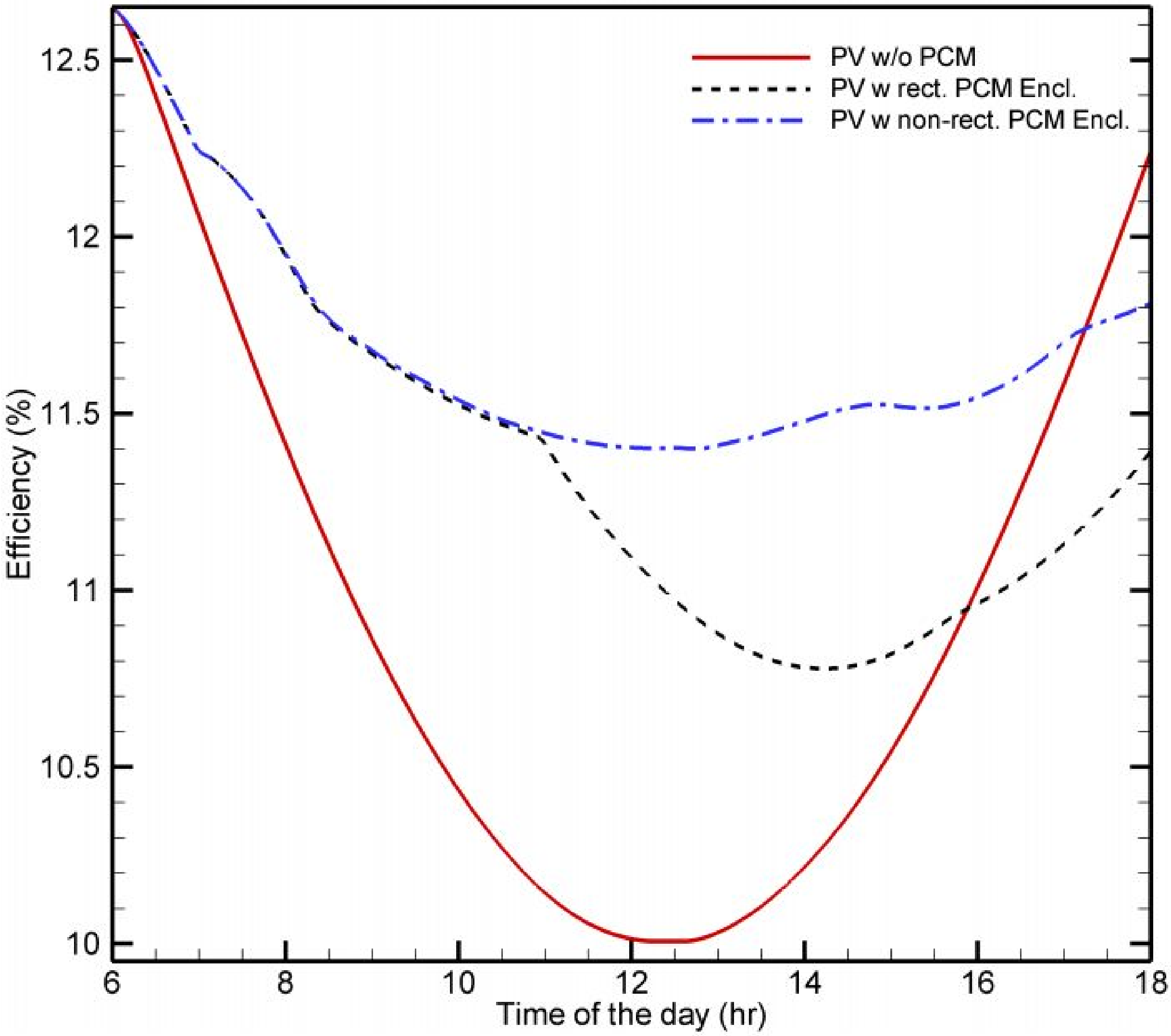

Figure 3.8: Transient Variation of electrical efficiency for all configurations of PV and PV/PCM systems.

any instant of time can be defined by following relation:

$$P_{out} = \eta_{pv}\alpha_{pv}\tau_g I_{solar} \tag{3.4}$$

Figure 3.9depicts the transient variation of electric power output for all configurations of PV system and PV/PCM system. PV panel works more efficiently at its reference condition and produces maximum possible electric power for a given incident radiation. The current PV panel has an ability to produce a maximum electric power of 106.02 W/m^2 at its refrence temperature and given solar insolation (Eq. 3.1). However, the maximum power output of PV panel is reduced to 85.63 W/m^2 due to rise in its operating temperature. The use of conventional rectangular enclosure, enhances the power output to 94.83 W/m^2 at peak insolation time. However, the performnce of PV panel is degraded in peak hours due to early ending of quasi-convection (10:54

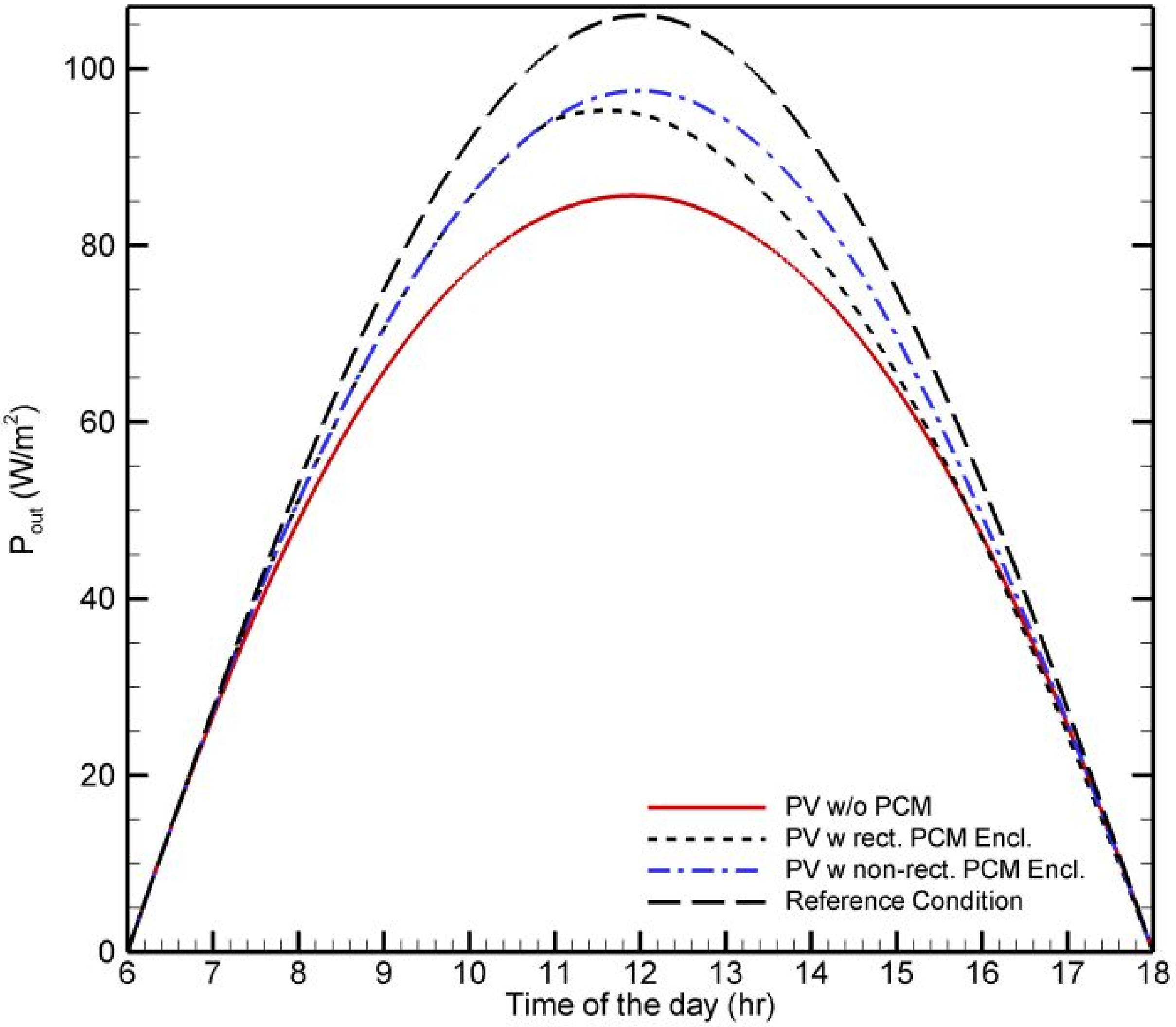

Figure 3.9: Transient variation of electric power output for all configurations of PV and PV/PCM systems.

hr) in conventional PV/PCM system. The modified PV/PCM system with non-rectabgular type PCM enclosure enhances the quasi-convection regime upto 14:12 hr which enhances the electric power output to 97.5 W/m^2 at peak insolation time. Furthermore, the modified PV/PCM system exhibit this significant enhancement in electric performance from 10:54 hr onwards. From these observation it can be deduced that modified PV/PCM system works at 92% of its rated performance while conentional PV/PCM system can work at 89% and PV system at 81% of its rated performance at peak insolation hours. Hence, the modified PV/PCM system not only produce extra electric power at peak time but it also provide it for longer duration of the day.

3.3.3.3 Total heat loss from the system

The performance of the system is also determined by analyzing the losses from the system to the ambient and performance is enhanced by minimizing these heat losses from the system. The total heat loss of the system can be calculated by adding the convective heat loss (Eq. 2.2) and radiative heat loss (Eq. 2.6).

Figure 3.10depicts the transient variation of total heat loss from the system to surroundings for all type of configurations. PV panel utilizes only a small fraction of incomimng radiation and remaing is wasted to the surroundings. Therefore, the total heat losses must be minimized for the better thermo-electric performance of the system. This waste form of radiation is absorbed by PCM in PV/PCM systems. The conventional PV/PCM exhibit degradation in heat loss in the begining of operation. However, the heat losses from system increases after the end of quasi-convection regime (10:54 hr). Simple PV system lost 914.38 W/m^2at time of peak insolation, however; conventional PV/PCM system exhibit a heat loss of 509.78W/m^2 and modified PV/PCM system exhbit a heat loss of 371.23W/m^2at time of maximum insolation. The heat loss from the system increases with propagation of time for conventional PV/PCM system and approches to 634.41W/m^2at 14:12 hr. However, the quasi-convection regime in modified PV/PCM system extends to 14:12 hr and heat loss is reduced to 313.65W/m^2. The discharging of the conventional PV/PCM starts at 16:00 hr while for modified PV/PCM system at 17:00 hr with almost half amount of heat losses to the surrounding. The modified system not only provides better thermo-electric performance but it also can store heat for longer duration with minimal loss to surroundings. Hence, the modified system is a good and sustainable option of conventional PV/PCM system.

3.3.3.4 Energy and exergy efficiency

The overall performance of the system can be estimated by its potential to utilize input energy. Energy and exergy efficiency analysis can be the relevant tools to analyze the overall performance of the system.

Energy efficiency analysis:

The total energy input (E_{total}) to the system during full day operation can be evaluated as [70]:

$$E_{total} = \int_{t_1}^{t_2} \alpha_{pv}\tau_g I_{solar} A_{pv} dt \tag{3.5}$$

where t_1 and t_2 indicates the initial (sun rise) and final (sun set) time. A_{pv} denotes the area of PV panel. The overall energy output($E_{overall}$) of the system consists of electric power output (E_{el}) and thermal stored energy(E_{th}) inside PCM enclosure.

$$E_{overall} = E_{el} + E_{th} \tag{3.6}$$

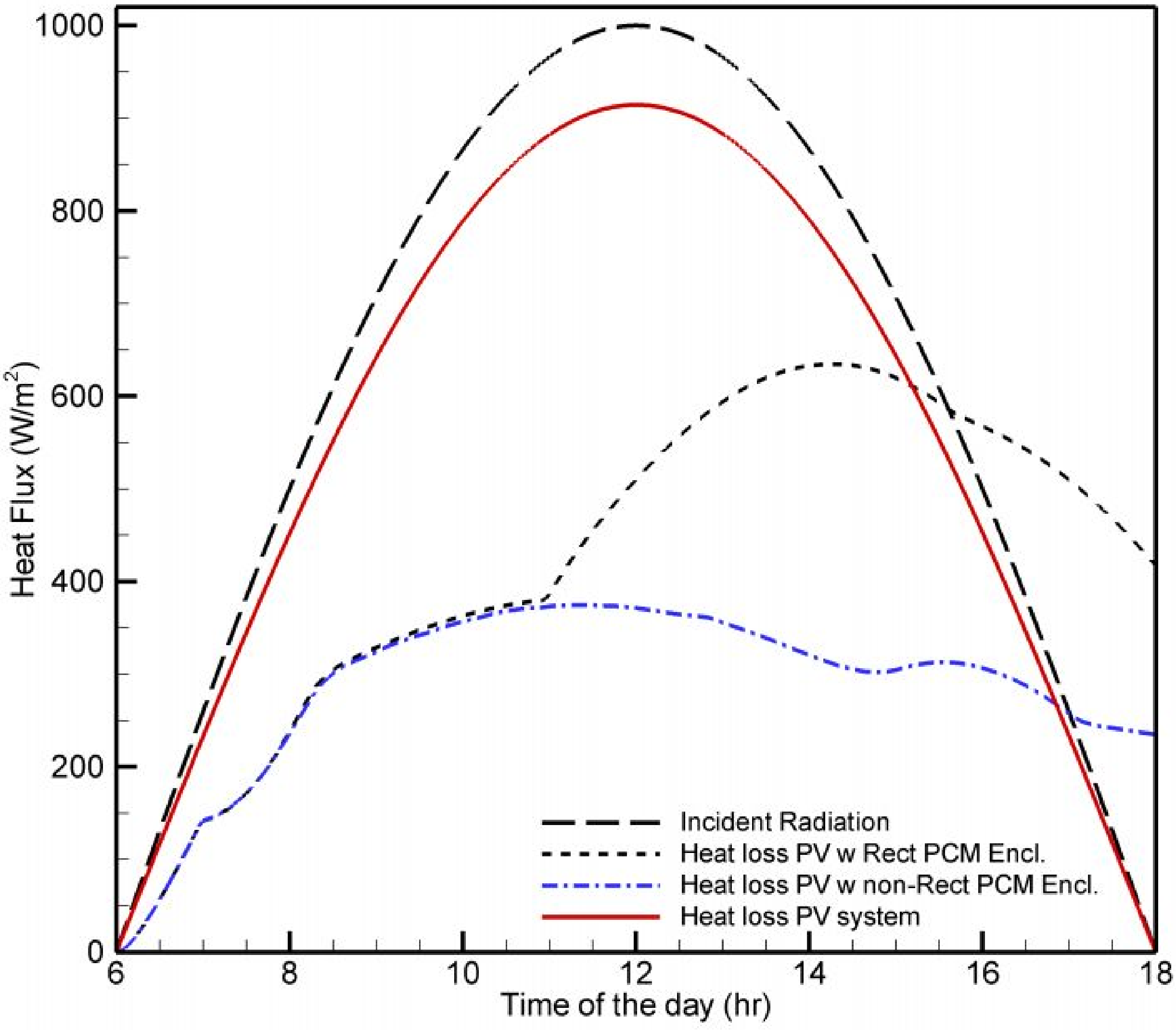

Figure 3.10: Transient variation of total heat loss for all type of configurations.

The electric energy output can be calculated as follows:

$$E_{el} = \int_{t_1}^{t_2} P_{out} * A_{pv} dt \tag{3.7}$$

The thermal energy stored in PCM enclosure consists of sensible heat as well as latent heat and can be evaluated as follows:

$$E_{th} = m_p(c_p \Delta T + f_l L_{sf}) \tag{3.8}$$

where m_p is mass of PCM inside the enclosure. The electrical energy efficiency (η_{pv}) and thermal energy efficiency (η_{th}) of the system can be calcultaed as follows:

$$\eta_{th} = E_{th}/E_{total} \tag{3.9}$$

$$\eta_{pv} = E_{el}/E_{total} \tag{3.10}$$

The overall energy efficiency ($\eta_{overall}$) of the system is sum of electrical and thermal energy efficiency.

$$\eta_{overall} = \eta_{pv} + \eta_{th} \tag{3.11}$$

The overall energy efficiency for PV system is equal to electrical energy efficiency as there is no PCM enclosure to store heat. However, the overall energy efficiency consissts of both electrical and thermal energy efficiency for PV/PCM systems as wasted heat is stored in attached PCM enclosures. Figure 3.11 depicts the comparision of various energy efficiencies for all different type of configurations. As stated earlier, simple PV system only produces electric power and remaining radiation is wasted as heat, therefore overall utilization of incoming radiation is only 10.52%. However, the use of PCM enclosure not only increases the electric power generation ability of the system but also allows the storage of heat in PCM enclosure. The electric energy efficiency has been increased to 11.24% and thermal energy efficiency approches to 58.53% for conventional PV/PCM system. Therefore, overall utilization ability of conventional PV/PCM system approaches to 69.77%. However, the shorter quasi-convection regime restricts the further improvement in the performance of the system. Hence, non-rectangular type PCM enclosure is introduced in modified PV/PCM system which enhances the duration of convection dominated melting and the performance of the system. The modified system system exhibits an enhanced electrical energy efficiency of 11.56% due to better thermal management of PV panel. The enhanced storage ability of non-rectangular PCM enclosure increases the thermal energy efficiency to 62.39% and overall energy efficiency to 73.95%. The modified PV/PCM system exhibits enhancement of 9.88% compared to simple PV system and 2.84% compared to conventional PV/PCM system in electric energy efficiency. The modified PV/PCM system also exhibits an enhancement of 6.59% and 5.99% in thermal and overall energy efficiencies compared to conventional PV/PCM system. Hence, the modified PV/PCM system exhibits better radiation utilization abilty among all configurations.

Exergy Efficiency analysis:

Exergy is the useful part of total utilized energy of the system. It is an indication of quality of different utilized energies. The quality of electric energy (high grade energy) is considered as high compared thermal energy (low grade energy). The exergy balance equation for any system can be written as [70]:

$$\sum Ex_{in} - \sum Ex_{out} = \sum Ex_{loss} \tag{3.12}$$

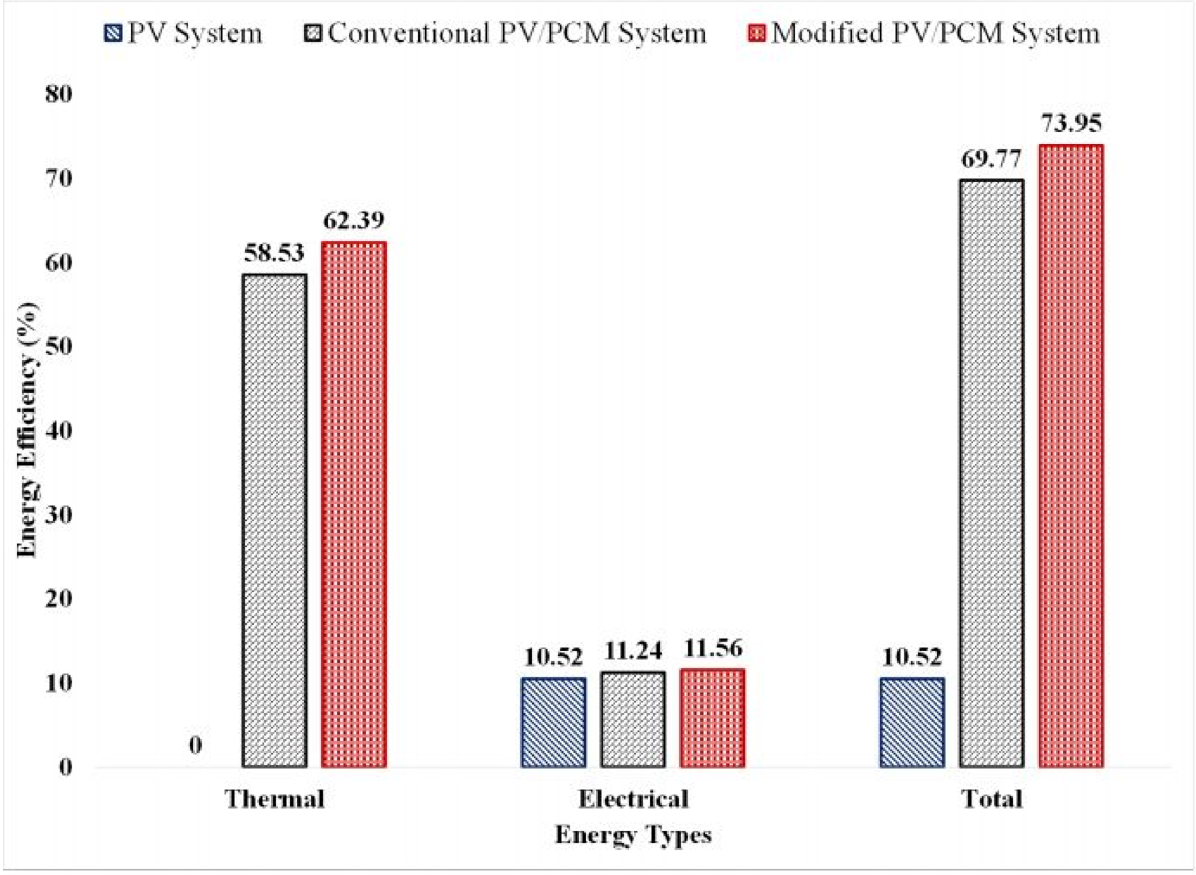

Figure 3.11: Comparision of energy efficiencies for all different configurations of PV and PV/PCM systems.

where Ex_{in}, Ex_{out}, and Ex_{loss} are input, output, and loss of exergy in the system. The input exergy to any PV or PV/PCM system can be written as:

$$Ex_{in} = A_{pv}\alpha_{pv}\tau_g I_{solar}[1-4/3(T_a/T_{sun})+1/3(T_a/T_{sun})^4] \tag{3.13}$$

where T_{sun} is temperature of sun (black body). The electrical energy can be completly utilized, hence electric energy is the electric exergy of the system. However total input exergy is not converted into electricity, therfore electric exergy efficiency of the system is:

$$\eta_{Ex,el} = Ex_{el}/Ex_{in} \tag{3.14}$$

The thermal exergy of system at any instant of time is calculated as:

$$Ex_{th} = m_p[c_p(T_f - T_i - T_a ln(T_f/T_i)) + L_{sf}(1 - T_a/T_m)] \tag{3.15}$$

And the thermal exergy efficiency of the system can be given as:

$$\eta_{Ex,th} = Ex_{th}/Ex_{in} \tag{3.16}$$

Total exergy output of the system is sum of electric and thermal exergy of the system. Therefore, the total exergy efficiency is sum of thermal and electrical exergy efficiency and can be calculated as follows:

$$\eta_{Ex,overall} = \eta_{Ex,el} + \eta_{Ex,th} \tag{3.17}$$

Figure 3.12depicts the comparision of various exergy efficiencies for all different type of configurations. The simple PV system doesn't absorb any thermal energy, hence; thermal exergy output of the system is zero but simple PV system depicts an electric exergy efficiency of 11.32%. The conventional PV/PCM system stores the wasted radiation inside PCM enclosure and depicts an thermal exergy efficiency of 1.57% and electric exergy efficiency of 12.09%. The thermal exergy efficiency is very low comparatively to electric exergy efficiency as stored heat is low grade of energy and can not be utilized completly for useful work. The electrical exergy efficiency of conventional PV/PCM system has been increased by 6.8% compared to simple PV system due to better thermal management of PV panel. However, smaller duration of quasi-convection regime put limitations to performance of the system in peak insolation hours. The modified PV/PCM system (with non-rectangular type PCM enclosure) exhibit elongated quasi-convection regime which results in lower PV panel temperature and enhaced electric power output. The electric exergy efficiency has been increased to 12.43% which is 9.8% higher than simple PV system and 2.81% higher than conventional PV/PCM system. The modified PV/PCM system stores more thermal energy compared to conventional system but still it depicts lower thermal exergy efficiency (1.38%) than conventional system (1.57%) as stored heat is available at lower system temperature. However, the overall exergy efficiency of modified system is higher than conventional system as contribution of electric energy is more in exergy production. The modified PV/PCM system exhibits an overall exergy efficiency of 13.81% which was 13.66% for conventional PV/PCM system and 11.32% for simple PV/PCM system. Hence, the modified PV/PCM system exhibit better utilization of useful energy among all configurations.

3.3.4 Feasibility of the system:

The idea of PV/PCM system has a constraint of capital requirement. Therefore, an economic, exergoeconomic and enviroeconomic analysis must be performed to estimate the feasibilty of the system. The feasibility study of any system predicts the viability of the system.

Economic and exergoeconomic analysis of the system:

The primary objective of PV and PV/PCM system is to reduce the cost of electricity and exergy production per kWh. The cost assesment deatils can be demonstrated in following steps [69]:

The first annual cost(FAC) of any PV and PV/PCM system can be calculated as:

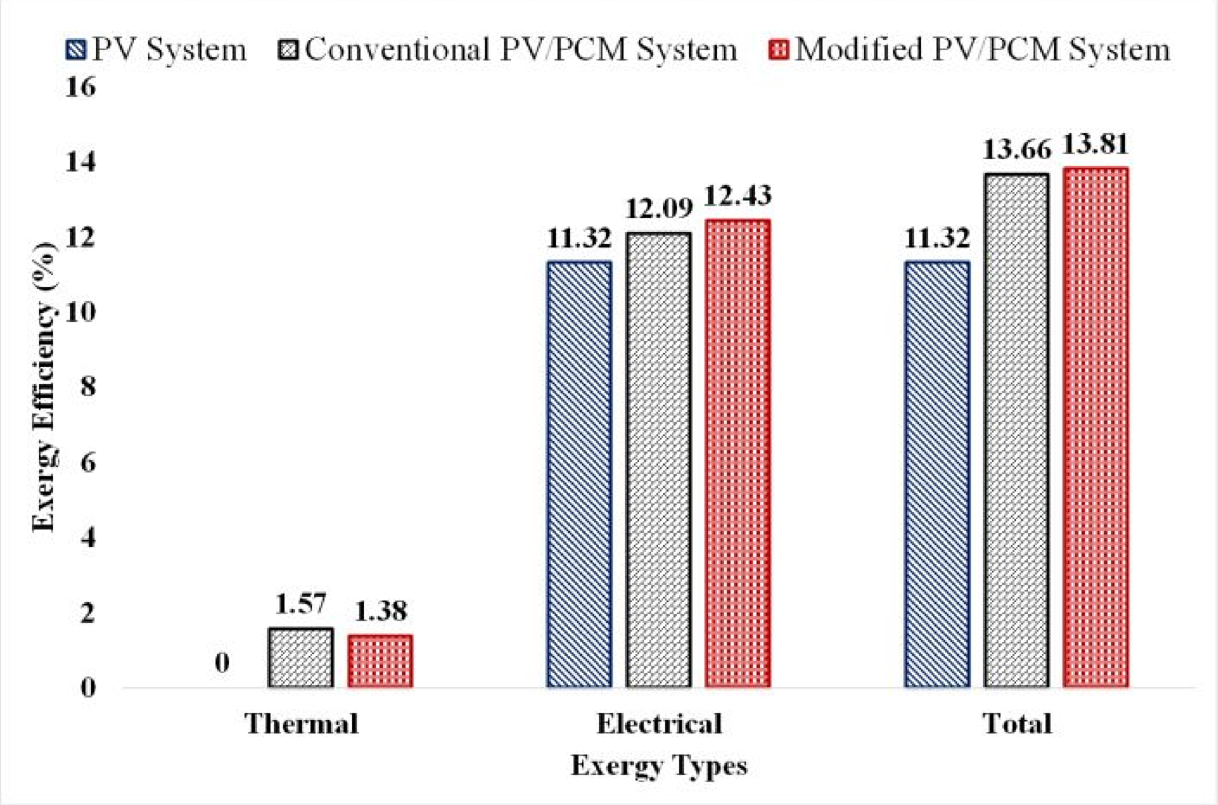

Figure 3.12: Comparision of exergy efficiencies for all different configurations of PV and PV/PCM systems.

$$FAC = CRF * C_{total} \tag{3.18}$$

where C_{total} is the capital investment and CRF is the capital recovery factor and is given as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.19}$$

where i is the interest rate and n is the life span of the system, which is considered as 4% and 20 years for the current case. The annual salvage value (ASV) of the system can be calculated as:

$$ASV = SSF * S \tag{3.20}$$

whereSSF and S denotes the shinking fund factor and salvage value respectively.

$$SSF = i/(1+i)^n - 1 \tag{3.21}$$

$$S = C_{total}(1 - i_d)^n \tag{3.22}$$

wherei_d represents the depreciation rate. The annual maintenance cost (AMC) is taken as 15% of the first annual cost(FAC).

$$AMC = 0.15 * FAC \tag{3.23}$$

The total annual cost (TAC) can be calculated as follows:

$$(TAC) = FAC + AMC - ASV \tag{3.24}$$

The cost of electricty production (C_{el}) and exergy production (C_{ex}) can be calculated as follows:

$$C_{el} = TAC/E_n \tag{3.25}$$

$$C_{ex} = TAC/Ex_n \tag{3.26}$$

where E_n and $Ex_n$are annual electricty and exergy production of the system in kWh.

The economic and exergoeconomic analysis for all configuration are provided in Table 3.1. It can be estimated from the findings that modified PV/PCM system exhibit lowest cost of electricty production among studied configuration. The modified PV/PCM system exhibits maximum electric power generation and exergy generation among all studied configuration. It must be noted that all calculation are done by considering 4% interest rate and 20 year life span of the system, also electricity and exergy generation are calculated for unit area of PV panel. The cost of electricity production for simple PV system is 0.0642$/kWh, which is reduced to 0.0637$/kWh by attaching a rectangular PCM enclosure. The cost is further reduced to 0.0618$/kWh by a better thermal managent of PV panel in modified PV/PCM system. The modified PV/PCM system possesses 3% lesser cost of electricty production compare to conventional PV/PCM system and 3.73% lesser than simple PV system. The PV/PCM systems also produce thermal exergy in addition to electricty, hence cost of exergy production is further reduced for both configuration of PV/PCM system. The cost of exergy generation is 0.0564$/kWh for conventional configuration and 0.0557$/kWh for modified configuration of PV/PCM system. The cost of exergy production for modified configuration is 1.24% lower than conventional configuration as it exhibit more overall annual exergy production. It can be deduced from this analysis the modified PV/PCM system seems to be more viable and cheaper source of clean energy.

Enviroeconomic analysis:

PV and PV/PCM systems are clean source of electricty and exergy production unlike fossil fuels based power plants. Therefore, harmful green house emmisions (like CO_2) can be allviated by augmenting the implantaion of PV/PCM technologies. Moreover, the augmentation in thermo-electric performance of PV/PCM system will further reduce the harmful CO_2 em-

Table 3.1: Economic and exergoeconomic investigation for all configurations of PV and PV/PCM systems.

System	PV System	Conventional PV/PCM System	Modified PV/PCM System
C_{total}(\$)	185	196	196.2
FAC(\$)	13.61	14.42	14.43
ASV(\$)	0.46	0.49	0.49
AMC(\$)	2.04	2.16	2.16
TAC(\$)	16.11	17.07	17.08
E_n(kWh/year)	250.91	267.94	276.01
Ex_n(kWh/year)	250.91	302.59	306.43
C_{el}(\$/kWh)	0.0642	0.0637	0.0618
C_{ex}(\$/kWh)	0.0642	0.0564	0.0557

misions and will help in maintaining a sustainable ecosystem by decreasing pollutants in the environment. Enviroeconomic analysis is a strategy to regulate of greenhouse gas emissions through imposition of fiscal incentives to acheive decay in emmision of pollutants. This strategy will also motivate to numerous developing countries and their people to empowered with renewable energy technologies.

The CO_2 corresponding to fossil fuels power plant is 2kg per kWh per year of electricity production [69]. Hence, decrement in production of CO_2 caused by a PV system is:

$$\varphi_{CO_2} = \frac{(E_n * 2)}{1000} \tag{3.27}$$

However, PV/PCM system produces thermal exergy in addition to enhanced electricty. Hence the decrement in emmision of CO_2 caused by a PV/PCM system can be given as:

$$\varphi_{CO_2} = \frac{(Ex_n * 2)}{1000} \tag{3.28}$$

where is φ_{CO_2} annual decrement in carbon emmision of the system. The amount of earned carbon credit can be calculated as:

$$Z_{CO_2} = z_{CO_2} * \varphi_{CO_2} \tag{3.29}$$

where $z_{CO_2}$is global carbon value which in current investigation is taken as 14.5\$ per ton of CO_2.

The enviroeconomic analysis for all studied configurations are provided in Table 3.2. The results disclosed that annual reduction in CO_2 emmisions has been reached to 0.502, 0.605, and 0.613 tons for unit area of PV panel in PV, PV/PCM, and modified PV/PCM systems respectively. The causes of higher reduction in PV/PCM configurations are generation of additional thermal exergy and enhanced electricty generation. The modified PV/PCM found to be greener than all

Table 3.2: Enviroeconomic investigation for all configurations of PV and PV/PCM systems.

Parameter	**PV System**	**Conventional PV/PCM System**	**Modified PV/PCM System**
E_n(kWh/year)	250.91	267.94	276.01
Ex_n(kWh/year)	250.91	302.59	306.43
φ_{CO_2}(ton)	0.502	0.605	0.613
Z_{CO_2}($)	7.28	8.77	8.89

other configurations. Furthermore, the modified PV/PCM system outperformed all other studied configurations in terms of earned carbon credit. The modified configuration of PV/PCM system earned 8.89$ per annum on basis of carbon credits whereas, conventional PV/PCM system and PV system depicts a earning of 8.77$ and 7.28$ per annum for a unit area of PV panel respectively. The modified PV/PCM system exhibit 1.36% more earning than conventional PV/PCM system and 22.11% compared to PV system. Hence, the modified PV/PCM system will not only be a viable option of cleaner and greener energy but it will also provide a boost to economy be earning more fiscal incentives.

3.4 Conclusions

In this chapter, the knowledge from previous chapter is implemented to non-rectangular design of PCM enclosure for PV/PCM system and examines its feasibility under variable boundary and ambient conditions (mimics real condition). The performance of conventional PV/PCM system is compared with the proposed PV/PCM system having a non-rectangular PCM enclosure by an experimentally verified numerical model under variable boundary conditions. The study focuses on improvement of thermo-electric performance by characterization the heat transfer according to melting front morphology in newly modified PCM enclosure. Exergy analysis, economic analysis, and enviroeconomic analysis are also conducted for both conventional and proposed system. Following are some key observations:

1. The proposed PCM encapsulation design exhibits 20.33% more melting compared to conventional design as the starting of solid shrinking regime is delayed by 3 hr 18 mins. The solid shrinking regime appears at 10:54 hr for conventional design which is more than an hour earlier than maximum insolation time (12:00 hr) while for proposed system it shifts to 14:12 hr which is more than two hours beyond maximum insolation time.

2. Enhanced melting rates leads to lower PV panel temperature and enhanced electric conversion efficiency. The PV panel in proposed PV/PCM system works at 92% of its rated performance which was 89% for conventional PV/PCM system and 81 % for simple PV panel. without any PCM encapsulation.

3. The heat loss to surrounding from the proposed system is approximately half compared to conventional PV/PCM system which explains higher insolation utilization abilty of proposed system. Also the conventional PCM enclosure starts to discharge stored heat approximately 2hr earlier than the end of the day while proposed system starts discharging only 1 hr earlier to the end of the day.

4. The proposed system exhibit an exergy efficiency of 13.81% which was 13.66% for conventional PV/PCM system and 11.32% for PV panel without any PCM encapsulation. The proposed system exhibit an energy efficiency of 73.95% which is 6% more than conventional PV/PCM system.

5. Economic analysis exhibit that the proposed system possesses 3% lesser cost of electricity production compared to conventional PV/PCM systems. More earned carbon credits also explains that the proposed PV/PCM system helps in reducing CO_2 emissions and thus a cleaner source of energy production.