
Effect of New Overhead Phase Change Material Enclosure Designs on Thermo-electric Performance of a Photovoltaic Panel

Photovoltaic (PV) panel harvests solar energy into electric energy; however, its electric conversion efficiency is very low and most of incoming radiation is wasted as heat to the surroundings. Electric performance of PV panel is badly affected by increased PV cell temperature as result of this wasted heat. A new design concept of overhead phase change material (PCM) enclosure design attached with a photovoltaic panel has been investigated in this chapter. Various design configurations studied and based on the melting front characteristics, an optimum final design is proposed. The new design enhances the solar radiation gain (ratio of utilized to unutilized radiation) by about 17 times the conventional PV system. Higher solar radiation utilization manifests in about 10% increase in energy storage density. With strategic distribution of PCM, duration of quasi-steady regime where convection dominates, has been increased that manifested into higher melting rates of PCM compared to the conventional rectangular design. The study revealed that electrical conversion efficiency of PV panel can approach to about 12% if suitable strategies are adopted as demonstrated in this paper. This study would be useful in developing efficient PV technologies to meet the ever-growing energy needs. The findings of this investigation are reported from an experimentally validated numerical model that accurately captures the melting behavior of PCM and other thermal characteristics of the system.

4.1 Introduction

Solar energy is one of the prominent options and perhaps it would be only option in near future of clean and pollution free energy as it reduces the dependency on fossil fuels to fulfill growing global energy demands. Photovoltaic (PV) panel harvests solar energy into electric energy, however its electric conversion efficiency is very low and most of incoming radiation is wasted as heat to the surroundings. Electric performance of PV panel is badly affected by increased PV cell temperature as result of this wasted heat [72]. Crystalline silicon (c-Si) demonstrate an efficiency reduction rate of 0.5%/°C temperature rise of PV cell [10]. Moreover Radziemska and Klugmann, [40] have reported a declination rate of 0.65%/°C in output electric power and 0.08%/°C decrease in electrical conversion efficiency. Strategies for thermal management of this waste heat must be devised to increase electrical efficiency by extracting heat from the panel. Heat extraction devices are attached to the back of PV panel which not only perform thermal regulation of PV cell but also works as thermal collector at the same time. Photovoltaic panel with thermal collector system is called photovoltaic-thermal (PV/T) system and has become center of extensive research in recent times [5, 9, 44, 73].

Thermal collector in PV/T system are designed on the basis of heat extracting technique such as active cooling methods and passive cooling methods. In active cooling technique, a heat transfer fluid is allowed to flow beneath or above PV panel. Such PV/T systems using air as heat transfer fluid are designated as air cooled PV/T systems [34, 43] and some PV/T systems using water as heat transfer fluid are classified as water cooled PV/T systems [46, 47]. All PV/T system based on active cooling technique consumes external power for extracting heat from the PV panel and thus overall performance of the system is reduced.

In passive cooling technique, excess heat from PV panel is extracted through absorbing materials. Phase change material (PCM) is one of the excellent absorbing material as they have a great potential of storing heat as latent heat. PV/T systems based on PCM storage technique are classified as PCM cooled PV/T systems [11, 74]. PCM cooled PV/T systems doesn't require any external energy to extract heat as PCM has very high latent heat and exchange heat by changing phase at its melting temperature [74]. PCM cooled PV/T system provide heat for the nocturnal usage and thus making the PV/T system effective for additional hours. PCM absorbs latent heat at constant phase change temperature and hence allowing PV panel to work on relatively constant operating temperature. Atkin and Farid [11] observed an increase of 12.97% in overall efficiency when graphite infused and aluminum fins are used with PCM to extract heat from PV panel. Stropnik and Stritih, [75] reported a maximum reduction of 35.6°C in operating temperature of PV panel during the day and 7.3% more production of electricity for a period of year by just using PCM. Naderi et al., [76] proposed a combination of PV/PCM system to thermal-electric generators thus making it PV/TEG/PCM system and observed an increment of 100% in power output with 1.38% increment in solar cell efficiency.

From the above discussed literature, it can be concluded that the most conventional PCM enclosure designs are rectangular type and PV panels with PCM enclosure exhibit enhanced thermo-electric performance. Ezan et al., [36] described the importance of natural convection in melting of PCM for PV/PCM systems. It was reported that convection dominated melting increases the heat extraction rate from PV panel and increases the performance of PV panel. However, decreased melting rates and degraded electric performance was observed in later stages of melting. Janny and Bejan, [38] describes the characterization of melting in a rectangular PCM enclosure which was further supported by Kamkari et al., [37]. Melting in a rectangular PCM enclosure can be divided into four different regimes of melting, namely (i) conduction regime, (ii) mixed regime of conduction and convection both, (iii) quasi-steady convection regime, and (iv) solid-shrinking regime [17]. After the dominance of conduction and then mixed regime, quasi-steady convection regime begins where significant enhancement in heat transfer rate is seen. This quasi-convection regime ends as melting front approaches the opposite wall of enclosure and give rise to solid-shrinking regime. Melting rate exhibit slowdown in solid-shrinking regime due to deceleration of convection current. Hence, it is desirable that span of quasi-steady convection regime is extended by strategically distributing the mass of PCM on the top part of enclosure. Many researchers employed fins [50, 51], nano-additive [60, 77], additional secondary fluid such as air [45], water [49], nano-fluid [57] to improve the heat extracting performance of PCM based thermal collector. A few researchers have focused on designing the enclosure according to melting front characterization and arranging more PCM in convection dominated region [39, 68]. Akshayveer et al., [39] reported non-rectangular enclosure designs of different types depending on the right wall profile of the enclosure to avail more PCM in top region of enclosure. It was reported that melting rate was enhanced by 17.18% in modified non-rectangular design compared to rectangular enclosure. Further, the PV panel had shown a temperature decrement of 38.77% and increment of 9.86% in electric efficiency compared to PV panel without PCM attachment. It was also reported that melting rate would be enhanced by increasing the course of quasi-steady regime and shortening the solid-shrinking regime. Furthermore, the non-rectangular bifurcated type PCM enclosure for bifacial PV/PCM system also exhibit significant improvement in its thermo-electric performance [68]. The demerit of non-rectangular PCM enclosure is that the compactness of system is lost to maintain same PCM volume. Rabie et al., [55] replaced rectangular enclosure by extended enclosure in concentrating PV panel and tested for an over-height ratio of 0 to 60% and different inclinations and a temperature uniformity of 13.7 to 5.3°C is maintained. Hence, the extension of PCM enclosure could be a viable option to achieve compactness and desired performance by characterizing the melting morphology.

From the above discussion, three points are clear: (1), that designs of PCM enclosure plays an important role in enhancing PV panel thermo-electric efficiency and (2), there is continuous effort by scientific community to improve the PCM enclosure designs. This paper is a step in

that direction and (3), that melting front can propagate in extended part and extract heat away from the panel. Hence, optimization of extended height for same volume of PCM is desirable to maintain a longer quasi-steady regime and compactness of the system. Considering the lower efficiency of PV panel, an effort has been made in this paper to take the research on PCM enclosure design to the next stage that provides longer quasi-steady regime and hence lower PV panel operating temperature.

In this study we present the investigation on new design concepts of PCM enclosure to aid natural convection dominated melting and consequently increasing heat extraction rate from PV panel. The main objective of this study is to distribute same volume of PCM in enclosure so that span of quasi-steady convection regime of melting gets extended by squeezing the solid-shrinking regime. The stated objective is achieved by conceptualizing new enclosure designs as demonstrated in Figure 4.1(b, c, and d). It is to be mentioned here that subsequent designs (from Figure 4.1 (a) to (d)) are result of improvement from the previous design. They are put together for readers' convenience. The rectangular enclosure is extended from the top of PV panel so that melting front can propagate in the overhead part of enclosure and extract heat away from the PV panel. Increase in extended height reduces the distance between PV wall and right wall of enclosure to ensure same volume of PCM which will decrease the span of quasi-steady convection regime. Hence extended enclosure is further modified to overhead type after optimizing the extended height. Overhead type enclosure is further modified by giving depression from top of PV panel so that quasi-steady convection regime is extended up to maximum duration. Though there can be numerous shapes of extended part that can be analyzed, the reported shapes can be used as guidance for further research and development of efficient enclosure designs. BIPV system with these different configuration of PCM enclosure has been investigated under same boundary conditions by using experimentally validated numerical model. The influence of shape of enclosure on melting rate of PCM and thermo-electric performance of PV/PCM system has been investigated for improved design and compared to conventional one.

4.2 Methodology

4.2.1 Problem description & definition

The PV/PCM system is modelled as two-dimensional computational domain (see Figure 4.1) to analyze the thermo-electric performance of PV/PCM system with four different configurations (type – A, B, C and D based on geometric modifications) of attached PCM enclosures. Type – A configuration (rectangular PCM enclosure) of PV/PCM system consists of a glass region of thickness ($t_g = 3mm$), PV panel region of thickness ($t_{pv} = 1mm$), and PCM enclosure region of thickness ($L = 20mm$) with the height of the numerical domain (H_{pv}) is 100 mm. In type-B configuration, the height of rectangular enclosure is extended by H_e and thickness is reduced to L_1

so that volume of enclosure remain exactly same as type-A configuration. Moreover in type-C configuration the extension is given in form of a rectangular overhead tank for further improvement of performance. Type-D configuration is a modified version of type-C configuration in which a depression (H_d) from top of PV panel is given in addition to an extension of H_e . The constraint of same volume of PCM enclosure and same geometric parameters of glass and PV region as of type-A is maintained in all modified configurations. Heat is pumped away from PV panel into these overhead tank in form of molten PCM as a result of natural convection current.

In all configurations of PV/PCM systems RT27 (properties listed in Table 2.2) is used as PCM because its melting temperature (27°C) is in proximity of reference temperature (25°C) of PV panel. RT 27 is a type of paraffin wax manufactured by Rubitherm technologies GmbH. It is a mixture of solid saturated hydrocarbons with molecular formula $C_n H_{(2n+2)}$ (4% alkane with C_{17} , 45% C_{18} , 36% C_{19} , 12% C_{20} , 2% C_{21} , and 1% other alkanes) [78]. 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 except density which is constant for solid phase and variable with temperature (Boussinesq approximation) for liquid phase.

4.2.2 Boundary conditions

Incident solar radiation (I_{solar}) on the left wall is divided into conductive heat transfer into the wall and convective heat flux losses ($q''_{conv.}$) and radiative heat flux losses ($q''_{rad.}$) which is better described by the Eq. 2.1.

Both forced convection as well as natural convection contributes to convective heat loss from wall to surroundings which is given by the Eqs. 2.2-2.5.:

The radiative heat loss from left wall to surroundings is determined according to Stefan-Boltzmann equation for radiative heat transfer and given by the Eq. 2.6.

The boundaries other than left wall i.e, top, right and bottom surfaces are considered perfectly insulated. The extended as well as overhead portion are also kept perfectly insulated.

In the present study a comparative study has been conducted among all configurations of PV/PCM system by performing various numerical simulations under constant boundary conditions. First type-B configuration is analyzed to obtain an optimum extended height(H_e) at different values of $H_e = 20\%$, 30% and 40% which is designated as type- B_1 , B_2 and B_3 respectively. Further, type-C configuration is analyzed at observed optimum H_e for improvement in thermal performance of PCM enclosure. Moreover, type-D configuration is examined for different values of H_d to obtain an optimum design of efficient PV/PCM system with an overhead heat storage PCM tank. Addition of overhead tank pumps the heat in the form of molten PCM away from PV panel due to enhanced natural convection and availability of more PCM on the top side. As a result, it also enhances the electric performance of PV panel by increasing melt-

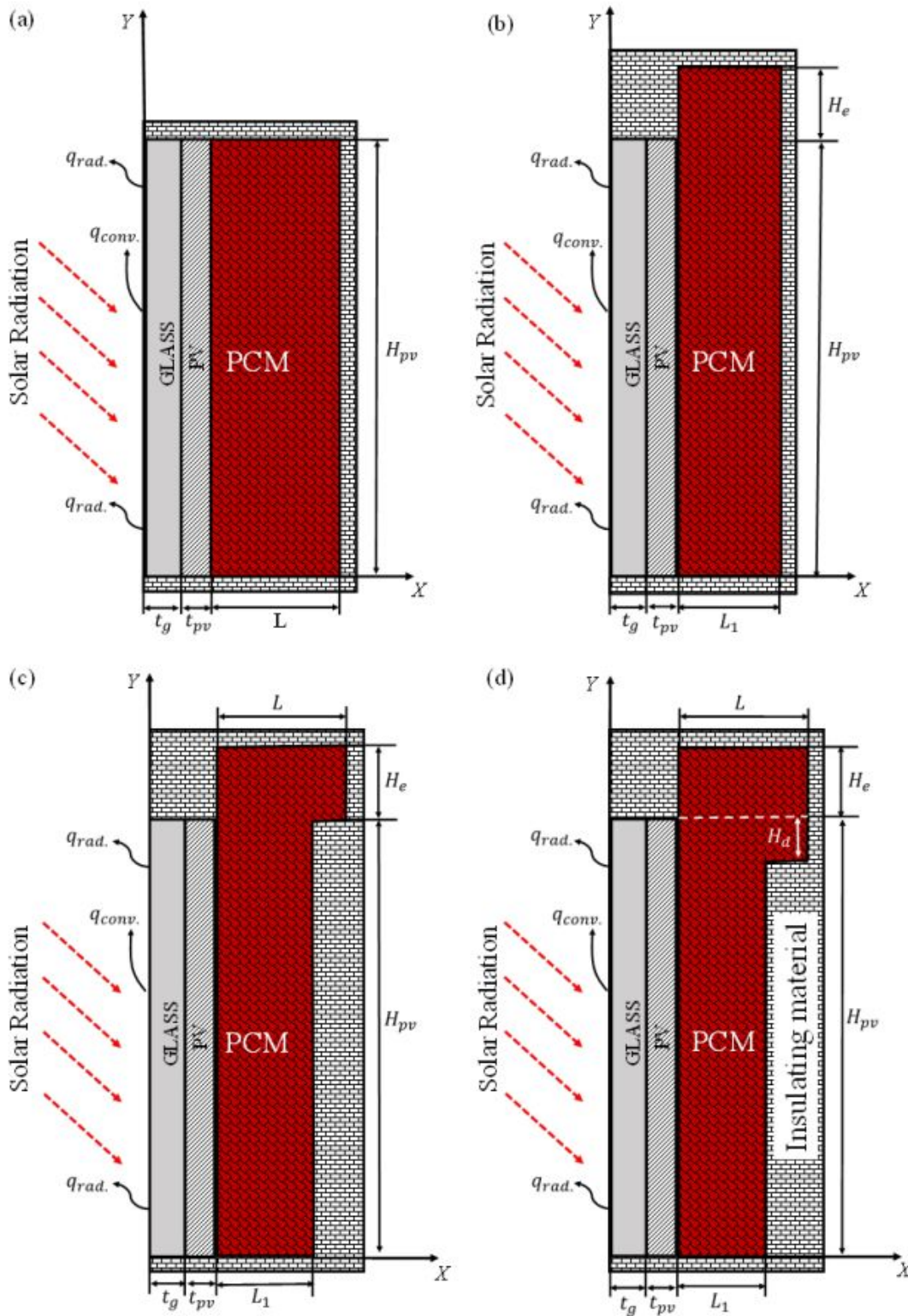


Figure 4.1: Two-dimensional view of PV panel with integrated PCM enclosure (a) rectangular enclosure (type-A), (b) rectangular enclosure with extension H_e (type-B), (c) rectangular enclosure with overhead tank extension H_e (type-C), (d) rectangular enclosure with modified overhead tank extension H_e and depression H_d (type-D). Note that subsequent designs from type-B to type-D was arrive after analyzing the performance of the previous design.

ing rate of PCM. The solar insolation ($I_{solar} = 800W/m^2$), the ambient temperature ($T_a = 20^\circ C$), and wind velocity ($v_w = 2.4m/s$) were considered for the numerical analysis. The value of wind velocity is chosen according to available average ambient conditions during peak radiation time (11 AM to 1 PM).

4.2.3 Solution method

The same assumptions and solution approach as in section 2.2.2 (solution method) of the chapter 2 are used to discretize and solve conservation equations and other governing equations (Eqs. 2.7-2.14). Grid-independent study for PV/PCM system is also considered, as described in section 2.2.3 of the chapter 2 (see Figure 2.2). Experimental work by Kamkari et. al [37] on convective melting of PCM inside rectangular cavity is used for validating the numerical model. In section 2.2.4 of chapter 2, the full analysis of experimental validation of the computational model, as well as error and limits, is better discussed. Experimental and numerical models are compared by plotting time evolution data of liquid fraction along with solid-liquid interface patterns as shown in Figures 2.3 and 2.4. The predicted results in numerical model are reasonably precise and mimics the experimental setup. Hence, the numerical model can be used for further design exploration for PV/PCM systems.

4.3 Results and discussions

4.3.1 Solid-liquid interface patterns

Heat transfer mechanism during melting of PCM can be better visualized by solid-liquid interface patterns. Figure 4.2 depicts the solid-liquid interface patterns superimposed with velocity streamlines for all type of configuration namely type – A (conventional rectangular enclosure), type – B_1 , B_2 , and B_3 (extended rectangular enclosure with extension $H_e = 20\%$, 30% , and 40% respectively), type – C (extended overhead PCM heat storage enclosure with extension $H_e = 35\%$), and type – D (extended overhead PCM heat storage enclosure with extension $H_e = 35\%$ and depression $H_e = 20\%$) respectively, when a solar radiation of $800W/m^2$ is incident on PV/PCM system. A part of the incident radiation is lost to surroundings as a consequence of radiative and convective losses from the glass surface. Remaining radiation is transmitted to PV panel which converts some part of it to electricity and leftover radiation is absorbed as heat and transmitted to PCM enclosure. PCM stores this wasted heat by changing phase from solid to liquid. Hence, melting process plays an important role in maintaining the PV panel to operate at lower temperature. In all type of configuration, melting starts approximately 5 minutes later as solar radiation hits the glass layer and initially governed by conduction only. In conduction regime, smaller melting layer thickness causes the viscous forces to dominate which restrict the fluid flow and

solid-liquid interface remains parallel to adjacent PV wall. 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 15 minutes after the incidence of solar radiation in all type of configuration.

In type – A configuration, fluid rises alongside the PV wall and approaches the top wall of enclosure, which diverts the flow direction and directs it towards solid-liquid interface. Hence, the erosion of melting interface takes place in upper part of enclosure by convective heat transfer and then fluid falls along the solid-liquid interface. Melting front propagation history for type – A configuration is clearly visible in Figure 4.2(a). Melting in upper part of enclosure is dominated by convective melting while in the bottom region it is still governed by conductive heat transfer in mixed regime of melting. Hence the shape of solid-liquid interface in top region is concave in shape while in bottom part it is still parallel to PV wall. After 30 minutes, convection starts to dominate in whole enclosure and shape of melting front in the bottom part changes to linear while in the upper part of enclosure it remains concave until the melting front extends to the right wall. In this regime melting is completely dominated by convection so this regime of melting is called quasi-steady convection regime and it exists up to 56 minutes. The shape of solid-liquid interface changes to convex as melting front reaches the right wall and solid starts to shrink along the right wall due to subversion of convection current. Clockwise convection current is dominated through liquid PCM as shown by velocity streamlines but a secondary convection current is being formed along the shrinking solid due to higher temperature gradient between solid-liquid interface and the PV wall.

Thus, the strength of convection current decreases during solid shrinking regime and slower melting rates are observed. Since convection is more dominated in the top region of the enclosure, hence modification of PCM enclosure is desirable so that higher volume of PCM is available for quasi-steady melting regime in top region of enclosure.

Figure 4.2(b, c, and d) represents the process of melting of PCM in type – B_1 , B_2 , and B_3 (extended rectangular enclosure with extension $H_e = 20\%, 30\%, \text{ and } 40\%$ respectively). Melting morphology in extended enclosure resembles rectangular enclosure for conduction regime, however, different melting front propagation field is obtained for other regimes. In mixed regime of melting, liquid PCM starts to penetrate in extended part of enclosure, hence the erosion is observed in the top part of enclosure. Liquid PCM is now free to move in both the directions as fluid is not restricted by top wall at this stage of melting. With development of convection current in enclosure, solid-liquid interface swell like a balloon in the extended cavity and heat is being extracted away from PV panel to extended part. Melting front approaches the right wall after 85 minutes from initial state which cause quasi-steady convection regime to increase, thus by delaying the quasi-steady regime, melting rate and performance of PV/PCM system is enhanced. In type – B_2 configuration with increase in extended height, the distance between

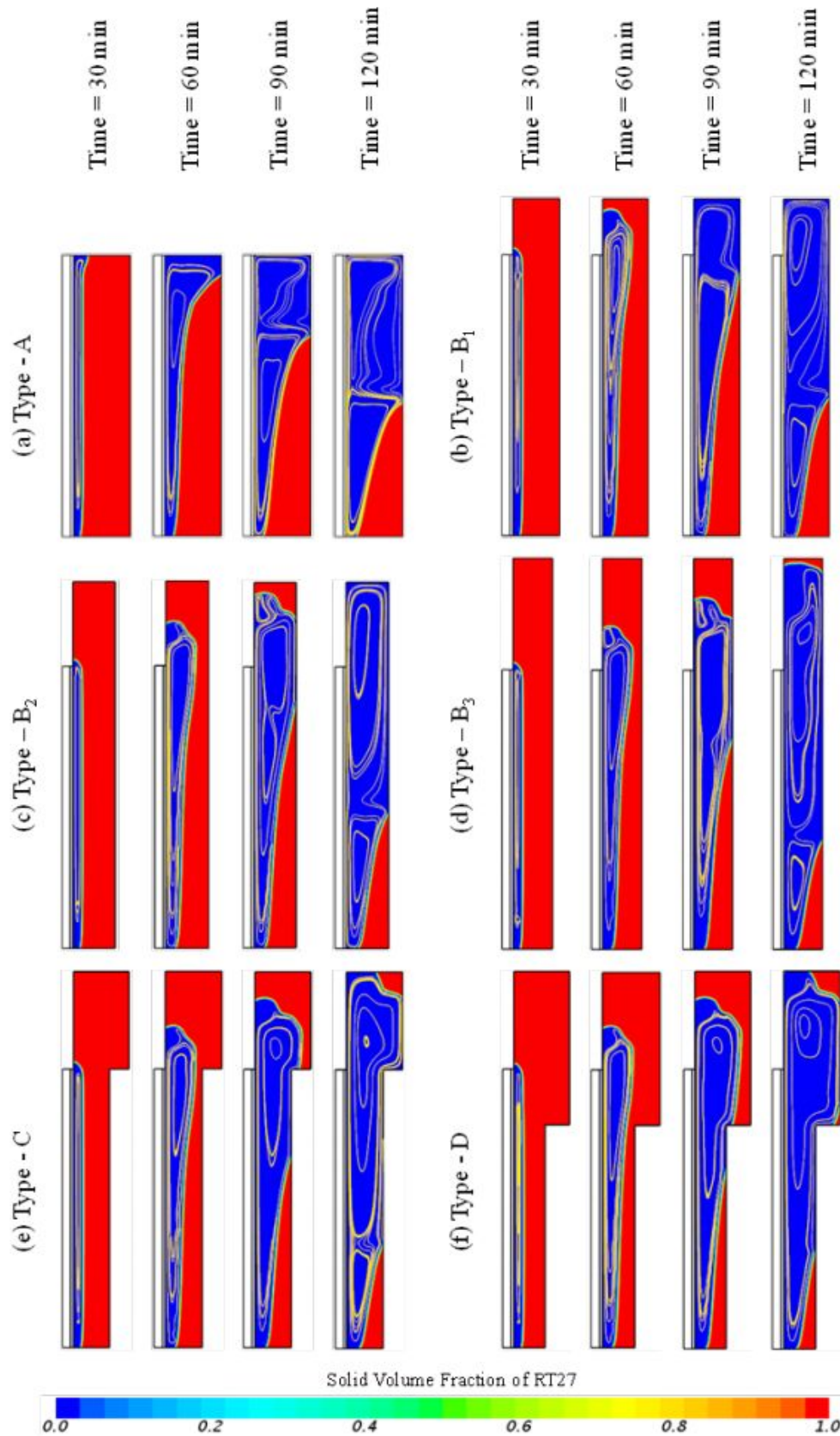


Figure 4.2: Transient history of solid fraction contours of the melting of PCM superimposed with velocity streamlines for all type of configurations.

right wall of enclosure and PV wall decreases to maintain the same volume and hence, melting front reaches the right wall in approx. 80 minutes but didn't reach the top wall. Besides earlier commencement of quasi-steady regime, melting rates are higher as solid PCM is available for convective melting. Here two different type of secondary vortices are formed, one of these kinds of vortices are formed in top region to melt out the remaining solid PCM and others are formed with shrinking solid along the right wall. Melting behavior is similar to solid shrinking regime as full PCM in the extended part is melted but higher melting rates are observed due to the convective melting in top part even after end of quasi-convection regime. Higher melting rate extract more heat away from PV panel and make them work more efficiently. In type – B_3 configuration, the extended height is further increased up to 40% of height of PV panel which make the PV wall and right wall of enclosure closer to each other. Due to this modification the duration of quasi-convection regime is further reduced to 75 minutes but higher melting rates are observed as solid PCM remains in top extended part. Since quasi-steady convection regime is decreasing with extension of height and whole PCM is still not melted in top extended part, further extension beyond 40% is not required and further design modifications are desirable to extend the duration of quasi-convection regime for more efficient PV/PCM system.

The extended part of the enclosure is further modified as rectangular overhead tank with an extension of $H_e = 35\%$ and width of overhead tank is equal to width of conventional rectangular enclosure for type – C configuration. Figure 4.2(e) shows the melting morphology of PV/PCM system with extended overhead heat storage enclosure. This design modification is done to give proper space to accommodate balloon-like swelling motion of solid-liquid interface. Melting behavior is similar to previous designs in conduction regime and mixed regime but quasi-steady convection regime extends up to 106 minutes as overhead tank provide ample space for melting front propagation and space between PV wall and right wall of enclosure also increases. Higher melting rates are observed due to delayed quasi-steady regime which make PV/PCM system work more efficiently. Thermo-electric performance of PV panel has been discussed in the later section.

In order to increase the duration of quasi-convection regime extended overhead heat storage enclosure is modified by providing depression from the top of PV panel. Depression of 20% of height of PV panel is provided in type – D configuration and its melting front propagation is shown in Figure 4.2(f). Quasi-steady convection regime extends up to 113 minutes because more PCM is available in top of PCM enclosure for convection dominated melting and depression provides the same distance between PV wall and right wall of enclosure as it was in conventional rectangular enclosure. Various study has been conducted for different values of depression such as 5%, 10%, 15%, 20 % and 25%. The enhancement in melting rate is negligible beyond 20% depression and hence, only 20% depression is discussed here. With modified overhead heat storage enclosure quasi-steady convection regime is enhanced by 102% which is reasonably significant.

4.3.2 Temperature distributions

Temperature distributions for PV/PCM system in all the different type of configurations is depicted in Figure 4.3(a). A bird's eye of the temperature contours shows how a non-uniform temperature distribution in conventional design becomes progressively uniform and reduced in magnitude from type-A to type-D design. As observed earlier, melting is driven by natural convection in upper part of the enclosure but quasi-steady convection regime ends very soon in conventional rectangular enclosure (type – A). With the end of quasi-convection regime, liquid PCM extracts heat in sensible form in top part of enclosure. This manifests into thermal stratification in PCM enclosure with a maximum temperature of 47.58°C and a temperature gradient of 20.58°C is observed between top and bottom side of enclosure. Performance of PV/PCM system decreases due to this thermal stratification. In type – B_1 extended rectangular enclosure, thermal stratification is reduced as heat is pumped to extended part of enclosure and thermal gradient reduced to 15.3°C with a maximum temperature of 42.3°C in the top of cavity. This temperature gradient is further reduced to 11.67°C, and 8.31°C with a maximum temperature of 38.67°C and 35.31°C in type – B_2 and type – B_3 respectively. In type – C configuration, extended part was given the shape of rectangular overhead tank of same width as conventional rectangular enclosure, hence melting front has more space to propagate and more heat can be extracted from the PV panel. Due to higher heat extraction rate, maximum temperature in the enclosure is reduced to 34.67°C and thermal gradient is reduced to 7.67°C. With further modification in extended overhead design, quasi-convection regime delays to 113 minutes. As a consequence, maximum temperature in the cavity reduced to 34.07°C with a diminished temperature gradient of 7.07°C with in the cavity. With reducing temperature gradient, thermal stratification with in the cavity is reduced and more uniform temperature distribution with in liquid PCM is observed. Low thermal stratification and uniform distribution of temperature allows PV panel to work at low and uniform operating temperature and hence, PV panel works more efficiently. PCM enclosure with natural convection domination and low thermal stratification absorbs more heat as latent heat and therefore, works as more efficient latent heat storage system.

Figure 4.3(b) depicts the variation of PV cell temperature with the height of PV panel along PV-PCM interface at 120 minutes. PV cell temperature rises to 56.78°C for PV panel configuration without any attached enclosure. This temperature is uniform through its height, hence power generation is also uniform but lower in this case. With the attachment of rectangular PCM enclosure, its temperature is reduced due to extraction of heat by PCM but temperature is not uniform along height of PV panel. The temperature of PV-PCM interface is 47.58°C at the top and 29.8°C at the bottom, and therefore PV panel is working more efficiently but power generation is not uniform along its height which can degrade the life of PV panel. With the use of extended enclosure, more heat is absorbed as latent heat that make PV panel to work at low range of temperature from top to bottom. With further modification in design of extended

part, positive effect of natural convection is visible on melting in enclosure and latent heat absorbing capacity of the system increases. This makes the system to work at lower and more uniform temperature. PV cell temperature at PV-PCM interface is reduced to 34.07°C at the top and 29.65°C at the bottom for type – D configuration of PV/PCM system. Temperature gradient at PV-PCM interface along the height of PV panel is reduced by 75.14% for type – D configuration as compared to conventional rectangular enclosure, which is quite a significant improvement. Uniformity of temperature is maintained in type – D configuration and at the same time it make PV cell to work more closely to its reference temperature which allow it to generate electricity more efficiently.

4.3.3 Heat transfer characteristics

4.3.3.1 Melting rate

Heat removal rate of PCM enclosure plays an important role in enhancement of thermo-electric performance of PV/PCM system. Heat removed by PCM at any instant of time can better be described by Eq. 3.3.:

The first term of right hand side of Eqn. 3.3 is sensible part of heat stored due to thermal gradient while second term is the latent heat stored due to melting. The contribution of latent heat is enormous compared to sensible heat in removing the heat away from PV panel and latent heat removed is directly proportional to liquid fraction (f_l). Hence, heat removal rate can be enhanced by augmenting the melting rate (rate of change of liquid fraction with time) of PCM with in the enclosure. Therefore, study of variation of liquid fraction with time is quite important.

Figure 4.4 shows the comparison of transient variation of liquid fraction among all different type of configurations. The transient variation of liquid fraction is linear in all type of configurations for most of the time. In type – A configuration, liquid fraction starts to deviate from linear trend with the end of quasi- steady convection regime at 56 minutes. With the end of quasi-regime, solid PCM starts to shrink along with the right wall 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 type – B_1 , B_2 , and B_3 configurations, conventional rectangular PCM enclosure is substituted by extended rectangular enclosure of extension $H_e = 20\%$, 30% , and 40% respectively. In type – A configuration, 75.17% of PCM gets melted which improves to 81.96% in type – B_1 configuration with an enhancement of 9.03%. Melting is further enhanced in type – B_2 and B_3 configuration of PCM enclosure hence 84.92% and 87.76% of PCM gets melted in type – B_2 and B_3 configuration with an enhancement of 12.97 % and 16.75% respectively.

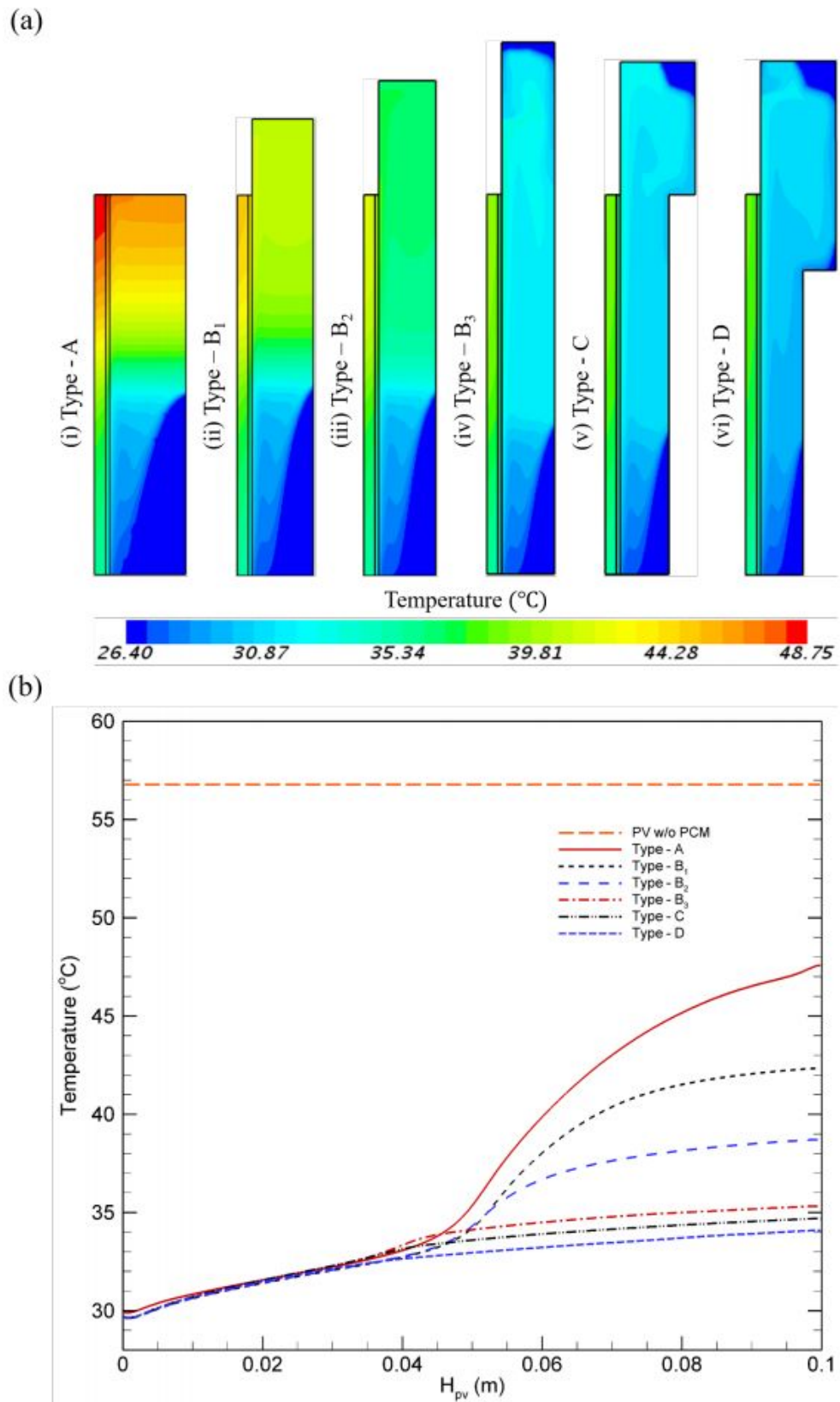


Figure 4.3: (a) Temperature contours for all type of configurations of PV/PCM system at 120 minutes, and (b) PV cell temperature variation with height of PV panel along PV-PCM interface at 120 minutes.

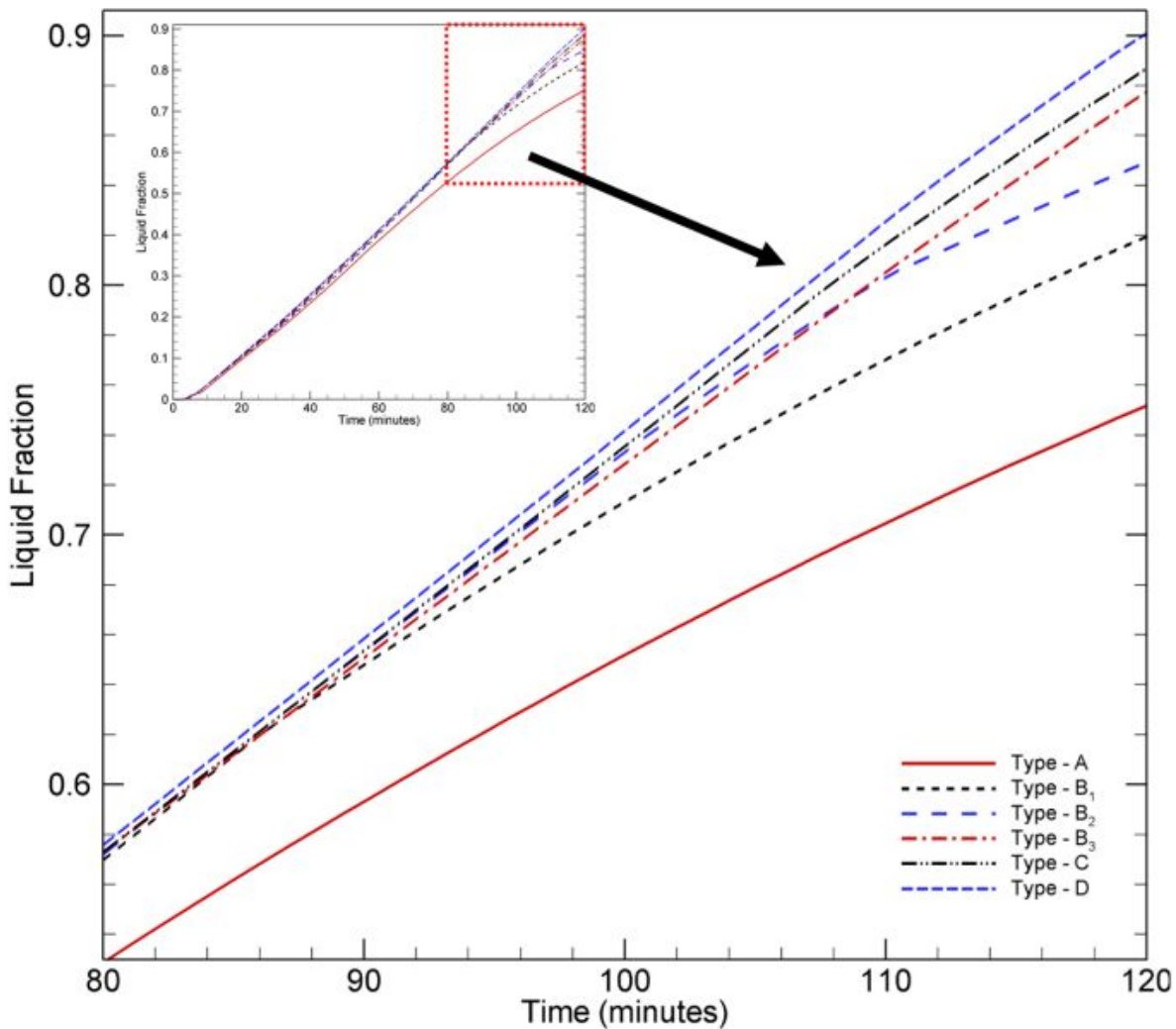


Figure 4.4: Expanded view of transient variation of liquid fraction shown in inset for all type of configurations. Full melting history has been shown in inset.

Melting front propagation morphology suggests that swelling balloon like structure of solid-liquid interface gets collapsed due to decreased distance between PV wall and right wall of enclosure with increase in extended height. However higher melting rates are observed due to availability of PCM in top region of enclosure and hence, melting rate can be further enhanced if extended part is designed as overhead rectangular cavity. Such overhead extended enclosure is provided in type - C enclosure with extension of $H_e = 35\%$ and with same width as of conventional rectangular enclosure. This overhead extended enclosure is further modified by giving depression from the top of PV panel to further increase the duration of quasi-convection regime by providing more space for melting front propagating balloon. Such overhead extended enclosure is provided in type - D enclosure with extension of $H_e = 35\%$, depression of $H_d = 20\%$, and with same width as of conventional rectangular enclosure. Depression beyond 20% shows negligible improvement in melting rates. In type - C configuration is enhanced to 88.68% with

an enhancement of 17.97% and liquid fraction varies linearly with time for approximately full duration of process due to increase in duration of quasi-convection regime. In type – D configuration, linearity trend of liquid fraction with time is also maintained for approx. full duration of process. Melting is enhanced to 90.10% with an enhancement of 19.86% as compared to conventional rectangular enclosure.

The above observations state that type – D configuration has maximum melting rate with more uniform temperature distribution. This makes PV cell to work more closely to its reference temperature compared to any other configuration of PV/PCM system. Hence, it is most essential and efficient configuration of PV/PCM system.

4.3.3.2 Nusselt number

With enhanced melting rate of PCM, investigation of heat transfer characteristics is also essential to understand the system behavior. Figure 4.5 compares the transient history of Nusselt number for all discussed PCM enclosures. Nusselt number (Nu) along characteristics length (H_{pv}) at any instant of time (t) is defined with the help of Eq. 2.15.

The height of PV-PCM interface (H_{pv}) is considered as characteristics length for all configurations because all heat interactions to PCM enclosure is through this interface. Initially melting process is governed by conduction mode of heat transfer which causes very thin fluid layer and hence, Nusselt number is high due to low thermal resistance. In conduction regime, fluid flow is restricted due to domination of viscous forces in liquid PCM. With increase in fluid layer, buoyant forces starts to prevail over viscous forces and convection current starts to develop at 15 minutes approx. in all configurations of PCM enclosures. In mixed regime of melting, natural convection starts to develop and conductive heat transfer starts to diminish due to which local minimum of Nusselt number arrived at approximately 30 minutes for all configurations. After this mixed regime, Nusselt number increases first and then becomes nearly invariant with time due to fully developed natural convection dominated melting in quasi-steady convection regime. The end of convection dominated regime gives origin to solid-shrinking regime when melting front extends to the right wall of enclosure. In this solid-shrinking regime Nusselt number decreases linearly with time. Hence, improved melting rates are observed with longer time span of quasi-steady regime.

In type – A configuration quasi-steady convection regime prevails up to 56 minutes only which is increased to 85 minutes in type – B_1 configuration by availing more PCM in convection dominated region and by designing the enclosure according to melting front propagation morphology. In type – B_2 and B_3 configuration span of quasi-steady convection regime decreases due to decreased distance between PV wall and right wall enclosure but Nusselt number shows a higher value in solid-shrinking regime due to availability of more PCM in upper part of the cavity. In type – C and D configuration, PCM enclosure is further modified according to melting

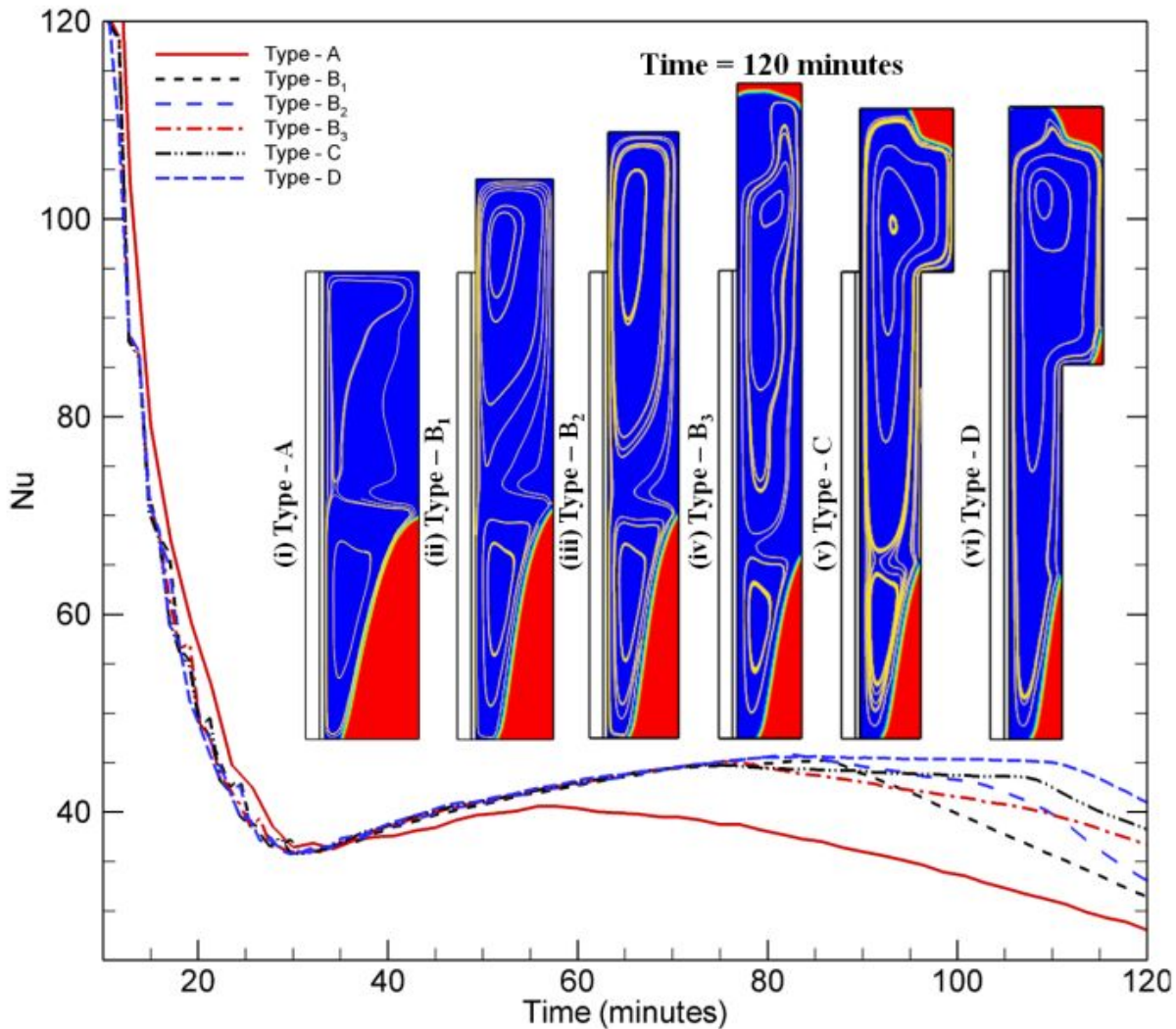


Figure 4.5: Comparison of transient history of Nusselt number among all type of configuration. Solid-liquid interface patterns for all configurations at 120 minutes are shown in inset.

front propagation and it is observed that quasi-convection regime extends up to 106 minutes and 113 minutes respectively. When compared with conventional rectangular enclosure, Nusselt number enhanced by 12.08%, 17.71%, and 30.65% in type – B_1 , B_2 , and B_3 configurations respectively, which is further enhanced by 36.25% and 45.91% in type – C and D configuration respectively at the end of simulation (120 minutes). Type – D configuration shows maximum enhancement in span of quasi-steady convection regime (102%) and Nusselt number (45.91%), hence it is best and requisite design among investigated enclosures.

4.3.3.3 Thermal energy storage performance

Thermal energy storage performance of PV/PCM system is analyzed by energy storage density (*ESD*) which is maximum possible derived thermal energy from the system. *ESD* for any thermal

system can be evaluated by using Eq. 2.16.

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.

Figure 4.6(a) depicts the distribution of *ESD* in different types of PCM encapsulation. Liquid PCM consists of both *LESD* and *SESD* while solid PCM consists only *SESD*. Also *LESD* for liquid PCM is constant and maximum as the value of liquid fraction (f_l) is 1 and it is variable for solid-liquid interface as f_l varies from 0 to 1. In type – A configuration, *ESD* distribution is not uniform due to thermal stratification and lower melting rates. *ESD* in the top region approaches to $210.46 \text{ MJ}/\text{m}^3$ as PCM absorbs maximum value *LESD* ($161.92 \text{ MJ}/\text{m}^3$) due to melting and *SESD* ($48.54 \text{ MJ}/\text{m}^3$) due to temperature rise. Overall average *ESD* gain ($148.64 \text{ MJ}/\text{m}^3$) is not sufficient due to lower melting rate as *LESD* is the major contributor comparatively to *SESD*. Localization of *ESD* is reduced in extended PCM enclosures of type – B_1 , B_2 , and B_3 and overall average *ESD* gain is increased to $158.66 \text{ MJ}/\text{m}^3$, $160.66 \text{ MJ}/\text{m}^3$, and $161.03 \text{ MJ}/\text{m}^3$ respectively due to more melting and low thermal stratification. This improvement is due to increased span of quasi-steady regime. However design of enclosure is further modified to type – C and D to avail more PCM for convection dominated region and it results in more uniform distribution of *ESD* and increased overall average *ESD* gains with increased melting rates. Overall average *ESD* gains has been further increased to $161.92 \text{ MJ}/\text{m}^3$ and $163.26 \text{ MJ}/\text{m}^3$ for type – C and D respectively. It can be clearly visualized that *SESD* decreases and *LESD* increases with modification of design due to increment of convection regime. Moreover, *ESD* ratio (ESD/ESD_A), where ESD_A denotes the energy storage density of type – A configuration) is plotted against time in Figure 4.6(b) to understand the thermal performance of different enclosures relative to the conventional rectangular (type – A) enclosure. Melting of PCM is not observed till 5 minutes in any type of enclosure and hence, all enclosures absorb only *SESD* and *ESD* ratio for them is approximately 1.

In conduction regime *ESD* ratio of extended enclosures (type – B_1 , B_2 , and B_3) and modified extended overhead enclosure (type – C and D) increases to 1.15. This increment is due to diffusion of heat from top of PV panel to extended part of enclosure. During this time the extended enclosure absorbs more heat as compare to rectangular enclosure. With the generation of convective currents and beginning of mixed regime, *ESD* ratio starts to decrease and reaches to 1.04 (approx.) and then become constant and stable. *ESD* ratio is constant until the quasi-steady regime for rectangular enclosure ends (56 minutes) and higher than type – A enclosure. Increment of approx. 4% in *ESD* is visible for all configurations. After 56 minutes, heat storing capacity of type – A enclosure decreases due to lower melting rates in solid-shrinking regime, however, quasi-steady still convection regime still persists. *ESD* ratio for extended enclosure and modified extended overhead enclosure begins to rise after 56 minutes and keep rising until PCM is available for convective melting in top region of enclosure. *ESD* increases by 10% for type – D configuration when compared to rectangular enclosure as *ESD* ratio reaches to 1.1 (at 120

minutes). It is clear that *ESD* of enclosure increases with increase in convective melting of PCM which is maximum in type – D configuration. Type-D design has best heat storage performance.

4.3.4 Performance characteristics

4.3.4.1 PV cell temperature

Figure 4.7 depicts the variation of average PV cell temperature with time and its deviation from reference operating temperature for all type of investigated configurations. PV cells are designed to work more efficiently at its reference temperature (25°C for c-Si PV cell). When PV panel (without any PCM enclosure attachment) is kept under a solar radiation (800 W/m^2), its temperature jumps up drastically to 56.78°C and exhibit a deviation of 31.78°C from reference temperature. This deviation is very large (127.12%) as compared to its reference temperature, hence PV panel doesn't operate up to its full potential and PV panel needed to be cooled down.

Rectangular PCM enclosure is attached on backplane of PV panel to cool it down by storing latent heat as well as sensible heat. Melting of PCM has a direct influence on PV cell temperature. In type-A configuration, average PV cell temperature rises to 35.1°C at the end of mixed regime of melting and decreases to 34.8°C with the development of convection current in the enclosure. PV cell temperature then remain constant till the end of quasi-steady convection regime (56 minutes) and start rising in solid-shrinking regime due to thermal stratification in the enclosure. Average PV cell temperature rises to 39.28°C at the end of 120 minutes. As a result of cooling by PCM, the temperature of PV cell reduced by 30.82% compared to PV panel without any attachment and PV cell observes a deviation of 14.28°C from reference temperature. This deviation from reference temperature is still 57.12% higher.

In type – B_1 , B_2 , and B_3 configuration, conventional enclosure is substituted by extended rectangular with extension of $H_e = 20\%$, 30% and 40% respectively. In type – B_1 configuration, the temperature of panel rises to 35.2°C at the end of mixed regime and reduces to 34.8°C with the start of convection dominated regime and then remain constant till the end of quasi-steady convection regime (85 minutes). Average PV cell temperature rises to 37.69°C at the end of 120 minutes which is 33.63% lesser as compared to PV system without any PCM attachment. The deviation from reference PV temperature is 12.69°C which is 50.76% far from reference temperature. In type – B_2 , and B_3 configuration, the trend of variation of PV cell temperature is similar to type – B_1 configuration but PV cell temperature reduced further due to availability of more PCM in upper part of enclosure. Average PV cell temperature is cooled down to 36.52°C and 35.44°C in type – B_1 , B_2 , and B_3 configuration respectively which is 35.69% and 37.59% lesser compared to PV system without PCM enclosure respectively. The deviation from reference temperature is reduced to 11.52°C and 10.44°C which is 46.08% and 41.76 % away from reference temperature respectively.

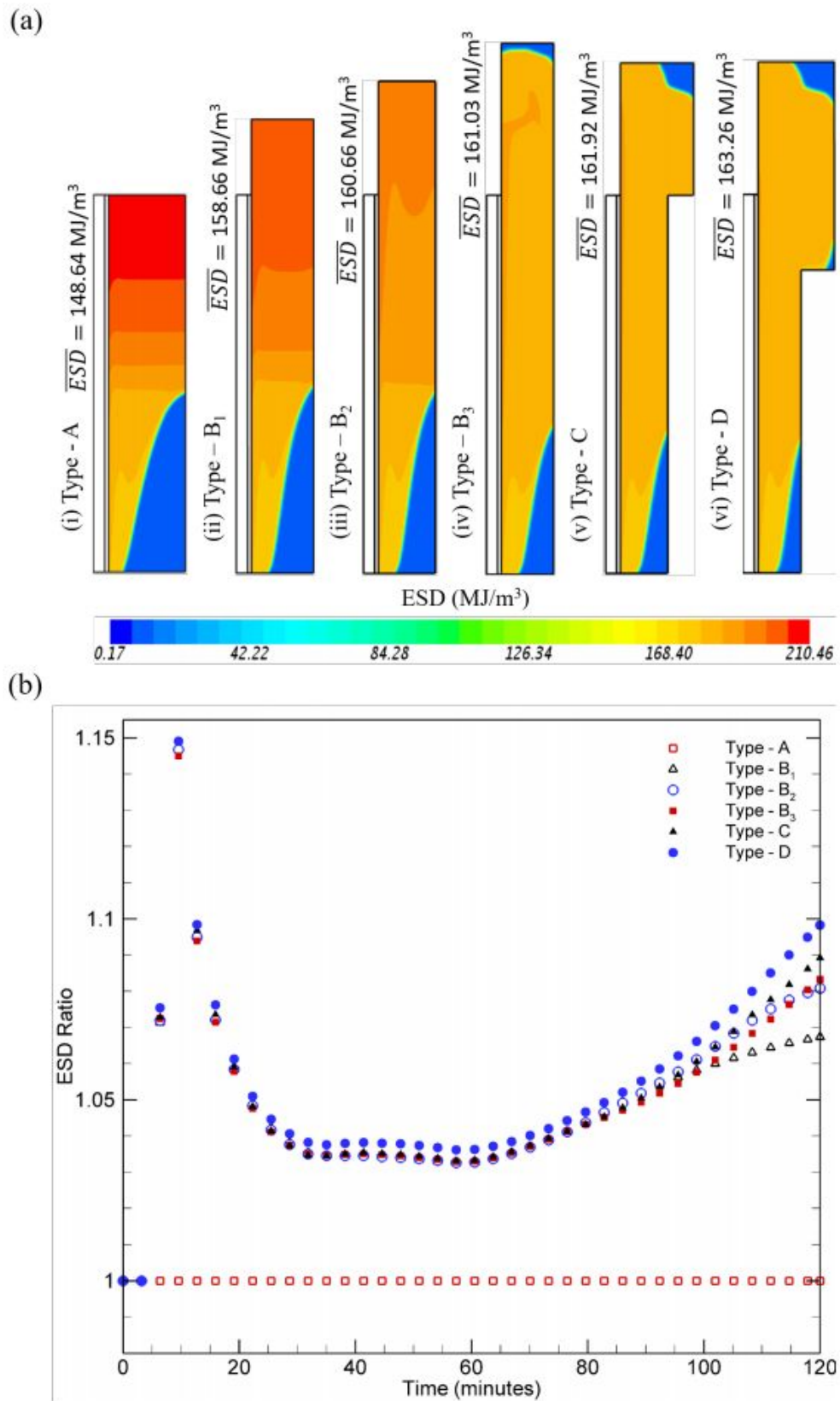


Figure 4.6: (a) Distribution of ESD in all configurations of PV/PCM systems at 120 minutes and (b) transient variation of ESD ratio for all configurations.

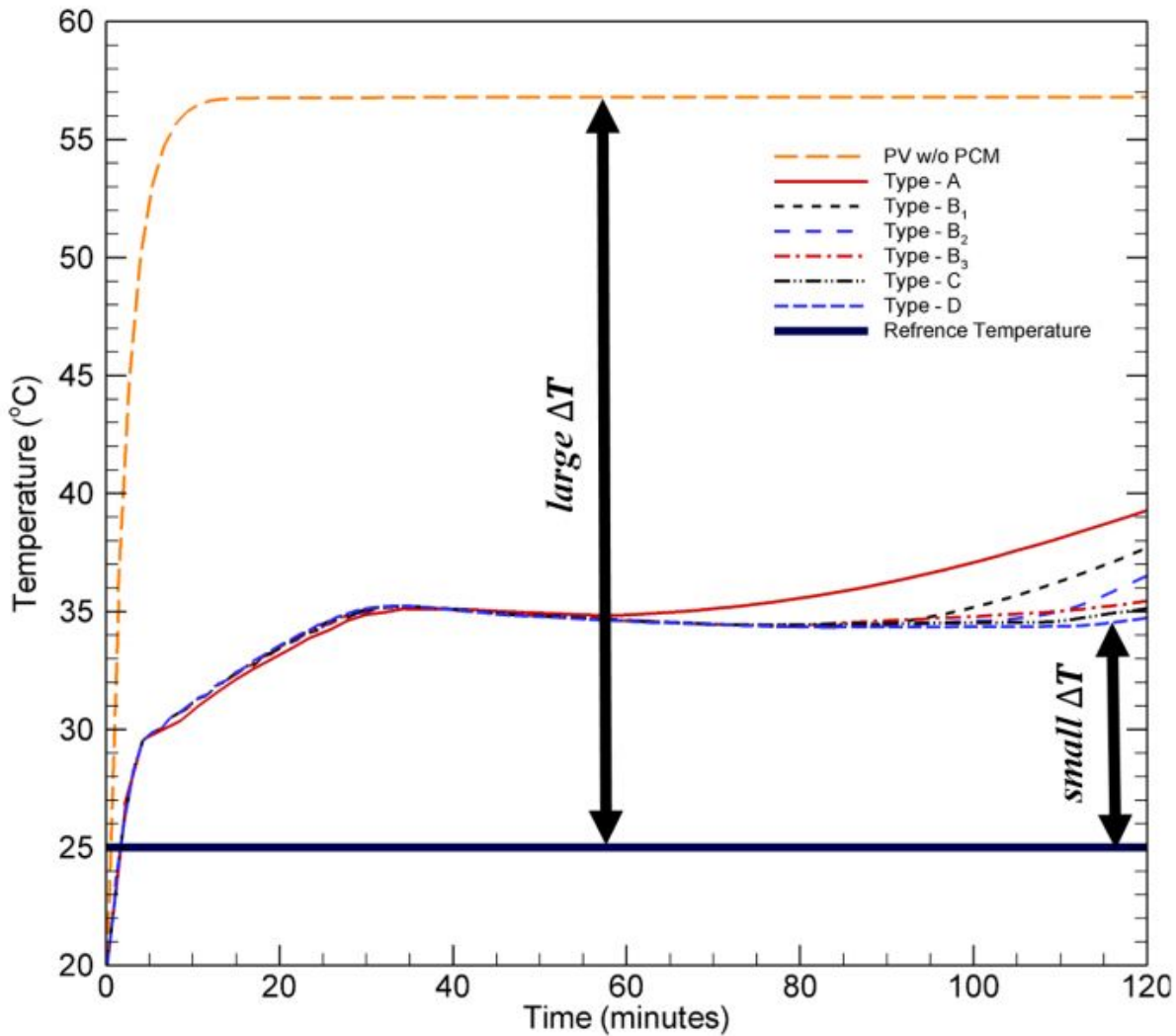


Figure 4.7: Transient variation of average PV cell temperature for all configurations of PV/PCM system.

Extended rectangular enclosure is further modified to overhead extended enclosure in type – C and D configuration to avail more PCM in convection dominated region. PV cell temperature dropped to 35.12°C and 34.72°C at the end of 120 minutes which is 38.15% and 38.85% lesser than PV system without any PCM attachment respectively. The deviation from reference temperature is reduced to 10.12°C and 9.72°C in type – C and D configuration respectively which is 40.48% and 38.88% far from reference temperature. The performance of PV system is enhanced by adding PCM enclosure and further enhanced by modifying the design of enclosures. The deviation from reference temperature is 127.12% in PV system without any attachment, which is reduced to 57.12% in type – A configuration and it further reduced to 38.88% in type – D configuration.

It is observed that type – D i.e. modified overhead extended PCM enclosure of PV/PCM system exhibits lowest PV panel temperature because of uniform temperature distribution with

in PCM enclosure.

4.3.4.2 Electrical conversion efficiency of PV cell

Electric conversion efficiency of PV panel depends on temperature as per Eqn. 2.14. Hence PV electrical conversion efficiency increases with decrease in PV cell temperature. When PV system is exposed to solar radiation, PV cell temperature increases to 56.78°C which results in decrease of electrical efficiency to 10.84%. PV cell works more efficiently at reference conditions (reference efficiency of 12.4% at a reference temperature of 25°C for c-Si PV cell). The transient variation of electrical conversion efficiency of PV panel for all configurations of PV/PCM system has been shown in Figure 4.8.

In type – A configuration electric conversion efficiency of PV panel drops to 11.91% at the end of mixed regime melting and approximately remain constant during full span of quasi-convection regime (up to 56 minutes). In solid-shrinking regime PV cell temperature increases due to thermal stratification in PCM enclosure. This results in decrease of efficiency of PV panel to 11.69% by the end of 120 minutes. In type – B_1 configuration, electric conversion efficiency drops to 11.91% by the end of mixed regime and then it is increased to 11.93% in quasi-steady convection regime due to developed convection current. The duration of quasi-convection regime has increased to 85 minutes. Electric convergence efficiency has been dropped to 11.77% at the end of 120 minutes which is 8.56% higher than normal PV system. The deviation of electric conversion efficiency from its reference value is 5.08%. In type – B_2 and B_3 configuration, duration of quasi-convection regime decreases with increase in extended height as distance between PV wall and right wall of enclosure decreases to maintain same volume of enclosure. However, the PCM enclosure still have cooling effect on PV panel due to availability of solid PCM in top region of enclosure which aid convective melting of PCM in solid-shrinking regime and avoid thermal stratification. Electrical conversion efficiency of PV/PCM system attains a value of 11.94% till the whole PCM in the top region gets melted and then decreases to 11.83% and 11.88% in type – B_2 and B_3 configuration respectively. Hence, an increment of 9.08% and 9.56% is observed as compared to PV system in type – B_2 and B_3 configuration respectively. The deviation from reference working conditions further decreased to 4.59% and 4.19% respectively for both the configurations of PV/PCM system.

In type – C and D configuration, as a consequence of increased quasi-convection regime and enhanced melting rates, electric conversion efficiency of PV/PCM system attains a value of 11.94% till the end of convection dominated regime. PV cell efficiency approaches to about 12% by the end of 120 minutes in both type – C and D configurations which shows an increment of about 10% compared to normal PV system. The deviation from reference value has been decreased to 4.09 % for type – C configuration and 3.87% for type – D configuration. It is observed

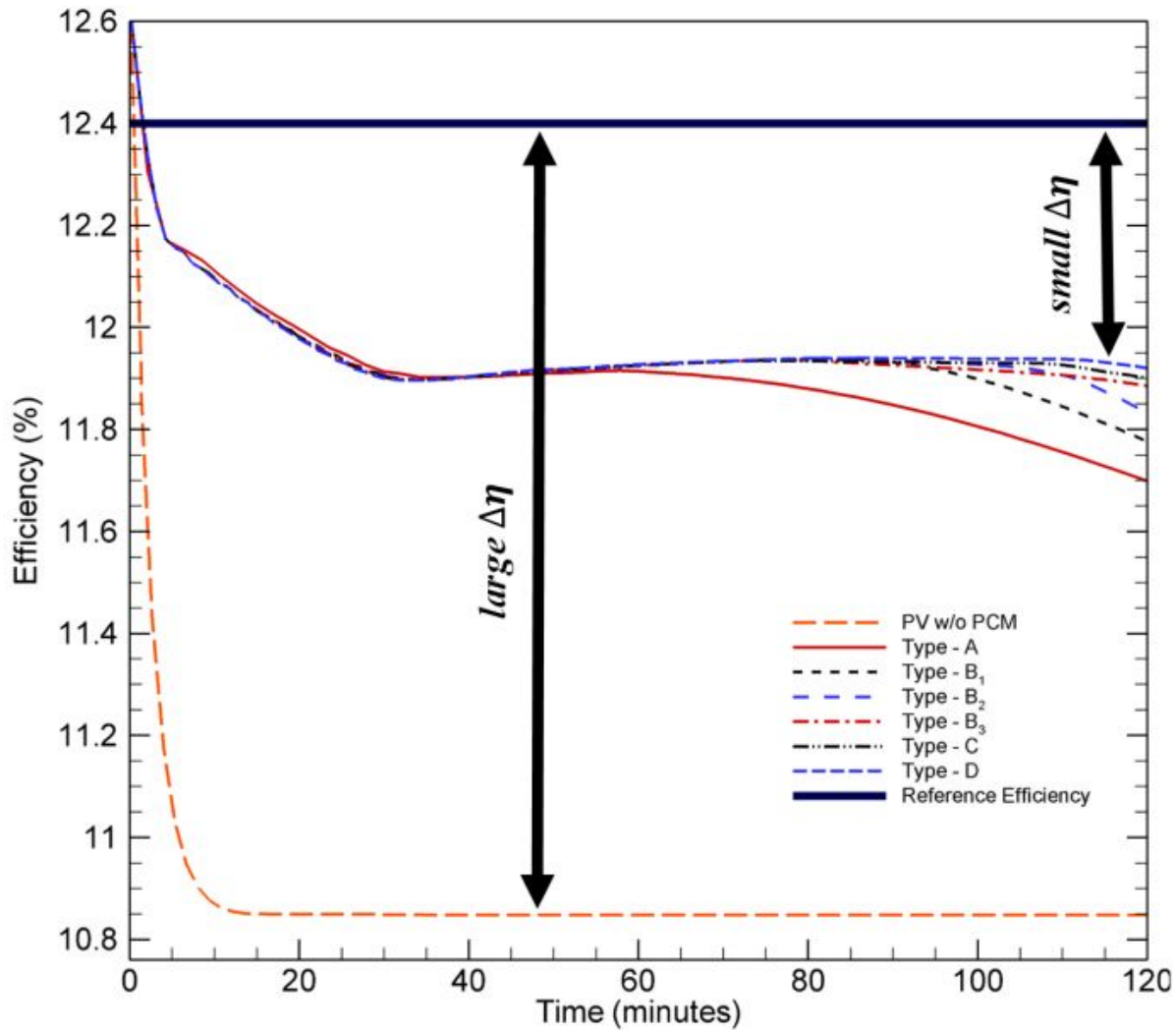


Figure 4.8: Transient Variation of electrical efficiency all configurations of PV/PCM system.

that electrical performance of type – D configuration of PV/PCM system is much better from all other design modification studied.

4.3.4.3 Total utilized radiation

Total utilized radiation ($I_{utilized}$) at any instant of time is defined as the sum of electric power output by PV panel and total heat stored by PCM enclosure. Hence $I_{utilized}$ at any instant of time can be calculated by the following relation:

$$I_{utilized} = \eta_{pv} * I_{solar} * \alpha_{pv} * \tau_{glass} + \frac{Q_{stored}}{(A_{pv} * t)} \quad (4.1)$$

In Eq. 4.1, first term on right hand side is electric power output per unit area which is product of electric efficiency and incident solar radiation while the second term is total heat stored per

unit incident area of PV panel. Further unutilized radiation ($I_{unutilized}$) can be calculated by subtracting the utilized radiation ($I_{utilized}$) from incident solar radiation as shown in Eq.4.2:

$$I_{unutilized} = I_{solar} - I_{utilized} \quad (4.2)$$

Overall performance of the system can better be visualized by plotting total utilized radiation against time for all configuration of PV system and PV/PCM systems as shown in Figure 4.9. For PV system, the total utilized radiation is in form of electric power output only while for PV/PCM system it consists both electric power output and thermal heat stored in PCM enclosure. PV system loses most of the incoming radiation in the form of waste heat and electric power output also decreases due to increased temperature of PV panel. Incorporating rectangular PCM enclosure (type – A configuration) on the rear side of PV panel not only decrease PV cell temperature but also absorb heat in PCM enclosure. Hence, increase electric power output and thermal heat storage enhances the performance of PV/PCM system. In type – B_1 , B_2 , and B_3 configuration of PV/PCM system, convectional rectangular enclosure is redesigned by extended rectangular enclosure of extension $H_e = 20\%$, 30% , and 40% respectively. Hence these configuration shows increased utilized radiation even during the beginning of conduction regime of melting as compared to type – A configuration due to diffusion of more heat in the extended part from top end of PV panel. In subsequent regimes, extended enclosure shows increased melting rate, and hence more heat is stored in PCM enclosure and PV panel exhibit increased electric power output due to reduced PV cell temperature. In type – C configuration, extended part of enclosure is modified like an overhead structure of same width as of conventional rectangular enclosure and extension of $H_e = 35\%$. It shows higher melting rate due to enhanced quasi-convection regime and absorb more heat with lower PV cell temperature. Hence, more electric output and thermal heat storage makes it to utilize more radiation. In type – D configuration, overhead shape of extended part is further modified by giving depression of $H_d = 20\%$ from top of PV panel which enhances quasi-steady convection regime and avail more PCM for convection dominated melting. It causes PV cell temperature to decrease further and more electric power output is generated. PV system utilizes only 86.43 W/m^2 of radiation which reduces to 74.20 W/m^2 as result of rise of temperature of PV cell at the end of 120 minutes. PV system only utilize 10.84% of incoming radiation while the remaining is wasted. In all PV/PCM systems, utilize radiation increases with time and then become constant till the availability of solid PCM in convection dominated region and then starts to decrease linearly due to decreased melting rates in solid-shrinking regime.

Type – A configuration shows utilized radiation of 492.90 W/m^2 which is 61.61% of incoming radiation at the end of 120 minutes. In type – B_1 , B_2 , and B_3 configuration of PV/PCM system, utilization radiation at the end of 120 minutes is 521.28 W/m^2 , 527.21 W/m^2 , and 528.59 W/m^2 respectively which is 65.16% , 65.90% , and 66.07% of incoming radiation respectively. Modification of enclosure to type – C and D has increased the utilized radiation to 531.16 W/m^2 and

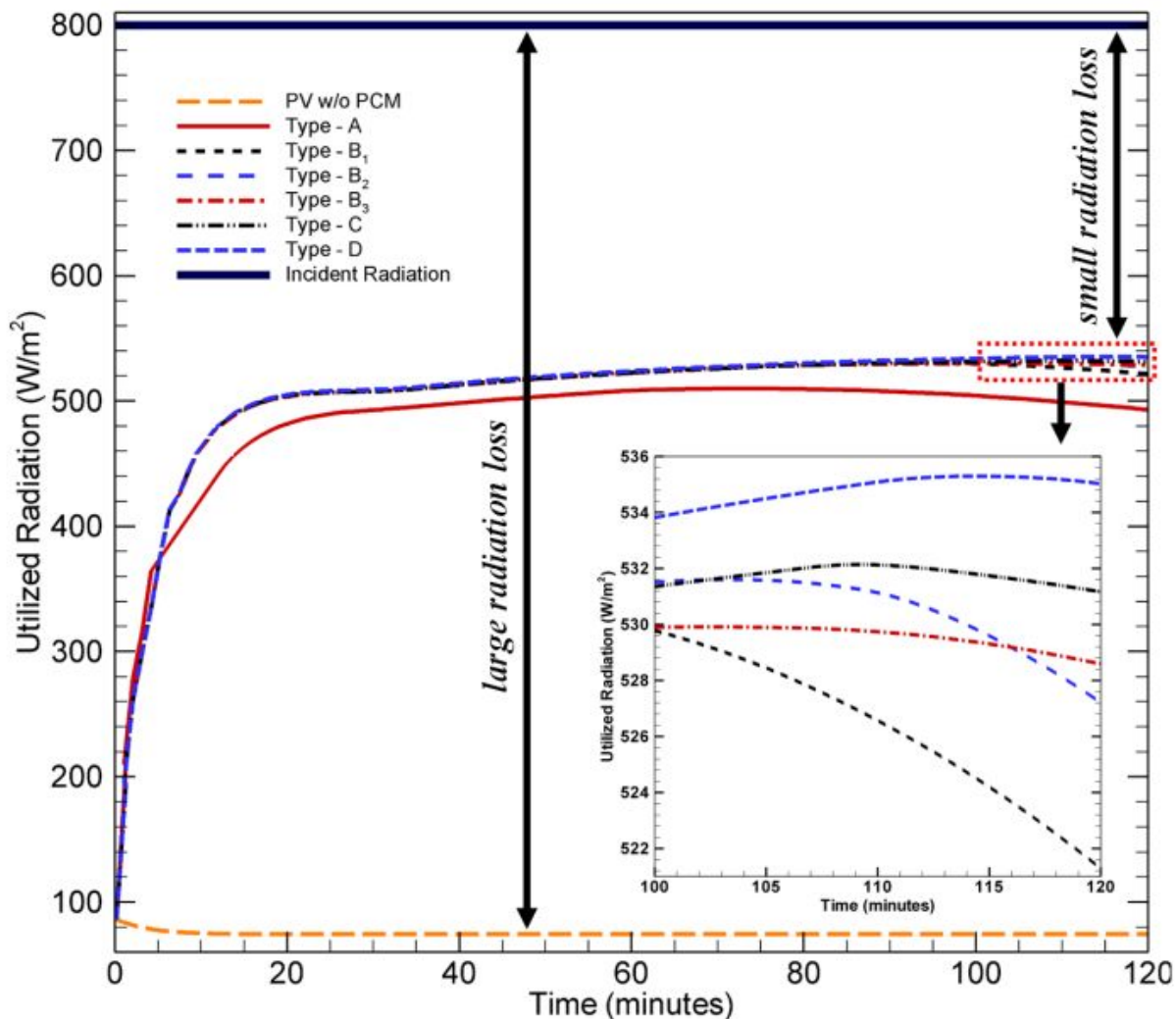


Figure 4.9: Variation of utilized radiation with time. (Expanded view for specific time period is shown in inset).

535.28 W/m^2 respectively which is 66.39% and 66.91% of total incident radiation respectively. The utilized radiation of type – D configuration is 7.21 times of PV system and 1.086 times of type – A configuration which is a significant improvement in performance of system. To further understand the performance enhancement in PV/PCM system, the ratio of utilized radiation to unutilized radiation (convective and radiative loss) is plotted against time as shown in Figure 4.10.

With increase in utilized radiation, the unutilized radiation decreases and hence, the ratio $I_{gain} = I_{utilised}/I_{unutilised}$ increases as total energy input is constant to the system. PV system exhibit a very low value of I_{gain} ($= 0.121$) which indicates that most of radiation is wasted to surroundings. In PV/PCM system, utilized radiation increase with increased melting rates and unutilized radiation decreases therefore the value of I_{gain} shows a substantial gain for modified enclosures as compare to conventional rectangular enclosure. In later stages of melting the gain

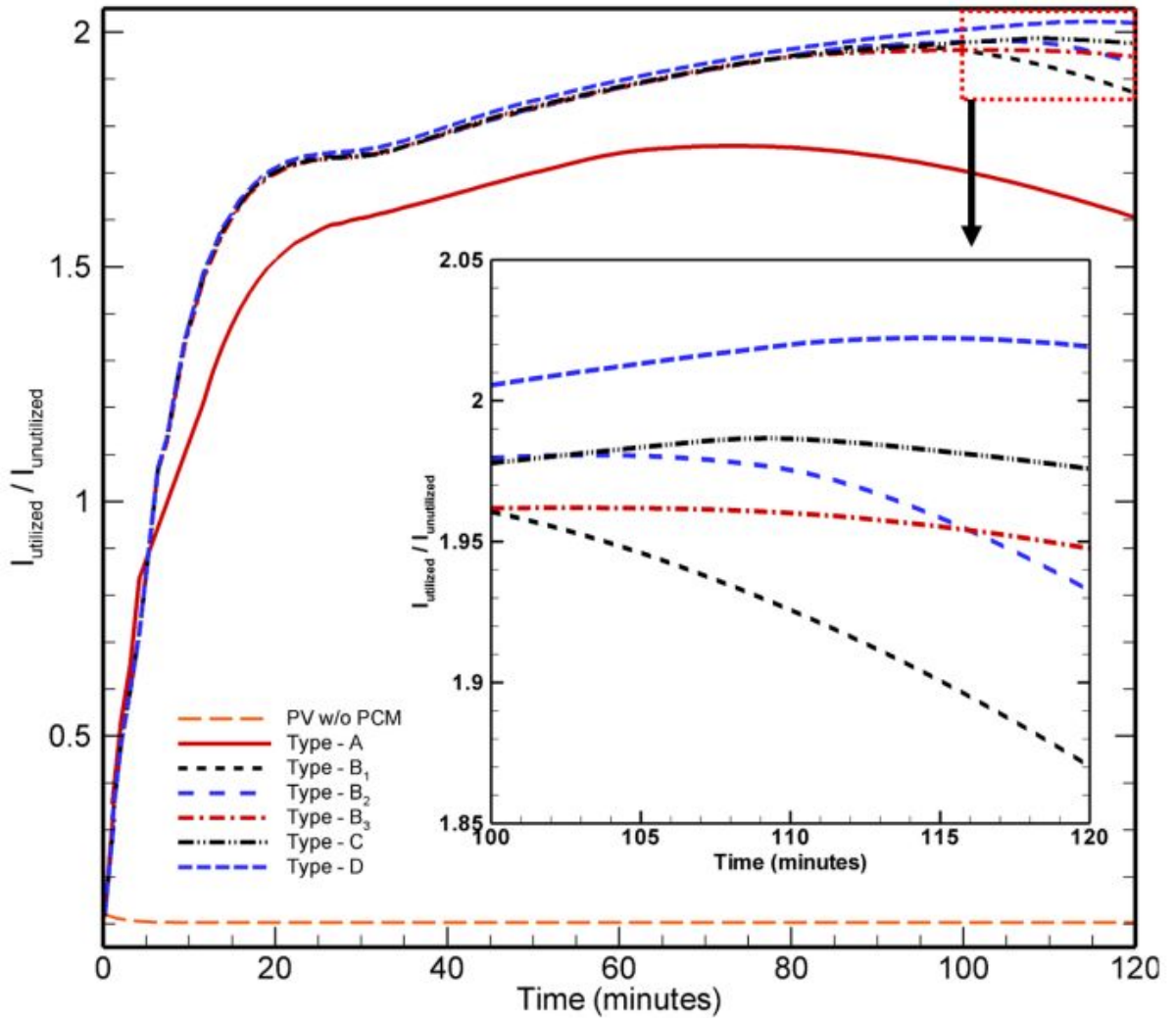


Figure 4.10: Variation of ratio of utilized radiation to unutilized radiation with time. (Expanded view for specific time period is shown in inset.)

in the value of I_{gain} is clearly visible in type - D configuration as compare to other modified PV/PCM systems. Type - A configuration of PV/PCM system shows that $I_{gain} = 1.605$ which is an indication of enhanced system performance. However, I_{gain} increased to 1.870, 1.932, and 1.947 in type - B₁, B₂, and B₃ configuration of PV/PCM system respectively at the end of 120 minutes. Further modification of design to type - C and D increased the I_{gain} ratio to 1.976 and 2.019 respectively. Design modification of enclosure has enhanced the performance of the system substantially. The ratio I_{gain} of type - D configuration is 16.69 times the PV system and 1.26 times of type - A configuration which shows better waste heat management with improved performance of PV/PCM system.

4.4 Conclusions

In this chapter, electric performance enhancement and waste heat management techniques of a PV panel with the use of PCM enclosure are proposed using an experimentally verified numerical model. Melting front morphology, electric conversion efficiency, and total utilized radiation have been reported in detail. Conventional rectangular PCM enclosure (type – A) was strategically designed to an overhead extended rectangular enclosure to avail more PCM for convection dominated melting keeping the same volume of PCM for all configurations. Extended enclosure are designated as type – B_1 , B_2 , and B_3 for an extension of $H_e = 20\%$, 30% , and 40% respectively. Overhead extended enclosures are designated as type – C and D with an extension of $H_e = 35\%$ of same width as of type – A configuration. In type – D enclosure, depression height $H_d = 20\%$ was also provided. Extended height $H_e = 35\%$ and depression height $H_d = 20\%$ are the optimized heights after many design iterations. Following are some valuable findings:

1. Maximum enhancement in melting ($\sim 20\%$) is observed in type – D configuration due to enhanced quasi-steady convection regime (102%) and Nusselt number ($\sim 46\%$) compared to conventional type – A configuration of PV/PCM system. As a result energy storage density is enhanced by approximately 10% compared to conventional rectangular enclosure.
2. Enhanced melting rate causes more uniform temperature distribution in the enclosure which allow PV panel to work at lower temperature and close to its reference temperature. In type – D configuration, PV panel work closest to reference temperature compared to all other configuration. Average PV cell temperature drops to about 34.72°C in type – D configuration which is about 39% closer to reference temperature. PV cell temperature is about 57% and 127% more than reference temperature in type – A configuration of PV/PCM system and PV system without any PCM enclosure respectively.
3. Electric conversion efficiency increased to about 12% in type – D configuration due to reduced PV cell temperature. The deviation from reference efficiency is just 3.8% in type – D configuration which was 6% in type – A configuration and about 13% in PV system without any PCM enclosure.
4. PV/PCM system in type – D configuration utilize about 67% of incoming radiation which was 61% in type – A configuration and 10.84% in PV system without any enclosure. Type – D configuration utilize 7.21 times incoming radiation than PV system without any enclosure. Type – D configuration exhibit best waste heat management among all investigated configuration. The ratio $I_{utilised}/I_{unutilised}$ for type – D configuration is 16.69 times than PV system without any enclosure and 1.26 times than type – A configuration of PV/PCM system. Type – D configuration of PV/PCM system is recommended due to better thermo-

electric performance as well as waste heat management compared to all other configuration.

This study would be useful to the research community in developing energy efficient PV/PCM systems with overhead type PCM encapsulation designs. The daily ever-growing energy consumption of the world can be lowered by storing passive energy in more efficient PCM encapsulations.