

CHAPTER 1

Introduction

As global energy demand is expanding at a faster rate with growth in population, phase change material (PCM) integrated photovoltaics (PV/PCM) systems could be a viable option to meet this ever-rising energy demand if suitable design innovations of PCM encapsulation are conceptualized and investigated to improve their thermo-electric performance. In this thesis, a series of new design concepts of PCM encapsulations for PV/PCM systems and bifacial PV/PCM systems working on principle of enlarged convection dominated melting regime are proposed and investigated by developing experimentally validated computational fluid dynamics (CFD) models. Various geometric and governing parameters are optimized to get improved electric conversion performance as well as heat storage performance. The first section presents the overview of advancement in photovoltaic (PV) technology and its future prospects as a potential source of clean and green energy to meet global energy demands. The second section describes conventional design of PV/PCM systems and its limitations. Further, discussions are focused on principles of melting process inside conventional rectangular PCM enclosure and their effect on performance of PV/PCM systems. The third section presents a brief introduction to novel efficient PCM encapsulation designs for PV/PCM systems and bifacial PV/PCM systems. The fourth section covers the objective of thesis. The last section , shows the layout of thesis. It is to be mentioned here that since each chapter (from chapter 2 onwards) of the thesis already include a comprehensive literature review, I have included only the essential information to lay the foundation of the thesis.

1.1 PV/PCM systems: Background

Global energy demand of world expands with growth in population which cause the excessive load on conventional energy resources such as fossil fuels [1]. The conventional energy sources are limited in quantity and cause various environmental problems such as air pollution, global warming, and sudden climate changes [2]. Therefore, emphasis must be given on increases in use of unconventional energy resources such as solar energy, wind energy, geothermal energy and other resources to meet future rising energy demands and to reduces these growing environmental problems.

Photovoltaic (PV) technology is a good option of clean and green energy. PV panels convert solar energy directly into electrical energy [3, 4]. However, most of incoming radiation is wasted in form of heat that increases the operating temperature of PV panel and degrades its electric conversion performance [5, 6]. The electric conversion efficiency of PV panel is inversely proportional to its operating temperature [7, 8]. Hence, electric performance of PV panel can be restored to its original state by reducing its operating temperature with the use of any appropriate cooling technique. The application of cooling technique not only enhances the electric performance of PV panel but also enhances the utilization of incoming radiation by absorbing waste heat. Cooling techniques are basically categorized as active cooling technique and passive cooling technique on the basis of type of thermal collector used to remove excessive heat. In active cooling technique, a thermal collector is attached beneath the PV panel to remove waste heat in which a heat transfer fluid is circulated by means of some external work [9, 10]. Addition of thermal collector to PV panel makes it a PV thermal (PV/T) system as shown in Figure 1.1(a). Major drawback of PV/T system is consumption of external power that will reduce the net power output of the system. The consumption of external power is low in air cooled PV/T system due to low density of air however heat extraction rate is also low due to small value of specific heat. Water cooled PV/T system posses high heat extraction rate but on the verge of high external power consumption. In passive cooling techniques, waste heat is removed and stored for later use by using various heat absorbing materials such as phase change material (PCM), molten salts, and various other materials without any consumption of external work. Molten salts, composites, and many other materials such as air, water, nano-fluid, and others absorb heat mostly in the sensible form, allowing PV panel temperatures to grow even while heat is being stored, and sensible heat gain is also quite modest in comparison to latent heat gain. For example, during the melting-solidification phase change process at a constant temperature of 0°C, water has a latent heat of 335 kJ/kg, but the sensible heat gain is 4.18 kJ/kg only. PCM is preferred due to its high value of latent heat of fusion and constant phase transition temperature. The integration of PCM to PV panel makes it PV/PCM system as shown in Figure 1.1(b). The adoption of PV/PCM systems not only allows PV panels to operate at relatively low and consistent temperatures, but also absorbs heat throughout the night. [11, 12]. PV technology is third largest renewable en-

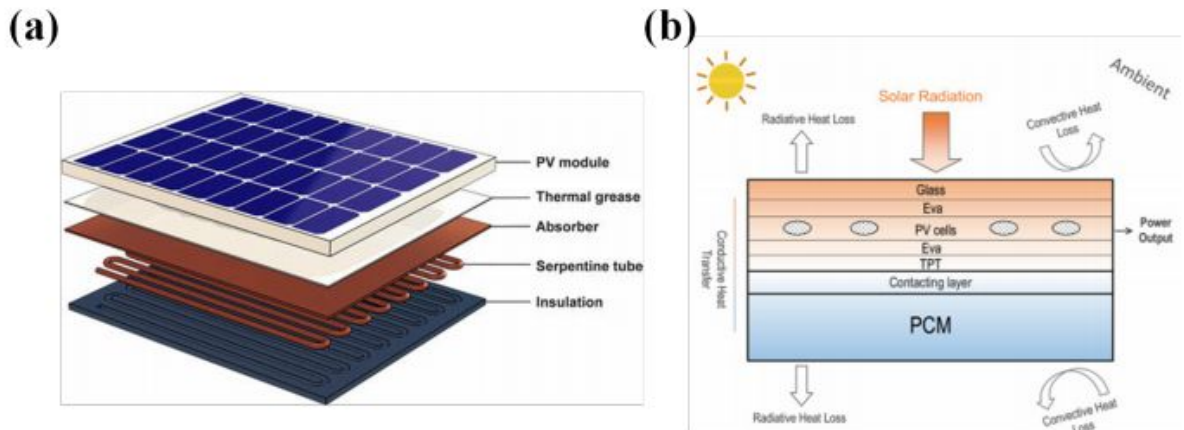


Figure 1.1: (a) Conventional PV/T system , (b) conventional PV/PCM system .

ergy source after hydro and wind energy in terms of global capacity and expected to grow by 700-880 GW during the period of 2019-2024 by International Energy Agency [13]. Government of India also have a target of 100 GW solar PV capacity and 40 GW for roof top PV capacity by 2022 [14]. Therefore, PV/PCM systems can be considered as an attractive choice to enhance the performance of PV panel and ability to utilize incoming solar radiation simultaneously.

1.2 Prior studies on PV/PCM systems

This section includes a literature review that covers prior investigations of various configurations of PV/PCM systems.

1.2.1 Conventional PV/PCM systems

In a conventional PV/PCM system, a rectangular PCM enclosure is included on the back side of the PV panel to absorb waste heat in latent form at a constant phase transition temperature. Thus PV panel works a relatively lower and invariable temperature for a certain period of time. Krauter et al., [15] used PCM fill bags on the backside of PV panels to achieve consistent temperature distribution and a 7°C decrease in PV panel temperature. Further, Mahamudul at al, [16] also reported a drop of 35°C in PV panel temperature in a numerical study of PV/PCM system compared to PV system. A enhancement of 3% in PV cell efficiency with a drop of 2.7 in average surface temperature was observed by Hachem et al., [17] during an experimental study. Kant et al., [18] also explores the effect of convective heat transfer in melting of PCM and reported 6°C more temperature reduction in case of convective melting. The studies mentioned above, as well as many others [19–21], indicated that using various types of PCMs improved the performance of PV panels. They did, however, mention the drawback of PCM's poorer heat conductivity, which leads to slower melting rates even when convective melting is addressed. The

slower melting rates leads to degraded performance of PV/PCM system after a certain interval of time. Therefore various techniques are used by fellow researchers to address this problem.

1.2.2 PV/PCM system with finned PCM enclosures

Many researchers preferred the usage of fins inside PCM enclosure to enhance the melting rates and performance of PV/PCM systems [22, 23]. Fins increase the conduction rate due to insertion inside the PCM and creating different nucleation sites for melting of PCM. Huang et al. [24] investigated PV/PCM system with different fin spacing and obtained a maximum temperature drop of 36°C when fins are placed 33mm apart. Tan et al., [25] also examines the performance of PV/PCM system under different number of equispaced fins and stated that PV/PCM system with 12 fins exhibits best performance with a temperature reduction of 15°C and 5.39% enhancement in electric conversion efficiency. Further, Nehari et al., [26] investigated the effect of fin length on the performance of PV/PCM system and optimized the fin length to 25 mm for enhanced thermo-electric performance. Sharma et al., [27] employed microfins and optimized the number of fins, their shape and size for enhanced performance of the system. They reported the temperature drop of 10.7°C and increase of 5.35% in power out of PV panel with implication of 20 microfins of 1mm thickness, 5mm height and 0.5mm of fin spacing. The discussed literature clearly indicates that employment of fins increases the melting rate of PCM by increasing the heat conduction rate and heat transfer area. The increase in heat transfer area will also promote the convective heat transfer area in PCM enclosure. However, incorporation of fins will unnecessarily lead to use of extra material which will increase the cost of the system also make the system bulkier. Also the amount of PCM inside enclosure will decrease as fins will occupy some space that will lead to decrement in overall storing capacity of PCM. The incorporation of fin is one of the solutions to enhance the performance but further investigations are required to optimize the performance of the system.

1.2.3 PV/PCM system with composite PCM

Some researchers promote the usage of composite PCM to overcome the drawback of poor thermal conductivity. A composite PCM material was made by integrating a matrix of highly thermo-conductive material (such as graphite) and PCM. The problem of slower melting rate is reduced and higher thermo-electric performance is achieved with the use of composite PCM in PV/PCM systems. Klemm et al., [28] uses composite of RT25HC with 90% porous metallic fiber structures inside a conventional PV/PCM system and reported a temperature reduction of 20°C for 50mm thickness PCM enclosure. Maiti et al., [29] reported a temperature drop of 17°C and 20°C in PV panel for indoor (solar simulator) and outdoor experiments (natural sunlight) with metal wax composite PCM. Atkin and Farid [11] uses PCM infused with graphite and reported an

increment of 7.32% in performance of PV/PCM system compared to conventional PV/PCM system. Luo et al., [30] attached composite PCM cuboids on the back of PV panel and reported an enhancement of 7.28% in power output of PV panel. Hachem et al., [17] uses a combined PCM (composite of white petroleum jell, Cu, and graphite) and reported an enhancement of 5.8% in conversion efficiency compared to convectional PV system. Sharma et al., added 0.5% CuO in RT42 and observed a reduction of 12.5°C in PV panel temperature which augments the power output by 6.25%. The literature clearly indicated that the usage of composite PCM in a PV/PCM system would aid in the increase of the system's thermo-electric performance. However, the technique for creating composite PCM is more expensive and excessively lengthy, which encourages researchers to do further research in composite PCM or explore for alternative ways to improve the performance of PV/PCM systems.

1.2.4 Hybrid PVT/PCM systems

Hybrid PVT/PCM systems are a technology in which heat sinks are connected to PV/PCM systems so that waste heat stored in the PCM may be released concurrently and the PV panel can be cooled more effectively. Air, water, nano-fluid, or any other fluid is cycled through the PCM enclosure to extract stored heat simultaneously. Preet et al., [31] circulates water in copper tubes through finned PCM enclosure and obtained a temperature drop of 24°C at a mass flow rate of 0.023 kg/s. Further, Malvi et al., [32] also circulates water through copper tube inside PCM layer and reports an enhancement of 9% in power output. Zhou et al., [33] reports a decrement of 47.2°C in PV panel temperature and 32% increase in power output at a flow rate of 10 kg/s of water. Su et al., [34] performed a numerical study of air based PVT/PCM system and reported a temperature drop of 7.4°C in PV module temperature. Further, Sardarabadi et al., [35] uses nano-fluid (ZnO-water, 35-45nm, 0.2 wt%/0.0083kg/s) with PVTPCM system and obtain a temperature drop of 16°C in PV panel temperature with an enhancement of 8% in electric conversion efficiency. Hybrid PVT/PCM systems exhibit a profound enhancement in thermo-electric performance of PV/PCM systems. However, the system would consume extra power due to flow of the working fluid. Also this technique focussed on overall performance enhancement of PV/PCM system without optimizing the thermal storage performance of PCM enclosure as it doesn't focus on enhancement of melting of PCM.

1.3 Research gap

The literature emphasises the significance of improving the thermo-electric performance of PV/PCM systems. However, optimization of enhancement is accomplished by either improving the thermo-physical characteristics of PCM or by adding intrusions such as fins to facilitate heat transport in the PCM. The enhancement in thermo-electric performance is also achieved

by increasing heat extraction rate using hybrid PV/T systems. A few researchers focus on characterising encapsulation designs based on PCM melting behaviour; nonetheless, the debate on augmentation of convective melting occurs, but only with the introduction of fins or by increasing the thermo-physical characteristics of PCM. Ezan et al [36] describe the importance of natural convection dominated melting and reports more than 50% augmentation in melting compared to conduction dominated melting. The promotion of convection dominated melting will also aid the thermo-electric performance of the system. For characterisation of encapsulation design according to melting front morphology, one must understand the melting behaviour of PCM, when PV/PCM system is exposed to solar radiation.

The orientation of PV panel must be such that solar radiation falls normally on PV panel for most of the time. At 0° latitude, the orientation of PV/PCM system is parallel to roof, hence melting is totally governed by conduction as buoyant forces are absent in top wall heating of PCM. However, at other places apart from 0° latitude, PV/PCM system is inclined to horizontal by some angle to get normal radiation. Therefore, melting behaviour of PCM will also be governed by convective heat transfer as buoyancy comes into play due to effect of gravity [37]. Since performance of PV panel is controlled by characterization of melting of PCM, therefore emphasis must be given on the melting procedure inside a rectangular enclosure under the affect of the gravity. The characterization of melting inside a vertical rectangular enclosure for side wall heating is better explained by Jany and Bejan [38] as shown in Figure 1.2. Melting is divided into four different regimes namely: 1. Conduction regime, 2. Mixed (conduction + convection) regime, 3. Quasi-steady convection regime, and 4. Solid-shrinking regime depending on the mode of heat transfer that guides the propagation of melting front. Initially melting is governed by conductive heat transfer only and melting front is parallel to the wall due to domination of viscous forces. However, buoyant forces start to overcome viscous forces with progression of time and give rise to mixed regime of melting where conduction is dominant in lower part and convection in upper part of enclosure. The melting front doesn't remain parallel to wall and starts eroding solid PCM in the top part of the region. Soon, buoyant forces dominates in full liquid region of PCM and convective heat transfer governs the melting process. This quasi-steady convection regime of melting ends as melting front reaches the opposite wall and give rise to solid-shrinking regime. Solid PCM shrinks along the wall and melting rate become slower in this regime due to thermal stratification in liquid PCM. Therefore, performance of PV/PCM system will deteriorate in this last regime of melting and overall performance of the system will depend on the span of quasi-steady convection regime and solid-shrinking regime. Longer quasi-steady convection regime and shorter solid-shrinking regime is desired for better thermo-electric performance of PV/PCM system [39].

Issues related to conventional PV/PCM systems:

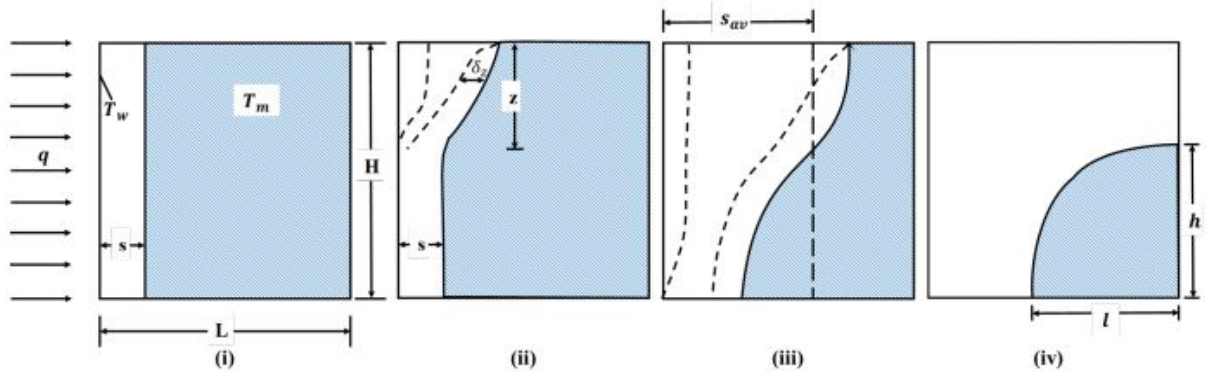


Figure 1.2: Melting process inside a rectangular PCM enclosure showing all four different regimes of melting: (i) conduction regime, (ii) mixed regime, (iii) quasi-steady convection regime, and (iv) solid-shrinking regime.

- Unsymmetrical melting interface causing non-uniform temperature distribution along PV panel,
- Elevation of PV panel temperature in top region due to more thermal stratification in liquid PCM,
- Decrement in electric conversion performance (low conversion efficiency) in later stages,
- Slow melting rates in later stages of melting,
- Depreciated heat storage capacity and,
- Requirement of more PCM to get the desired effect.

It can be concluded that under the influence of gravity, PCM shows unsymmetrical melting patterns (accelerated melting at the top part of the enclosure). As a result, modelling the design of the PCM enclosure based on melting front morphology would improve the thermo-electric performance of the PV/PCM system without the usage of any extra technology such as fins, composite PCM, or hybrid PVT/PCM systems. Even if we improve the thermophysical characteristics of PCM, include fins, or create a hybrid PVT/PCM system using the suggested encapsulating designs, it will be an added benefit and aid in improving the thermo-electric performance of PV/PCM systems. The proposed PCM encapsulation designs are explored in the following portion of this chapter, and a more extensive explanation is offered in the thesis's other chapters.

1.4 Research methodology

The unsymmetrical melting behaviour of PCM inside conventional rectangular enclosure urges the need the detail analysis of melting morphology of PCM and its implications on performance

of PV/PCM systems. The analysis can be performed either experimental investigations or numerical investigations. PV/PCM systems will provide realistic results in experimental investigation, however, the experimental setup will prove costly for current investigation as tracking of melting front (high resolution cameras required) is involved here. Apart from that thermal imaging infra-red camera is required to see the temperature distribution in PV panel and PCM enclosure. Various other measurement devices such as thermo-couple, temperature indicator, and multimeter etc are required. Moreover, the making of unconventional designs of PCM encapsulations can be costly at testing phase or experimental phase of the study. The experimental set up will also face the problem of discrete ambient conditions that will also be a hinderance in comparative study. Error and uncertainty in measuring devices would be another factor that will affect the investigation. On the other hand, numerical investigation is cheaper than experimental study and also it promotes more feasibility to understand the physics and optimize the design of PCM enclosure according to melting front morphology. However, the computational model also has some limitation of mimicking real conditions and accuracy of method. The limitations can be minimised by validating the numerical model with some existing lab controlled research with proper grid independent and time independent study. The characterisation of melting involved study of evolving melting fronts, their propagation and behaviour under different conditions. In the present study, the design of PCM encapsulation is based on melting front morphology, therefore numerical investigation is chosen for convenience and more accurate predictions.

PV/PCM system is modelled as two dimensional computational model which consists of different regions like glass region, PV region and PCM region. Glass and PV region are modelled as solid region and only energy equation is solved for them under prescribed boundary condition. However, PCM region is multiphase region which changes phase from solid to liquid after reaching phase transition temperature. Only energy equation is solved for solid PCM where as all three conservation equations (continuity, momentum, and energy equation) are solved for liquid PCM by assuming it as newtonian and incompressible liquid with laminar flow. The effect of gravity is being taken care of by adding boussinesq equation in the momentum equation and mushy zone has been characterized by darcy term (see Eq.2.9). The conservation equations are discretized into algebraic equations using implicit stepping approach. The velocity-pressure flow field have been resolved using SIMPLER algorithm. Algebraic finite volume coefficients are computed by using power law scheme in ANSYS-FLUENT solver. All study is performed at an optimized grid size obtained after a number of grid optimization investigation. All these studies has been carried out with numerical validated experimental model. The findings of the research is analysed and suitable design implementations are suggested according to melting front morphology. The detailed solution methodology is explained in section 2.2.2 (solution method) of chapter 2. Same numerical model is adopted for modified PCM encapsulation designs. The procedure follows through out the thesis is explained as follows:

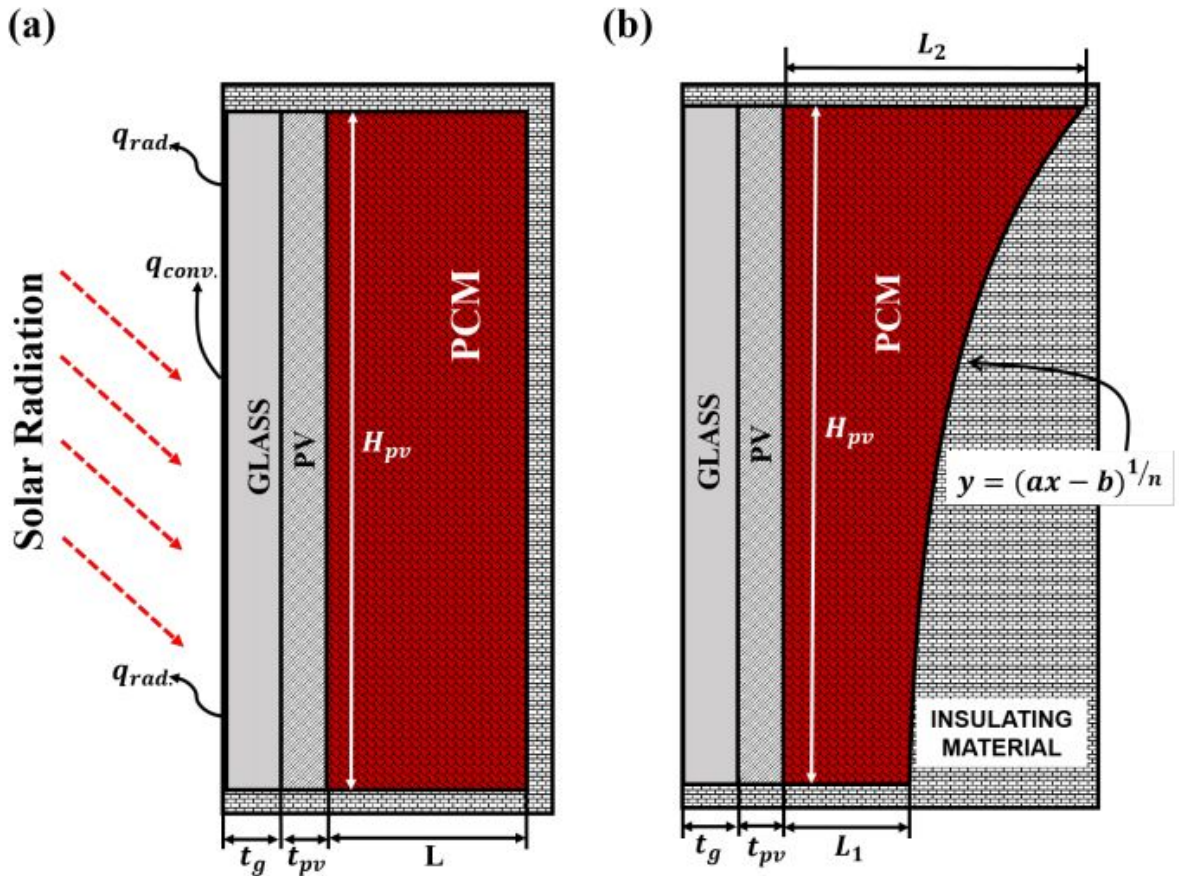


Figure 1.3: (a) Conventional PV/PCM system, (b) PV/PCM system with non-rectangular enclosure of generic opposite wall profile

1.4.1 Novel PCM encapsulation designs for PV/PCM systems

Conventional PV/PCM system (Figure 1.3(a)) exhibits drooping thermo-electric performance characteristics during later stages of melting process. The thesis compiles various novel PCM encapsulation designs to enhance the thermo-electric performance of PV/PCM system using an experimentally validated computational model. A brief discussion of thesis about various novel designs of PCM encapsulation for PV/PCM systems and bifacial PV/PCM systems are described here for better understanding and clarity. A PV/PCM system is highly versatile system which has a vast potential not only to provide electricity but also process heat for nocturnal applications if designed efficiently. Figure 1.3(b) depicts the new non-rectangular design of PCM enclosure with various possible opposite wall profiles.

The attachment of non-rectangular PCM enclosure of a generic opposite wall profile to PV/PCM system is first of its kind investigation (chapter 2). The non-rectangular enclosure avails more PCM in top part of the enclosure so that more amount of PCM is available for convection driven melting. Further, the variation of generic opposite wall profile ($y = (ax - b)^{(1/n)}$, with $n=1$

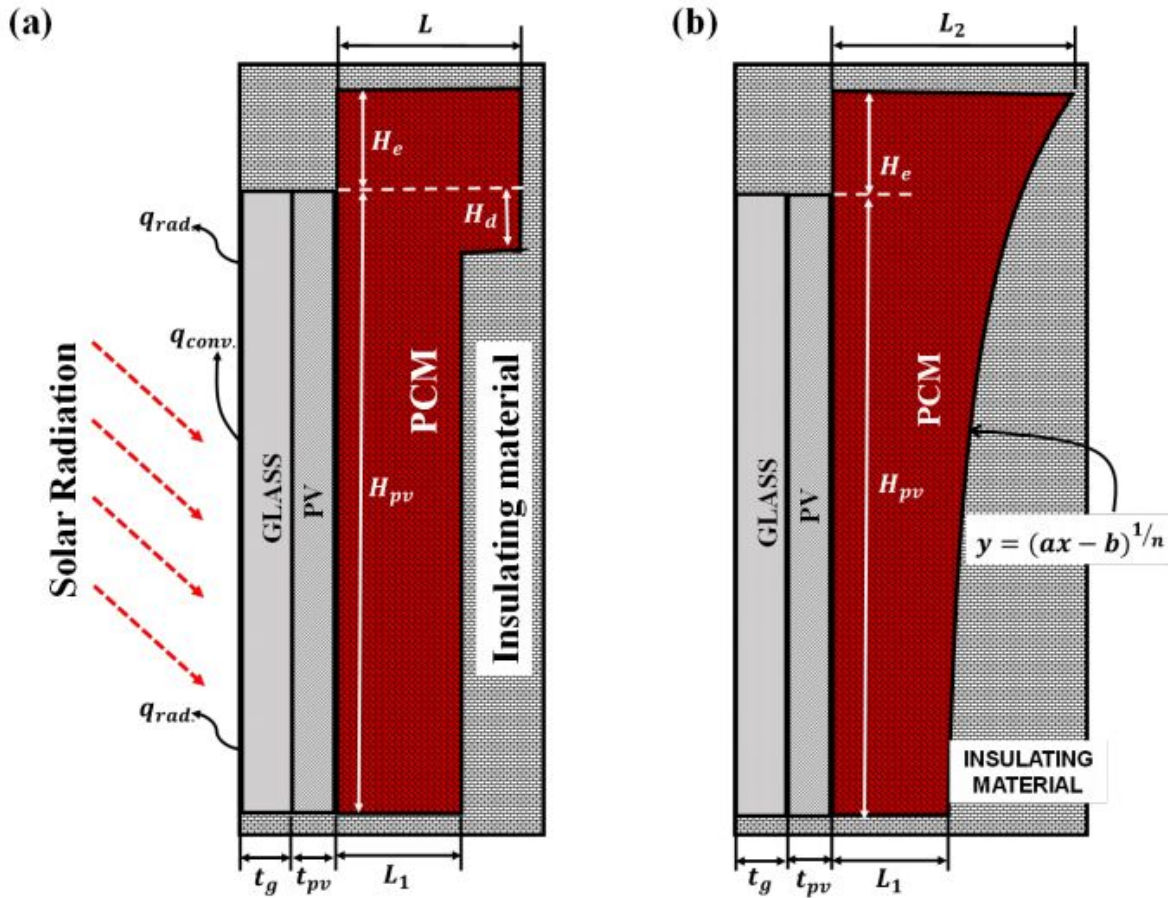


Figure 1.4: (a) PV/PCM system with overhead type rectangular PCM enclosure, (b) PV/PCM system with extended non-rectangular PCM enclosure with generic opposite wall profile.

(linear), 2 (parabolic) and 3 (cubic)) and while lower thickness ratio ($\frac{L_1}{L}$) controls the strategic distribution of PCM within the enclosure for same quantity of PCM. The availability of more PCM in top region of enclosure increases the span of quasi-steady convection regime and reduces the thermal stratification in liquid PCM region. The numerical investigation has been carried out to find a suitable profile of opposite wall and optimum lower thickness ratio for non-rectangular PCM enclosure. PV/PCM system with suggested non-rectangular PCM enclosure configuration exhibit higher electric conversion efficiency with more uniform temperature distribution and enhanced heat storage capacity compared to conventional design. If many such PV/PCM systems are installed in a specific region enriched with sun shine hours, it not only can produce power of million of people but also produce process heat for diurnal and nocturnal applications.

Further, behavior of non-rectangular enclosure PCM enclosure is analyzed numerically and compared to conventional rectangular enclosure for PV/PCM system under variable boundary conditions which are approximately similar to real atmospheric conditions (chapter 3). PV/PCM

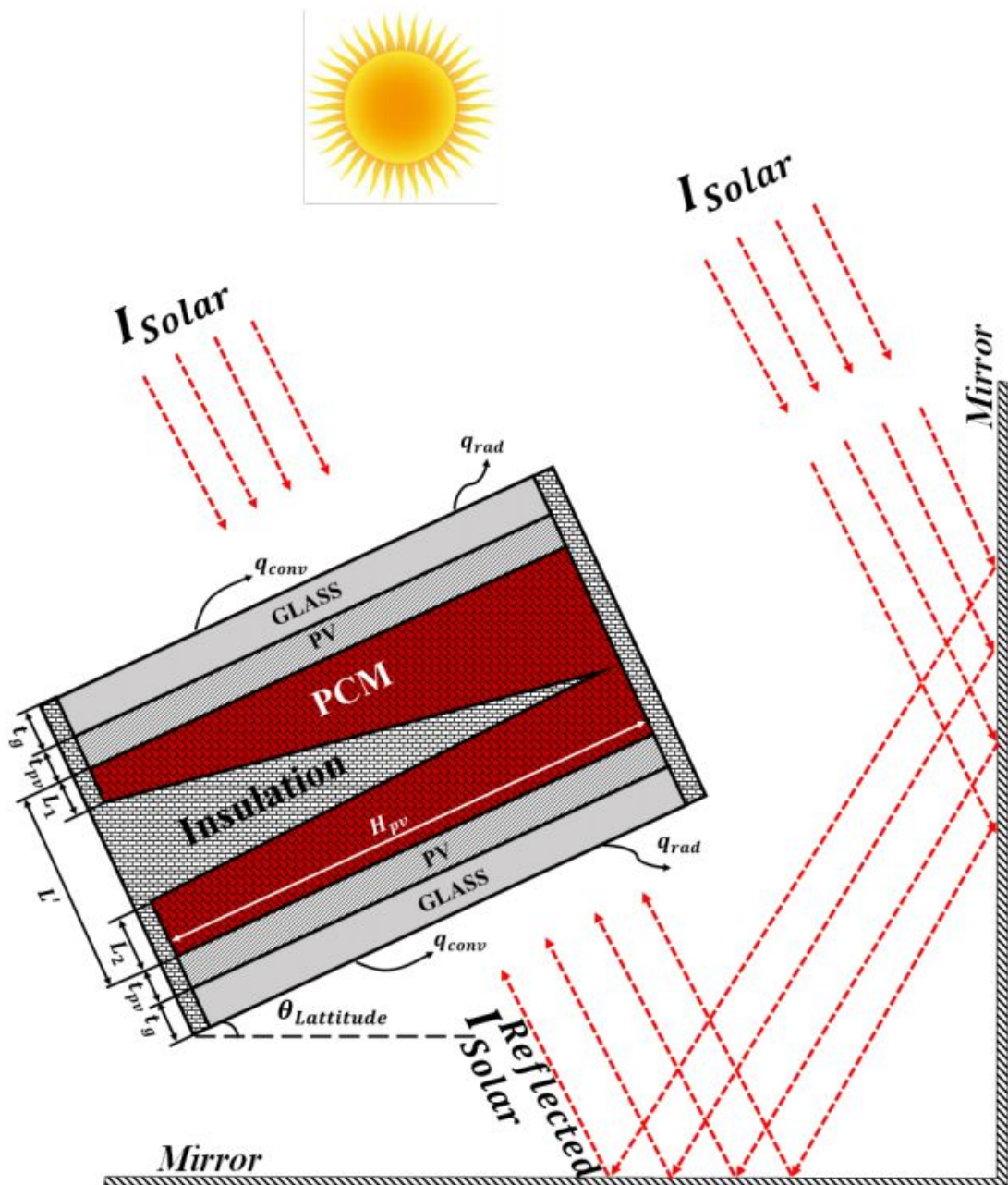


Figure 1.5: Bifacial PV/PCM system with modified non-rectangular PCM enclosure.

system with non-rectangular PCM enclosure not only exhibited enhanced electric performance for many hours but also exhibited better heat storage performance than conventional design. The rectangular PCM exhibits better charging capacity, faster melting rates, and lower energy loss to surrounding. This advancement in thermo-electric performance is due to change in design of enclosure and doesn't require any external running power and available for all operational hours.

The major advantage of such design modification in PV/PCM systems is that performance enhancement is achieved without any external consumption of work and without varying the

thermo-physical properties of PCM. However, the compactness of the system is compromised in order to avail more PCM for convection dominated melting. Therefore, new overhead type rectangular PCM enclosures (see Figure 1.4(a)) are investigated numerically for thermo-electric enhancement of PV/PCM system (chapter 4). The investigation is based on the assumption that PCM absorbs sufficient amount of energy that can pump melted PCM in overhead region and a bidirectional melting can be obtained in the top part of enclosure. Overhead type PCM enclosures have ability to pump heat away from PV panel with melted PCM. In this investigation, the extended height (H_e) and depression height (H_d) of overhead region of PCM enclosure from the top of PV panel is optimized to get more uniform melting patterns for better thermo-electric performance. The PV/PCM system with overhead type enclosure exhibits more uniform temperature distributions inside PV panel and exhibit improved electric conversion efficiency and heat storing ability compared to conventional design as well as non-rectangular design of the system.

The PV/PCM system with overhead type enclosure also possesses compactness approximately similar to conventional design, however thermo-electric performance of system degraded a bit in later stages of melting due to narrow PCM region in vicinity of upper side of PV panel. Convection dominated melting ends earlier in vicinity of PV panel compared to overhead region, that cause increase in thermal stratification near PV panel and thus decrement in thermo-electric performance. Therefore, new extended non-rectangular enclosures with generic opposite wall profile (see Figure 1.4(b)) are numerically investigated for thermo-electric enhancement of PV/PCM system (chapter 5). In this investigation, extension ratio $\left(\frac{H_e}{H_{pv}}\right)$, lower thickness ratio $\left(\frac{L_1}{L}\right)$, and profile of right wall is optimized to get more uniform melting morphology so that more uniform temperature distribution is observed with substantial decrease in thermal stratification. The problem of narrow PCM region in vicinity of PV panel of overhead type rectangular enclosure is well addressed in non-rectangular extended enclosures and compactness of the system is marginally compromised. The new proposed design of extended non-rectangular PCM enclosure shows significant increase in electric conversion performance, and heat storage performance of PV/PCM system.

Furthermore, a new design of bifacial PV/PCM system (see Figure 1.5) is proposed with modified non-rectangular PCM enclosure to maximize the utilization of incoming solar radiation, electric power output, and heat storing ability of the system (chapter 6). Numerical investigation has been carried out to find an optimum configuration of PCM enclosure for bifacial PV/PCM system that can exhibit uniform melting morphology for the bifacial system and thus uniform temperature distributions. Bifacial PV/PCM system is a sandwich like structure in which PCM is sandwiched between two PV panels. The nearby passing radiation is reflected back to bottom PV panel with the help of L-shape mirror system and extra electric power is produced. Energy input to PCM enclosure is increased due to reflected radiation that increases the thermal stratification in conventional rectangular PCM enclosure. A better melting front morphology in

modified non-rectangular PCM enclosure of bifacial PV/PCM system not only maintain lower thermal stratification but also exhibit better heat storage ability. Uniform temperature distributions for both PV panel also produce enhanced electric power. Bifacial PV/PCM system also exhibit better space management ability as they produce 86% more electricity than simple PV panels. If solar power plant uses bifacial PV/PCM systems in spite of conventional PV/PCM system or PV systems, they can be a big contributor to meet global energy demand. A detailed analysis with description of above discussed PV/PCM systems are presented in various chapters of thesis.

1.5 Objective of the thesis

Conventional PV/PCM systems deviate from its reference efficiency due to early completion of quasi-convection regime of melting that promotes thermal stratification in top region of the enclosure. Thermal stratification leads to elevated temperature and degraded thermo-electric performance. The limitations of PV/PCM system can be minimized by promoting quasi-convection regime of melting that can be enhanced after analyzing the melting behaviour of PCM. Therefore, one of the objective of thesis is to develop novel PCM encapsulation designs and examine the melting front morphology of PCM under constant and variable boundary condition. The other objective of thesis is to study the effect of enclosure design on thermo-electric performance of PV/PCM systems and bifacial PV/PCM systems and optimize the design for best performance. The examination of the feasibility of optimized configurations of PV/PCM system and bifacial PV/PCM systems for economic and enviroeconomic aspects is also one of objective of thesis. Therefore, from above discussion it can be concluded that the thesis focuses on developing such models of PV/PCM and bifacial PV/PCM systems that not only provide better thermo-electric performance but also are cost effective and environment friendly. The objectives can be achieved by following steps:

- Develop novel designs of PCM encapsulation for PV/PCM systems and bifacial PV/PCM systems.
- Develop experimentally validated CFD models for the novel designs.
- Analyse the melting front morphology for all novel designs of encapsulation.
- Analyse the new designs for: (a) Electric conversion performance; (b) Heat storage performance.
- Analyse the system for range of geometric and governing parameters.
- Analyse the system for various ambient conditions and analyse the feasibility of its application.

1.6 Organization of the thesis

The thesis discuss about the novel concept of non-rectangular PCM encapsulation and overhead type PCM encapsulation for PV/PCM systems and bifacial PV/PCM systems. The change in geometry of encapsulation aids the convective melting of PCM and thereby considerable enhancement in heat storage performance. Furthermore, electric conversion performance of PV/PCM system is enhanced and restored approximately equal to its rated performance. A modified non-rectangular PCM encapsulation design is also proposed for bifacial PV/PCM system that is able to maintain electric conversion performance of both PV panel close to its rated value in spite of increased incident radiation. Thermo-electrically efficient designs of PV/PCM system and bifacial PV/PCM systems have been proposed that can address both electricity requirement and process heat requirement applications for domestic and industrial use.

This thesis contains seven chapters. Each chapter follows other in such a way to bring progressive improvement in electric conversion performance and heat storage performance of PV/PCM systems and bifacial PV/PCM systems. Various possible ways have been examined to optimize the novel PCM encapsulation design for enhanced thermo-electric performance of PV/PCM systems and bifacial PV/PCM systems. Its layout is as follows:

- In chapter 1, introduction, motivation, and objective of the thesis is presented.
- In chapter 2, PV/PCM systems with non-rectangular PCM enclosure is examined for variable boundary conditions and compared to conventional PV/PCM system.
- In chapter 3, the new concept of non-rectangular PCM encapsulation of generic opposite wall profile is investigated for PV/PCM systems.
- In chapter 4, investigation is done for overhead type rectangular PCM enclosures for PV/PCM systems.
- In chapter 5, the new concept of extended non-rectangular PCM encapsulation of generic opposite wall profile is investigated for PV/PCM systems.
- In chapter 6, bifacial PV/PCM system is introduced and modified non-rectangular PCM enclosure is examined for bifacial PV/PCM systems.
- In chapter 7, conclusion drawn from various chapters and suggestions for future work are presented.