CHAPTER 7

Conclusions and Recommendations

This thesis numerically investigates a series of efficient novel PCM encapsulation designs for conventional and bifacial phase change material integrated photovoltaic (PV/PCM) systems. The main objective of the thesis is to propose innovative designs of PCM encapsulations that promotes convection dominated cooling of the PV system. Increase in PV panel temperature deteriorates its electrical performance. Suitable computational fluid dynamics models were developed and calibrated against the available experimental data. Different variants of encapsulation designs such as non- rectangular enclosures with specific right wall profile, overhead type rectangular enclosures, extended type non-rectangular enclosures were examined for simple PV/PCM systems. The conventional and modified configurations are analyzed under constant and variable boundary and ambient conditions to test their thermo-electric performance. The basic principle of enhancement of thermo-electric performance is lowering down the PV panel temperature by increasing the heat storage performance of the enclosed PCM encapsulation which is achieved by characterizing the melting front morphology according to developed convection current. The design modification of PCM enclosure enhances the convection dominated regime of melting and enhances the waste heat extraction and storage rate for a given amount of PCM. All the aforesaid modified configurations exhibit significant improvement in thermo-electric performance of PV/PCM system and also evolve to maintain geometrical simplicity and compactness of the system. Further, the PCM enclosure is also modified for bifacial PV/PCM system according to melting front morphology. Since bifacial system receives radiation from both sides, melting morphology will be a bit different then a simple configuration, therefore a bifurcated type non-rectangular enclosure was found best suited for configuration. The modified bifacial PV/PCM system generates approx. twice the power compared to a conventional PV system and stores more than twice heat for nocturnal hours compared to conventional PV/PCM systems. The feasibility analysis also shows that modi-

fied bifacial PV/PCM system not only generates more power per unit land area but also electricity and exergy generation are cheaper and cleaner for this configuration compared to other configurations. Following key conclusions drawn from various chapters and fruitful thoughts for future work are presented in this chapter.

7.1 Conclusions

The PV panels with traditional rectangular PCM enclosure are expected to have enhanced thermoelectric performance; nevertheless, the conventional PV/PCM system has reduced performance due to supression of convection current in later solid-shrinking melting regimes. Therefore, traditional rectangular PCM encapsulation has to replaced with noval PCM encapsulation designs characterised by gravity-driven melting front morphology to enhance the performance. The improved convection-dominated melting in novel encapsulation designs allows for higher latent energy absorption and provides a quasi-steady, uniform, and lower temperature distribution in both the PCM enclosure and the PV panel. The change in encapsulation design not only augments the electric conversion performance as well as heat storage performance of the PV/PCM system. However, some challanges and limitations emerge during optimisation of encapsulation design. The key conclusions from various chapters are as follows:

Effect of novel PCM encapsulation designs on electrical and thermal performance of a hybrid photovoltaic solar panel

In this chapter, thermo-electric performance improvement techniques for a conventional PV/PCM system has been proposed using an experimentally validated numerical model. Melting rate characterization and PV panel efficiency was reported under constant boundary condition. Mass of PCM in the new encapsulation designs was strategically distributed for better thermal management by varying the profile of right wall ($y = (ax - b)^{(1/n)}$) to linear ($n = 1, linear$), parabolic ($n = 2, parabolic$), and cubic ($n = 3, cubic$) shape with different lower thickness ratio($\frac{L_1}{L}$) keeping the volume of PCM same for all designs. Following are some important findings:

1. Due to suppression of convection current (smaller quasi-steady convection regime; only upto 56 minutes) in conventional rectangular enclosure, the liquid fraction deviates from the linear trend in melting – time curve. However, with strategic distribution of PCM by using non-rectangular enclosure, extends quasi-steady regime by 109% (up to 117 minutes) for cubic configuration. As a consequence Nusselt number is increased by 48% and 17% increase in melting rate was observed. Thus liquid fraction varies linearly with time for a longer time.

2. With no PCM the PV cell electrical efficiency drops to 10.84% as PV cell temperature increases upto 56.78°C. On attachment of conventional rectangular encapsulation, electrical efficiency increases to 11.69 % with an improvement of 7.84 % as PV temperature dropped to 39.28°C. However, further improvement of 1.87% in electrical efficiency was observed in cubic configuration and electrical efficiency reached to 11.92%. This is due to further decrement of 11.5% in PV cell temperature. It has been observed that electrical efficiency improved by approximately 0.45% per degree temperature rise.

3. Parabolic enclosure at $\frac{L_1}{L} = 0.3$ has best heat storage performance while cubic enclosure at $\frac{L_1}{L} = 0.5$ show better temperature uniformity among all configurations. Since thermo-electric performances are comparable in both the configurations, parabolic enclosure is recommended due to its compact design.

The overall energy demand can be reduced through efficient and passive thermal regulation using better PCM encapsulation designs. However, it would be interesting to investigate the the feasibility of the system under variable boundary and ambient conditions to examine the acceptibility of the system under real conditions.

Behaviour of novel design of non-rectangular PCM enclosure for PV/PCM systems under variable boundary and ambient conditions

In this chapter, the previous chapter's information is applied to non-rectangular design of a PCM enclosure for a PV/PCM system and its viability is investigated under variable boundary and ambient conditions (mimics real condition). Furthermore, the system's feasibility is assessed in terms of economic, enviroeconomic, and exergic aspects. The performance of conventional PV/PCM system is compared with the proposed PV/PCM system having a non-rectangular PCM enclosure by an experimentally verified numerical model under variable boundary conditions. The study focuses on improvement of thermo-electric performance by characterization the heat transfer according to melting front morphology in modified PCM enclosure. Following are some key observations:

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

2. Enhanced melting rates leads to lower PV panel temperature and enhanced electric conversion efficiency. The PV panel in proposed PV/PCM system works at 92% of its rated

performance which was 89% for conventional PV/PCM system and 81 % for simple PV panel. without any PCM encapsulation.

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

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

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

The study's findings revealed that the findings under variable boundary conditions are relatively comparable to those under constant boundary conditions, and it can be concluded that future design recommendations may indeed be examined using constant boundary conditions. It is also evident that design modification to proposed non-rectangular shape exhibits a significant improvement in thermo-electric performance due to enlarged quasi-convection regime. However, the compactness of the system is compromised due to non-linear profile of right wall of PCM enclosure. Therefore, further modifications in shape of enclosure are desired to get a compact design of PV/PCM system for enhanced thermo-electric performance.

Effect of new overhead phase change material enclosure designs on thermo-electric performance of a photovoltaic panel

In this chapter, 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. The objective of providing overhead enclosure is to ensure enlarged quasi-convection regime by allowing melting front to propagate in both horizontal and vertical directions. 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.The 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. Following are some valuable findings:

1. Maximum enhancement in melting (~ 20%) is observed in type – D configuration due to enhanced quasi-steady convection regime (102%) and Nusselt number (~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.

The study's findings show that the overhead type enclosure not only assures a compact design but also a greater improvement in thermo-electric performance when compared to the conventional design than the previously suggested non-rectangular design. However, the overhead type enclosure exhibits some design limitations as the vicinity of the right wall of the enclosure and the PV panel rises in the process of assuring more PCM in the overhead area, resulting in an early end to the qausi-convection regime. The design limitations are needed to adressed and enclosure must be design according to characterization of melting front to ensure prolonged quasi-convection melting regime.

Effect of new extended type non-rectangular PCM enclosure on thermo-electric performance of PV/PCM systems

In this chapter, new extended non-rectangular designs of PCM enclosures has been proposed by combining the approach of both previous (non-rectangular and overhead) designs to promote the prolonged quasi-steady convection regime and enhanced thermo-electric performance. The evolution of design of non-rectangular enclosures are done on basis of certain geometrical parameters such as profile of right wall, lower thickness ratio (L_1/L), and extension ratio (H_e/H_{pv}) to enhance the span of convection driven melting. These geometrical parameters affects the PCM distribution with in the enclosure and also decides the compactness of the system. The non-rectangular PCM enclosure has the same volume as rectangular enclosure (type – A). Non-rectangular enclosure are designated as type – B, C, & D for linear, parabolic, & cubic right wall profile respectively. The optimum extension ratio and lower thickness ratio are found according to melting front morphology, and thermo-electric performance after many design iterations. Melting behavior, energy storage density, electric conversion efficiency, total utilized radiation and I_{gain} ratio are reported in detail by using an experimental validated numerical model. Some important outcomes are as follows:

1. Type – B configuration ($H_e/H_{pv} = 0.3, L_1/L = 0.3$), exhibit prolonged span of quasiconvection regime (120 minutes) due to which convective heat transfer is dominant in enclosure (Nu is enhanced by 66.87%) and 20.5% more melting is achieved compared to type – A configuration of PV/PCM system.

2. Electric conversion efficiency approaches to 96.37 % of its rated value which was 87.41% for simple PV system and 94.27% for type – A configuration of PV/PCM system. This enhancement is due to reduction of 22.57°C in PV cell temperature compared to simple PV system.

3. The ability to utilized incoming radiation has been increased to 67.35% with a total utilized radiation of 538.76 W/m^2 in Type – B configuration ($H_e/H_{pv} = 0.3, L_1/L = 0.3$) which was just 61.61% (492.09 W/m^2) in type – A configuration of PV/PCM system.

4. Enhanced I_{gain} ratio (2.18) suggest that Type – B configuration ($H_e/H_{pv} = 0.3, L_1/L = 0.3$) system has better incoming radiation management ability than any other discussed configuration.

Type – B configuration ($H_e/H_{pv} = 0.3, L_1/L = 0.3$) is recommended for not only exhibit maximum thermo-electric performance but for also most compact structure among all good performing configurations. The proposed encapsulation design optmizes the thermo-electric performance only for mono-facial PV/PCM. However, the monofacial technology has the limitations of low power output density and energy output density which are eliminated by using bifacial PV/PCMsystems with utilization of more incoming radiation. The bifacial PV/PCM system will exhibit higher PV panel temperatures and degradtion in thermo-electric performance consequently. Therefore, PCM encapsulation designs for bifacial PV/PCM systems needed to be optimized for better performances.

Thermal energy storage design of a new bifacial PV/PCM system for enhanced thermo-electric performance

In this chapter, a new bifacial PV/PCM technique has been proposed with the help of an experimentally calibrated computational model. In this technique, two PV panels are used with a sandwiched thermal energy storage PCM enclosure (bifurcated type) between the panels. The enhancement in thermo-electric performance is obtained by using proper thermal management and insolation management strategies. Insolation management strategies include an L-shape reflector system which avails the bypassing radiation to the bottom PV panel. However, thermal management strategies include lowering the PV panel temperature with a proper characterization of melting by changing the shape and design of the enclosure. The shape and ratio of the volume bifurcated system are chosen according to melting front morphology, incident radiation, and reflected radiation after many design iterations. Melting behavior, absolutely absorbed energy, electric power output, exergy efficiency, and overall system efficiency are reported in detail. Some essential outcomes are as follows:

1. The new bifacial PV/PCM system exhibit 10.98% and 105% more melting than L_{30} BIF-PV/PCM system and L_{30} PV/PCM system respectively due to more prolonged quasiconvection regime (105 minutes).

2. Electric power output is 77% more in modified BIF-PV/PCM system than L30 PV/PCM due to additional reflected radiation to bottom PV panel and better thermal management of PV panels.

3. The modified BIF-PV/PCM system exhibit high energy utilization efficiency of 73.71%, which is just 10.69%, 10.84%, and 68.74% in conventional BIF-PV, PV, and PV/PCM system respectively.

4. The new bifacial PV/PCM system exhibit 1.21 times power output density and 7.39 times total energy utilization density compared to the conventional PV system.

5. The modified BIF-PV/PCM system exhibit an enhancement of 2.57% in exergy efficiency compared to conventional PV system and seems to be most economical in both electricity and exergy production.

Hence, the modified BIF-PV/PCM system with a bifurcated thermal storage design is recommended due to better thermo-electric performance and waste heat management performance compared to all other configurations. This research would help the research community develop an energy-efficient BIF-PV/PCM system with rectangular and non-rectangular PCM enclosures.

The research work throughout different chapters of thesis presents a chronological way to optimize the design of PCM encapsulation to achieve enhanced thermo-electric performance of monofacial PV/PCM system without any additional active cooling technique. The research work also assist us in finding a suitable PCM enclosure design for bifacial PV/PCM system for augmented performance which avails more energy procuction for given land area. The research work would be a valuable asset in meeting the world's ever-increasing energy demands, which can be reduced by creating more electric power and passively storing extra heat with approximately fewer space requirements.

7.2 Major contribution from the thesis

A series of new designs of PCM encapsulations for monofacial PV/PCM systems and bifacial PV/PCM systems have been proposed and investigated in this thesis. Conventional PV system exhibit degraded performance at elevated temperature. However, conventional PV/PCM systems also exhibit degraded thermo-electric performance in the later stages of melting due to shorter regime of convection dominated melting. For the first time, a new concept of characterization of designs of enclosure according to melting morphology has been proposed to enhance the thermo-electric performance of PV/PCM systems. Few important contributions are listed below:

- The concept of enhancing the heat storage performance by designing the PCM enclosure according to melting front morphology is very rare in literature. However, encapsulation of such innovative designs with photovoltaic panel to increase its thermo-electric performance is not documented in scientific community. PV/PCM systems are capable of generating more electric power as they have the capability to work in proximity of its rated performance by cooling them closer to their reference temperature. Therefore, the proposed design ensures longer life for the photovoltaic panels with enhanced generation of electric power.

- At the same time the availability of stored heat for nocturnal hours make them extremely useful for domestic applications. These type of system could be proved as boon especially for colder regions or in weather conditions where room heating and water heating is a primary requirement. Moreover, these PCM encapsulations are easily attachable to the existing PV panels without any major cost and modifications. We hope that new designs would be useful to the scientific community in designing efficient PV panels integrated with non-rectangular encapsulation designs.

- The concept of bifacial PV/PCM system with a simple design of L-shape reflector system can enhance the electric power out approximately twice of the currently existing PV panels. If we observe the power output density (power output per unit land area) is also approximately 1.21 times of conventional PV panel. It exhibits the feasibility of the proposed system to replace simple PV panels as they will produce extra power in addition to process heat for nighttime hours. The economic and enviroeconomic analysis also gave a brief information that the proposed system would be a cheaper and cleaner source of energy. Therefore, the proposed system could be a great contributor to meet ever growing global energy demands with lesser space requirements.

7.3 Assumptions and limitations of present investigation

The proposed novel PCM encapsulation designs has been investigated under the following assumptions: (1) PCM is considered as pure substance with invariable phase change temperature depicting negligible mushy zone. (2) The properties of material are considered to be isotropic, homogenous and constant. (3) The effect of dust deposition on glass cover is ignored. (4) The optical properties of the material are independent of the wavelength. (5) Neglible contact resistance is considered between different layers of glass, PV panel and PCM. (6) All boundaries except front wall of glass layer are considered as perfectly insulated. (7) Liquid PCM is considered as incompressible and newtonian fluid. (8) The flow is considered as laminar flow for liquid PCM region. (9) The sky temperature is assumed equal to ambient temperature for radiative losses from the system. (10) The incoming radiation is always assumed to incident normal to the PV/PCM systems.

Thus the investigations presented in this thesis has been performed under ideal conditions. The objective was to achieve high thermo-electric performance which is most important aspect to justify its feasibility and wide acceptability. Environmental conditions has severe impact on thermo-electric performance when the system has to work under real conditions such as rainy day, cloudy day, foggy weather, changing wind directions, variable heat transfer coefficient between glass layer and ambient, deposition of dust on panels and improper tracking of solar radiation etc. These factors deteriorate thermo-electric performance of PV/PCM system which is not considered in the present research work. A separate examination would be needed to predict the thermo-electric performance under real ambient and climatic conditions. PV/PCM systems has the capabilty to provide the stored heat for nocturnal uses which is not studied in the current research work. The charging and discharging cycle would also impact the working of the system, therefore a separate study is also needed to predict the behavior of PV/PCM system under different charging and discharging cycles of PCM. The other limitation of this work is the material property that is asssumed to be constant even if PCM has significant variation in its solidus and liquidus properties and possesses significant mushy zone. Even PV panel has many layers such as EVA layer, tedlar layer, and PV cell layer etc, however; cumulative properties are considered for this region as thickness of these layers are significantly small. Though its effect might be small, but its quantification would add new body of knowledge in scientific literature.

7.4 Recommendations for future research

Based on these findings, following suggestions can be implemented for further advancement of PCM based PV systems:

1. These investigations has been carried out under ideal conditions, the effect of real climatic conditions such as rain, cloudy day, and bad weather has been ignored. The effect of deposition of dust on PV panel is also ignored. The consideration of all these parameters would affect the direct insolation for the system, therefore experimental investigations of proposed designs must be carried out to know their feasibility under various climatic, weather, and ambient conditions.

2. The investigations has been carried out for charging period of PCM only, however the dischrging of PCM in nocturnal hours would affect both performance and life of PV/PCM system. The PV/PCM system will behave differently after a number of charging and discharging cycles. Therefore, further investigations are needed for proposed designs to study the bhaviour of PCM during discharging of PCM and after different number of charging and discharging cycles.

3. The overhead type rectangular and non-rectangular PCM encapsulation has a propensity to remove waste heat away from the PV panel, which might be a benefit to the technology if we make it a heat sink by linking some discharging unit with the system. Simeltaneous charging and discharging of PCM in such overhead system would be a good scope of future investigation to optimise the design of PCM encapsulation.

4. The reflector in bifacial PV/PCM system has been modelled by assuming the normal incident radiation to the system. However, the incident radiation is not normal to the system all the time, hence a separate study must be conducted to optimise the shape, size and orientation of the reflector for such systems.

5. PV/PCM systems have the capability of generating electricity as well as storing the heat for nocturnal hours. Therefore, these type of system can also be used for purification of water such as integration of such system to solar still so that purification of water can also be done at nocturnal hours.

6. PV/PCM system could be a potential option for collector of solar air heater (SAH) and solar chimney power plant (SCPP) as they have the capability to keep both of these technologies functional after sunshine hours due to their heat storage capacity.

7. Investigations must be carried out to further enhance the performance of the proposed designs by doing significant improvements in designs such as use of nano-PCM can be analyzed such convective melting dominated enclosure. Also performance of bifacial PV/PCM system under different type of reflectors must be analyzed or some improvement in design of PCM enclosure must be entertained to get enhanced performance.

8. Analysis of proposed new designs of PV/PCM systems and bifacial PV/PCM systems can be further extended using techniques such as artificial neural network and wavelet neural network model.