
Contents

Certificate	iii
Declaration	v
Copyright	vii
Acknowledgement	ix
Table of Contents	xi
List of Figures	xv
List of Tables	xxi
Nomenclature	xxiii
Abstract	xxvii
1 Introduction	1
1.1 PV/PCM systems: Background	2
1.2 Prior studies on PV/PCM systems	3
1.2.1 Conventional PV/PCM systems	3
1.2.2 PV/PCM system with finned PCM enclosures	4
1.2.3 PV/PCM system with comoposite PCM	4
1.2.4 Hybrid PVT/PCM systems	5
1.3 Research gap	5
1.4 Research methodology	7
1.4.1 Novel PCM encapsulation designs for PV/PCM systems	9
1.5 Objective of the thesis	13
1.6 Organization of the thesis	14
2 Effect of Novel PCM Encapsulation Designs on Electrical and Thermal Performance of a Hybrid Photovoltaic Solar Panel	15

2.1	Introduction	15
2.2	Material & method	20
2.2.1	Problem description & definition	20
2.2.2	Solution method	23
2.2.3	Grid independence test	26
2.2.4	Validation with experimental results	26
2.3	Results and discussions	28
2.3.1	Solid-liquid interface patterns	28
2.3.2	Temperature distributions	33
2.3.3	Effect of enclosure design on flow behavior during PCM melting	34
2.3.4	Heat transfer characteristics	36
2.3.4.1	Melting rate	36
2.3.4.2	Nusselt number	39
2.3.4.3	Heat storage Performance	40
2.3.5	Performance characteristics	42
2.3.5.1	PV cell temperature	42
2.3.5.2	Effect of enclosure design on PV electrical efficiency	44
2.4	Conclusions	46
3	Behaviour of Novel Design of Non-rectangular PCM Enclosure for PV/PCM Systems under Variable Boundary and Ambient Conditions	49
3.1	Introduction	50
3.2	Methodology	52
3.2.1	Problem description & definition	52
3.2.2	Boundary conditions	53
3.2.3	Solution method	54
3.3	Results and discussions	55
3.3.1	Thermal analogy of melting front propagation	55
3.3.2	Heat transfer characteristics	58
3.3.2.1	Liquid fraction	58
3.3.2.2	Nusselt number	60
3.3.2.3	Thermal energy storage performance	61
3.3.3	Performance characteristics	63
3.3.3.1	Effect of PV cell temperature on electric conversion efficiency	63
3.3.3.2	Electric power output	64
3.3.3.3	Total heat loss from the system	67
3.3.3.4	Energy and exergy efficiency	67
3.3.4	Feasibility of the system:	71

3.4 Conclusions	75
4 Effect of New Overhead Phase Change Material Enclosure Designs on Thermo-electric Performance of a Photovoltaic Panel	77
4.1 Introduction	78
4.2 Methodology	80
4.2.1 Problem description & definition	80
4.2.2 Boundary conditions	81
4.2.3 Solution method	83
4.3 Results and discussions	83
4.3.1 Solid-liquid interface patterns	83
4.3.2 Temperature distributions	87
4.3.3 Heat transfer characteristics	88
4.3.3.1 Melting rate	88
4.3.3.2 Nusselt number	91
4.3.3.3 Thermal energy storage performance	92
4.3.4 Performance characteristics	94
4.3.4.1 PV cell temperature	94
4.3.4.2 Electrical conversion efficiency of PV cell	97
4.3.4.3 Total utilized radiation	98
4.4 Conclusions	102
5 Effect of New Extended Type Non-rectangular PCM Enclosure on Thermo-electric Performance of PV/PCM Systems	105
5.1 Introduction	105
5.2 Solution methodology	108
5.2.1 Problem formulation	108
5.2.2 Boundary conditions	108
5.2.3 Numerical solution	110
5.3 Results and discussions	111
5.3.1 Solid-liquid interface patterns	111
5.3.2 Temperature distributions	114
5.3.3 Heat transfer characteristics	116
5.3.3.1 Melting process	116
5.3.3.2 Nusselt number	120
5.3.3.3 Thermal energy storage performance	123
5.3.4 Performance characteristics	126
5.3.4.1 Effect of PV cell temperature on power conversion efficiency	126
5.3.4.2 Overall system performance	127

5.4 Conclusions	134
6 Thermal Energy Storage Design of a New Bifacial PV/PCM System for Enhanced Thermo-electric Performance	137
6.1 Introduction	138
6.2 Solution methodology	142
6.2.1 Problem formulation	142
6.2.2 Boundary conditions	142
6.2.3 Numerical solution	145
6.2.4 Experimental calibration of numerical model	145
6.3 Results and discussions	146
6.3.1 Solid-liquid interface patterns	146
6.3.2 Temperature distributions	149
6.3.3 Heat transfer characteristics	151
6.3.3.1 Melting process	151
6.3.3.2 Nusselt number	154
6.3.4 Performance characteristics	155
6.3.4.1 Effect of PV cell temperature on power conversion efficiency	155
6.3.4.2 Total electric power output	159
6.3.4.3 Overall system performance	161
6.3.4.4 Feasibility of the system	164
6.4 Conclusions	169
7 Conclusions and Recommendations	171
7.1 Conclusions	172
7.2 Major contribution from the thesis	178
7.3 Assumptions and limitations of present investigation	179
7.4 Recommendations for future research	180
Bibliography	183
Author's Personal Profile and Publication List	193

List of Figures

1.1 (a) Conventional PV/T system , (b) conventional PV/PCM system	3
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.	7
1.3 (a) Conventional PV/PCM system, (b) PV/PCM system with non-rectangular enclosure of generic opposite wall profile	9
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.	10
1.5 Bifacial PV/PCM system with modified non-rectangular PCM enclosure.	11
2.1 Schematic diagram showing cross-section of PV/PCM system with (a) type-A conventional rectangular PCM enclosure, (b) type-B, C, & D non-rectangular PCM enclosure with a general profile, $y = (ax - b)^{(1/n)}$, $n=1$ for type-B, $n=2$ for type-C and $n=3$ for type-D.	17
2.2 Variation of centerline temperature at 3600 s for different number of grids. Inset shows the melting front of PCM. Location of centerline is marked in the figure by dash-dot line.	24
2.3 Variation of liquid fraction of PCM predicted from numerical model and experimental study (Kamkari et. al 2014). Two figures in the inset shows the instantaneous liquid fraction: left [experimental] and right [numerical].	25
2.4 Solid-liquid interface patterns predicted from (i) experimental study by Kamkari et al., (2014) and (ii) numerical model.	27
2.5 Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 1. .	29

2.6 Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 2.	30
2.7 Sequential solid fraction contours of the melting process of PCM in rectangular enclosure (type – A) and in non-rectangular enclosure (type – B, C, and D) for Case 2.	31
2.8 Temperature distribution in all type of configuration of PV/PCM systems at 120 minutes.	35
2.9 Variation of Temperature along the height of PV panel at 120 minutes for case 3.	36
2.10 Velocity streamlines superimposed on solid volume fraction map for Case 3 at 120 minutes. Black color on the right wall shows solid PCM.	37
2.11 Expanded view of liquid fraction vs time shown in inset for all type of configurations for case 3.	38
2.12 Variation of Nusselt number for all type of configuration for case 3.	39
2.13 (a) Expanded view of variation of ESD with time shown in inset, (b) ESD values for all configurations at 120 minutes.	43
2.14 Variation of PV cell temperature with time for all type of configuration of PV/PCM system for case 3.	44
2.15 Variation of electrical efficiency with time for all type of configuration of PV/PCM system for case 3.	45
3.1 Schematic diagram showing cross-section of PV/PCM system with (a) type-A conventional rectangular PCM enclosure, (b) type-B, C, & D non-rectangular PCM enclosure with a general profile, $y = (ax - b)^{(1/n)}$, $n=1$ for linear, $n=2$ for parabolic and $n=3$ for cubic right wall profile.	53
3.2 Diurnal variation of (a) incident radiation, (b) ambient temperature with time.	54
3.3 Transient history of (a) solid-liquid interface patterns, and (b) temperature distribution patterns.	57
3.4 Transient variation of liquid fraction for both type of configurations. Full melting history has been shown in inset.	59
3.5 Comparison of transient history of Nusselt number for both type of configuration. Solid-liquid interface patterns for both configurations at end of quasi-steady convection regime are shown in inset.	61
3.6 Transient variation of ESD for all configurations.	62
3.7 Transient variation of average PV cell temperature for all configurations of PV and PV/PCM systems.	64
3.8 Transient Variation of electrical efficiency for all configurations of PV and PV/PCM systems.	65
3.9 Transient variation of electric power output for all configurations of PV and PV/PCM systems.	66

3.10 Transient variation of total heat loss for all type of configurations.	68
3.11 Comparision of energy efficiencies for all different configurations of PV and PV/PCM systems.	70
3.12 Comparision of exergy efficiencies for all different configurations of PV and PV/PCM systems.	72
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.	82
4.2 Transient history of solid fraction contours of the melting of PCM superimposed with velocity streamlines for all type of configurations.	85
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.	89
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.	90
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.	92
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.	95
4.7 Transient variation of average PV cell temperature for all configurations of PV/PCM system.	96
4.8 Transient Variation of electrical efficiency all configurations of PV/PCM system.	98
4.9 Variation of utilized radiation with time. (Expanded view for specific time period is shown in inset).	100
4.10 Variation of ratio of utilized radiation to unutilized radiation with time. (Expanded view for specific time period is shown in inset.)	101
5.1 Two dimensional schematic diagram of PV/PCM systems (a) with rectangular PCM enclosure (Type – A), and (b) non-rectangular extended PCM enclosure with a general right wall profile, $y = (ax - b)^{(1/n)}$, $n = 1$ for type-B, $n = 2$ for type-C and $n = 3$ for type-D.	109
5.2 Transient history of solid-liquid interface patterns for different configurations of PV/PCM system.	115

5.3 Transient history comparison of melting front contours with temperature distribution contours for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$) and extension ratio ($H_e/H_{pv} = 0.3$)	117
5.4 Temperature distribution at 120 minutes for different configurations of PV/PCM systems at lower thickness ratio	118
5.5 Transient variation of liquid fraction for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	119
5.6 Fraction of liquid melted after 120 minutes of process for all configurations of PV/PCM system with non-rectangular PCM enclosure.	121
5.7 Variation of Nusselt number with time for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Transient history of melting front contours for same configuration at extension ratio ($H_e/H_{pv} = 0.3$) is shown in inset.	122
5.8 Comparison of Nusselt number at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	123
5.9 Transient variation of energy storage density (<i>ESD</i>) for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	124
5.10 Comparison of <i>ESD</i> at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	125
5.11 Transient variation of (a) PV cell temperature (b) PV cell electric conversion efficiency for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Full transient history are shown in inset for each curve.	128
5.12 Comparison of (a) PV cell temperature, and (b) PV cell electric conversion efficiency at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	129
5.13 Transient variation of total utilized radiation for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	130
5.14 Comparison of total utilized radiation at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	132
5.15 Transient variation of I_{gain} ratio for type – B configuration of PV/PCM system at lower thickness ratio ($L_1/L = 0.3$). Expanded view of selected part of curve is shown in inset.	133
5.16 Comparison of I_{gain} ratio at 120 minutes of process among all configuration of PV/PCM system with non-rectangular PCM enclosure.	134
6.1 Schematic diagram of conventional PV/PCM system.	140

6.2 Schematic diagram of BIF-PV/PCM system with sandwiched rectangular PCM unit.	141
6.3 Schematic diagram of modified BIF-PV/PCM system. Note how the rectangular PCM enclosure is modified to a bifurcated non-rectangular design. This design has been arrived after studying the melting front in the rectangular design.	144
6.4 Comparison of liquid fraction – time curve between numerical and experimental model for (a) conventional mono-facial heating of PCM , and (b) bifacial heating of PCM . Solid-liquid interface patterns are given in inset for specified time.	147
6.5 Solid-liquid interface patterns for PV/PCM systems and BIF-PV/PCM systems. . .	149
6.6 Temperature distribution at 120 minutes for PV/PCM systems and BIF-PV/PCM systems.	150
6.7 Variation of (a) liquid fraction with time, and (b) absolute amount of melted PCM with time.	152
6.8 Variation of (a) Nusselt number for top PV-PCM interface with time for PV/PCM systems and BIF-PV/PCM systems (b) Nusselt number for bottom PV-PCM interface with time for BIF-PV/PCM systems. Solid-liquid interface patterns at peaks and kinks are shown in inset.	156
6.9 Transient variation of PV cell electric conversion efficiency of (a) top PV panel, and (b) bottom PV panel for all configurations of PV and PV/PCM systems.	158
6.10 Variation of overall electric power output with time for different configurations of PV and PV/PCM systems.	160
6.11 Variation of overall system efficiency with time for different configuration of PV and PV/PCM systems.	163
6.12 Comparison of exergy efficiency for different configurations of PV and PV/PCM systems.	164
6.13 Schematic of calculation of land area requirement of integration of a single bifacial PV/PCM unit.	165
6.14 Comparison of (a) total energy utilization density, (b) power output density among bifacial PV/PCM unit, simple PV/PCM unit and conventional PV system unit. . . .	166

List of Tables

2.1	Relevant literature on PCM integrated with PV module. Note that only rectangular type encapsulation design has been reported.	17
2.2	Thermo-physical properties of materials	22
2.3	Design specifications and boundary conditions for all geometric configurations.	22
2.4	Results of PV and PV/PCM systems. The results in bold are crucial for comparing some of the top performing configurations to conventional ones.	41
3.1	Economic and exergoeconomic investigation for all configurations of PV and PV/PCM systems.	74
3.2	Enviroeconomic investigation for all configurations of PV and PV/PCM systems.	75
5.1	Design specifications for all PV /PCM configurations with non-rectangular PCM enclosure.	110
5.2	Timing of melting front reaching right and top wall for all non-rectangular configurations. Note 120* indicates that melting front does not reach the respective wall in 120 minutes of process.	113
6.1	Equations for energy efficiency and exergy efficiency analysis.	161
6.2	Equations for energy efficiency and exergy efficiency analysis.	162
6.3	Equations for economic, exergoeconomic and enviroeconomic analysis	167
6.4	Economic, exergoeconomic, and enviroeconomic analysis for studied configuration of PV and PV/PCM systems.	168