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DECLARATION BY THE CANDIDATE

I, **Akshayveer**, certify that the work embodied in this thesis is my own work and carried out by me under the supervision of "**Dr. Om Prakash Singh**" from "**July 2016**" to "**December 2021**" at the "**Department of Mechanical Engineering, Indian institute of technology (BHU), Varanasi**". The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any others work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc. or available at websites and have not included them in this thesis and have not cited as my own work.

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Akshayveer

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Nomenclature

A_{pv}	Area of PV panel (m^2)
B_{mush}	Mushy constant (kg/m^3s)
C_{el}	Cost of electricity generation ($/kWh)
C_{ex}	Cost of exergy generation ($/kWh)
c_p	Specific heat at constant pressure (J/kgK)
C_{total}	Capital cost ($)
E_{el}	Electric energy generation (kWh)
E_n	Annual electric energy generation (kWh/year)
$E_{overall}$	Overall energy generation (kWh)
E_{th}	Thermal energy generation (kWh)
E_{total}	Total incident energy (kWh)
Ex_{el}	Electric exergy output (kWh)
Ex_{in}	Total exergy input (kWh)
Ex_n	Annual exergy generation (kWh/year)
Ex_{out}	Total exergy output (kWh)
Ex_{loss}	Total exergy loss (kWh)
Ex_{th}	Thermal exergy output (kWh)
f_l	Liquid fraction (-)
G	Effective incident radiation (W/m^2)
H_{pv}	Height of PV panel (m)
h_t	Total heat transfer coefficient (W/m^2K)
H_d	Height of depression (m)
H_e	Height of extension (m)
h_n	Natural heat transfer coefficient (W/m^2K)
r h_w	Forced heat transfer coefficient (W/m^2K)
i	Interest rate (%)
i_d	Depreciation rate (%)
I_{max}	Maximum incident solar radiation (W/m^2)
$I_{gain}ratio$	Ratio of utilized radiation to unutilized radiation (-)
I_{solar}	Incident solar radiation (W/m^2)
$I_{solar}^{reflected}$	Reflected solar radiation (W/m^2)
$I_{unutilized}$	Unutilized solar radiation (W/m^2)
$I_{utilized}$	Utilized solar radiation (W/m^2)
k	Thermal conductivity (W/mK)
L	Thickness of rectangular PCM enclosure (m)
L_1	Lower thickness of non-rectangular PCM enclosure (m)

L_2	Upper thickness of non-rectangular PCM enclosure (m)
L_{sf}	Latent heat of fusion (J/kg)
m_p	Mass of PCM (kg)
$\frac{m_{upper}}{m_{lower}}$	Bifurcation mass ratio (-)
Nu	Nusselt number (-)
p	Pressure (Pa)
P_{out}	Electric power output per unit area of PV panel (W/m^2)
$P_{out}^{'''}$	Power output per unit volume (W/m^3)
$P_{out,top}$	Electric power output per unit area of top PV panel (W/m^2)
$P_{out,bottom}$	Electric power output per unit area of bottom PV panel (W/m^2)
$q_{conv}^{''}$	Convective heat loss rate (W/m^2)
$Q_{gen}^{'''}$	Heat generation rate per unit volume (W/m^3)
$q_{in}^{''}$	Conductive heat flux into the system (W/m^2)
$q_{loss}^{''}$	Cumulative effect of convective and radiative heat loss rate (W/m^2)
$q_{rad}^{''}$	Radiative heat loss rate (W/m^2)
Q_{stored}	Stored heat inside PCM enclosure (J)
S	Salvage value ($)
$S_{Boussenisq}$	Boussenisq source term (N/m^3)
S_{Darcy}	Darcy source term (N/m^3)
t	Time (s)
T_a	Ambient temperature (°C)
T_{amp}	Amplitude temperature (K)
T_{avg}	Average ambient temperature (K)
T_f	Final temperature (°C)
t_g	thickness of glass layer (m)
T_i	Initial temperature (°C)
T_m	Melting temperature of PCM (°C)
T_{PCM}	Local PCM temperature (°C)
t_{pv}	thickness of PV layer (m)
T_{ref}	Reference temperature of PV panel (°C)
T_s	Surface temperature (°C)
T_{sky}	Sky temperature (°C)
T_{sun}	Sun temperature (°C)
$\vec{u}$	velocity (m/s)
v_w	Wind speed (m/s)
V_L	Volume of left side of bifacial PCM enclosure (m^3)
V_{PCM}	Volume of PCM enclosure (m^3)
V_R	Volume of right side of bifacial PCM enclosure (m^3)

x, y	Cartesian coordinates (m)
z_{CO_2}	Global carbon value (\$)
Z_{CO_2}	Earned carbon credit (\$)

Greek symbols

α_{pv}	Absorptivity of PV surface (-)
β	Thermal expansion coefficient of PCM (K^{-1})
$\beta_{ref.}$	Reference thermal expansion coefficient of PV panel (K^{-1})
γ	Reflectivity (-)
ε	Emmisivity
ϵ	Small constant (-)
η_{pv}	Electric energy efficiency or electric conversion efficiency of PV panel (-)
$\eta_{Ex,el.}$	Electric exergy efficiency (-)
$\eta_{Ex,overall}$	Overall exergy efficiency (-)
$\eta_{Ex,th.}$	Thermal exergy efficiency (-)
$\eta_{overall}$	Overall energy efficiency (-)
$\eta_{pv,top}$	Electric conversion efficiency of top PV panel (-)
$\eta_{pv,bottom}$	Electric conversion efficiency of bottom PV panel (-)
$\eta_{ref.}$	Electrical efficiency at reference condition of PV panel (-)
η_{th}	Thermal energy efficiency (-)
μ	Dynamic viscosity (kg/ms)
ρ	Density (kg/m^3)
σ	Stefan-Boltzman constant (W/m^{2}K^4)
τ_{glass}	Transmissivity of glass (-)
φ_{CO_2}	CO_2 emmisions (ton)

Subscripts

$a.$	Ambient condition
$conv$	Convective
cum	Cumulative
d	Depression
e	Extension
el	Electrical
f	Final condition
g	Glass layer
i	Initial condition
in	Input
L	Leftside of enclosure

m	Melting
n	Natural
out	Output
s	Surface
sf	Fusion
t	Total/cumulative
th	Thermal
pv	PV panel
R	Rightside of enclosure
ref	Reference condition
rad	Radiative condition
w	Wind

Abbreviations

AE	Absorbed energy
AECP	Annual electricity provurement cost
AMC	Annual Maintenance cost
AS	Annual savings
ASV	Annual salvage value
BIF-PV	Bifacial photovoltaic
BIPV	Building integrated photovoltaic
BIF-PV/PCM	Bifacial PV/PCM systems
CRF	Capital recovery factor
ESD	Energy storage density
FAC	First annual cost
LESD	Latent energy storage density
PCM	Phase change material
PV	Photovoltaic
PV/PCM	Photovoltaic integrated with phase change material
PVT/PCM	Photovoltaic thermal system integrated with phase change material
SESD	Sensible energy storage density
SSF	Sinking fund factor
TAC	Total annual cost

Abstract

The global energy demand of the world expands with population growth which causes excessive load on conventional energy resources such as fossil fuels. Conventional energy sources are limited and cause various environmental problems such as air pollution, global warming, and sudden climate changes. Therefore, an increase in unconventional energy resources such as solar energy, wind energy, geothermal energy, and other resources must be emphasized to meet future rising energy demands and reduce the growing environmental problems. Photovoltaic (PV) technology is an excellent clean and green energy option. PV panels convert solar energy directly into electrical energy. However, most incoming radiation is wasted in the form of heat that increases the operating temperature of the PV panel and degrades its electric conversion performance. The electric conversion efficiency of the PV panel is inversely proportional to its operating temperature. Hence, the electric performance of the PV panel can be enhanced by reducing its operating temperature using appropriate cooling technique. The application of the cooling technique enhances also enhances the utilization of incoming radiation by absorbing waste heat. The phase change material (PCM) integrated PV panels (PV/PCM systems) could be a viable option to enhance PV panel's electric performance and store heat for nocturnal hours. However, the conventional rectangular PCM enclosure exhibit degradation in performance in later stages of melting process. The unsymmetrical pattern of melting in conventional enclosures leads to non-uniform temperature distribution, which degrades the electric and heat storage performance of conventional PV/PCM systems. Therefore, design modifications and innovations of PCM encapsulations are desired to improve thermoelectric performance. In this thesis, a series of new design concepts of PCM encapsulations for PV/PCM systems and bifacial PV/PCM systems working on the principle of augmented 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 improve electric conversion performance and heat storage performance. Firstly, a non-rectangular PCM enclosure (same volume as the conventional enclosure) is integrated into the PV panel to take advantage of unsymmetrical melting caused by the natural convection of liquid PCM. The PV panel exhibits significant enhancement in thermoelectric performance; however, the compactness of the PV/PCM system is partially compromised. Secondly, an overhead type rectangular PCM enclosure is examined for the PV/PCM system to take the waste heat away from the PV panel and reduce the PV panel temperature. This design modification is based on the concept that the melting front can propagate in both (horizontal and vertical directions) if the enclosure is extended to an optimum height. Further, another novel enclosure design is conceived in the form of an extended non-rectangular enclosure to investigate the effect on performance. The idea was to provide optimum distance to the melting front to travel in horizontal and vertical directions. This modified configuration exhibits better thermo-electric performance and provide compact geometry. Lastly, a more efficient bifacial PV/PCM system is proposed to enhance thermoelectric performance. This modification involves radiation reflection by an L-shape mirror system and PCM enclosure modification according to melting morphology. The bifacial PV/PCM system enhanced power output by 1.91 times that of the conventional PV system and 1.77 times that of the conventional PV/PCM system. The energy, exergy, economic, and viroeconomic analysis were carried out for the bifacial PV/PCM system. The proposed system not only exhibits better thermo-electric performance but also help in reducing energy procurement cost and carbon emissions. All the aforesaid new designs show significant improvement in thermos-electric performance compared to conventional systems.

Chapter 2 explored the avenues to improve the electrical efficiency of photovoltaic (PV) panel by absorbing waste heat in encapsulated phase change materials (PCM) during the melting process. Previous investigators reported the melting process of PCM in a rectangular encapsulation and observed four transient regimes of heat transfer in sequence as: conduction, mixed conduction-convection, quasi-steady convection and solid-shrinking regimes. For higher heat extraction from the PV panel, longer duration of quasi-steady convection regime is desirable. However, this steady regime is suppressed in the rectangular PCM enclosure due to the nature of natural convection and consequently, the melting rate of the PCM is arrested. In this chapter, we report on electrical and thermal performance of non-rectangular PCM integrated PV panels using an experimentally validated numerical model that enhances the quasi-steady regime by more than 100% compared to the conventional rectangular design. The strategic mass distribution of PCM for better thermal management was achieved with encapsulation designs having profile of right wall varying as $y = (ax - b)^{1/n}$,with $n = 1$ (linear),2 (parabolic) and 3 (cubic) with different lower thickness ratio. Compared to conventional design, the proposed design increased the PCM melting rate by 17% due to which PV cell temperature dropped by 11.5% and consequently, electrical conversion efficiency approaches to 12%.

Chapter 3 examines the feasibility of non-rectangular type encapsulation for PV/PCM system under variable boundary and ambient conditions (similar to real conditions). The conventional design exhibits slow melting rates and degraded thermo-electric performance due to shorter regime of convective melting (ends before maximum insolation). The unsymmetrical loading of PCM in non-rectangular enclosure encourages characterization of melting according to natural convection. The proposed non-rectangular PCM enclosure for PV/PCM systems exhibits elongated quasi-steady convection regime far beyond the maximum insolation time causing increased melting rates. Compared to conventional design, the proposed design exhibits 20% more melting and PV panel works at 92% of its rated performance. The heat loss from the proposed system is approximately half compared to conventional system that explains higher insolation utilization ability of the system. Energy efficiency, exergy efficiency, economic, exergoeconomic, and enviroeconomic analysis are carried out for both conventional and proposed systems. The proposed system exhibits higher exergy efficiency (13.81%) and energy efficiency (73.95%) whereas conventional system exhibits somewhat lower exergy efficiency (13.66%) and a lower energy efficiency (69.77%). The economic analysis suggests that the proposed system exhibits approximately 3% lesser cost of production of electricity compared to conventional PV/PCM system. In terms of earned carbon credits, the proposed system also helps in reducing the CO_2 emissions to the environment. Hence, the proposed design of PV/PCM system would be beneficial in domestic and industrial applications.

In the chapter 4, a new design concept of overhead phase change material (PCM) enclosure design attached with a photovoltaic panel has been investigated. 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 chapter. The liquid PCM has a tendency to rise against gravity force but restricted by the top wall of enclosure alongside of PV panel in conventional PV/PCM system. However, the usage of extended enclosure allows the convection current to erode the melting interface in both horizontal and vertical direction. This phenomenon accelerates the melting process as the excessive heat is being taken away from the PV panel in the extended part of enclosure. This modification in design also solves the issue of compactness of the system and also provide encouraged thermo-electric performance. 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.

Chapter 5 examines an innovative concept of extended non-rectangular phase change material (PCM) enclosure integrated with a photovoltaic (PV) panel that manifests 7.26 times incoming solar radiation than the simple PV system. In extended rectangular type enclosures, the horizontal width of the PCM encapsulation is customized with same volume of PCM is maintained in the enclosure. This will hinder the movement of melted PCM in horizontal direction and affects thermo-electric performance due to slower melting rates. Hence the enclosure design is changed to an extended non-rectangular enclosure to improve further performance. The strategic distribution of PCM is achieved by controlling certain geometric parameters such as lower thickness ratio, extension ratio and profile of right wall. With optimization of these parameters, the span of convection dominated regime is prolonged to more than 120 minutes which conceded 20.5% more melting compared to the conventional rectangular design of same PCM volume. Electric conversion efficiency can approach to 96.37% of its rated value with the application of strategies demonstrated in the paper. Moreover, incoming radiation absorbing capacity can approach to 67.35% for recommended configuration. An experimentally validated numerical model is used to report the findings of this investigation which can predict exact melting morphology and thermal behavior of the system. This study provides useful information that will be helpful in developing more efficient PV techniques that can meet the ever rising global energy demands.

Chapter 6 examines a new concept of bifacial PV/PCM (BIF-PV/PCM) system with sandwiched thermal energy storage enclosure that possesses 1.21 times power output density and 7.39 times total energy utilization density per unit land area compared to the conventional PV system. Based on the melting morphology and thermo-electric performance of the initially rectangular PCM enclosure, an optimized bifurcated non-rectangular design of the enclosure is proposed to enhance the incident radiation utilization ability by 87% more than a simple one PV/PCM system. Enhanced utilization of solar radiation manifests into 105% more melting compared to conventional PV/PCM system. With the strategic mirror reflection and bypassing the solar radiation towards the rear PV panel and strategic design of PCM enclosure to aid convection-driven melting, electric power output has been increased significantly (about 77%) compared to similar conventional PV/PCM system. The study revealed that overall system efficiency could approach about 74% if suitable strategies are adopted, as demonstrated in this chapter. Results are discussed in terms of energy utilization efficiency, exergy efficiency, power conversion efficiency, tracking melting front morphology, and its effect on heat transfer characteristics, etc. This investigation has been carried out with the help of an experimentally validated numerical model that accurately mimics the melting morphology of PCM and other heat transfer characteristics of the system. The findings of this study would help design and develop a more efficient BIF-PV/PCM system to meet exponentially increasing energy needs.

A series of novel designs of PCM encapsulation for PV/PCM systems have been investigated in the thesis using computational fluid dynamics with an objective to meet global energy demands. The efforts put in the present research certainly adds contribution to the global theme of *'**Clean and green energy for all**'*.