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Performance study and analysis of an inclined concentrated photovoltaic-phase change material system

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ABSTRACT

The performance of an inclined concentrated photovoltaic-phase change material (CPV-PCM) system is investigated. The influence of a CPV-PCM system inclination angle in the range of −45° to 90° in an interval of 45°, with a concentration ratio (CR) of 5, and 20, and a phase change material thickness of 50, and 200 mm, is considered. To determine the effect of these variables on the thermal and electrical behavior of the system, a comprehensive model comprising of the energy equations for CPV layers and a transient melting-solidification thermo-fluid model for the phase change material is developed. The model is numerically simulated, and the predicted results are validated using the available experimental and numerical data. Results indicate that the CPV-PCM system inclination angle has a notable effect on the time required to reach the complete melting state, the transient variation of average cell temperature, and PV local temperature uniformity. It is found that a remarkable reduction of the average solar cell temperature with enhanced uniformity is achieved, as the inclination angle varies from 0° to 90°. On the contrary, at an inclination angle of −45°, the maximum average temperature along with an unfavorable abrupt change of local cell temperature is obtained. In addition, at an inclination angle of 45°, the highest cell electrical efficiency is attained for the entire time period until complete melting occurs, whereas at an inclination angle of −45°, the solar cell electrical efficiency is dramatically reduced with time. The findings of the present study reveal that the CPV-PCM at an inclination angle of 45° reaches the minimum average temperature with reasonable uniformity of local solar cell temperature. These conditions achieve the highest solar cell electrical efficiency and help to prevent hot spots in the solar cell.

1. Introduction

Concentrated photovoltaic (CPV) systems are one of the most promising applications of solar energy due to their high solar energy gain with a small capital cost. In addition, more PV power output could be acquired by using less solar cell material compared to other conventional non-concentrated PV systems. In CPV, relatively inexpensive materials such as plastic lenses or mirrors are used to capture the incident solar irradiance on a relatively large area and concentrate that energy onto small solar cell (Du et al., 2012). However, only 15–20% of the incident solar irradiance received by the PV panel can be transformed into electricity, while the rest is dissipated as heat. This absorbed heat raises the PV operating temperature, and as a result, both the electric conversion efficiency and the solar cell lifetime decreases (Norton et al., 2011). It has been reported that, when the temperature of crystalline silicon cells is above the standard operating temperature 25 °C, the solar cell electrical efficiency is likely to decrease by approximately 0.4–0.65% per one degree rise of temperature in the cell (Ma et al., 2015); therefore thermal regulation of CPV systems is of great importance.

Many researchers have been searching for an efficient cooling system to mitigate the impact of excessive temperature rise in the CPV conversion efficiency by removing heat from CPV module surface in order to maintain high performance. The effective cooling method would achieve high efficiency, prolong the lifetime of PV system, and enhance the possibility of using concentrators. It was reported that incorporating phase change materials (PCM) within PV systems for thermal regulation is an efficient cooling methodology (Elarga et al., 2016; Hasan et al., 2017; Kant et al., 2016a). The PV-PCM system absorbs a significant amount of energy as latent heat during the PCM phase changes from solid to liquid

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Nomenclature

A_{mush}	mush zone constant (kg/m^3 s)
ARC	anti-reflective coating
BIPV	building integrated photovoltaic
C	specific heat (J/kg K)
CR	concentration ratio
EVA	ethylene vinyl acetate
g	gravity acceleration (m/s^2)
G(t)	concentrated solar irradiance (W/m^2)
G	reference solar irradiance, 1000 (W/m^2)
$h_{conv,g\text{-}amb}$	convection heat transfer coefficient from the glass cover to the atmosphere (W/m^2 K)
$h_{rad,g\text{-}sky}$	radiation heat transfer coefficient between the glass cover and the sky (W/m^2 K)
$h_{cond,sc\text{-}g}$	conduction heat transfer coefficient between the silicon cell and the glass cover (W/m^2 K)
h_b	convection heat transfer coefficient from exterior back wall to the surrounding (W/m^2 K)
h_1	sensible enthalpy (J/kg)
H	total enthalpy of the material (J/kg)
H_1	solar cell height (m)
K	thermal conductivity (W/m K)
L	PCM container thickness (m)
L_1	latent heat (J/kg)
P	pressure (N/m^2)
PCM	phase change material
q“	rate of energy per unit area (W/m^2)
t	time (min)
T	temperature (°C)
T_{amb}	ambient temperature, 25 °C
T_{ini}	initial temperature, 25 °C
T_m	melting temperature of the PCM
T_{ref}	reference solar cell temperature, 25 °C
T_{sky}	sky temperature (°C)
ΔT_m	phase transition range
V_w	wind velocity (m/s)
u,v	velocity in x and y-direction respectively (m/s)
α	absorptivity
β_{sc}	solar cell backing factor
$\beta_{1,ref}$	solar cell temperature coefficient (1/K)
β_2	thermal expansion coefficient
ε	emissivity
τ	transmissivity
μ	dynamic viscosity (Pa s)
σ	Stephan–Boltzmann constant, $5.67 * 10^{-8}$ ($W/(m^2 K^4)$)
ρ	density (kg/m^3)
δ	thickness (m)
η_{sc}	solar cell electrical efficiency
η_{ref}	solar cell reference efficiency
λ	liquid fraction
Θ	inclination angle (°)

over a very narrow range of transition temperature. Consequently, the electric conversion efficiency increases by preventing the overheating of the system during the day time. A comprehensive review of PV thermal regulation using PCM as a heat sink has been carried out by (Ma et al., 2015) and (Browne et al., 2015). They indicated that although different configurations of PV-PCM's were investigated, newly designed systems are still needed to overcome complications and achieve higher efficiency.

Most experimental research on PV-PCM systems was conducted under controlled conditions. The first numerical and experimental study using the PCMs with building integrated photovoltaic (BIPV) for thermal regulation was introduced by (Huang et al., 2004). Paraffin wax RT25 PCM was contained in a rectangular container fabricated from aluminum and subjected to solar irradiance of 750–1000 W/m^2. The front surface and PCM average temperatures were measured with and without metallic fins. Their experimental results were compared with the numerically predicted results. The comparison indicated a good agreement between experimental and numerical results. Huang et al. (2011), (2006a), (2006b), Jun Huang (2011) investigated the effect of using metal fins inserted inside the PCM on the thermal performance of the PV-PCM system. Their results indicated that added fins improved the PCM's thermal conductivity and reduced the PV cells' operating temperature compared to systems without fins. Hasan et al. (2010) investigated five different types of PCMs, with a phase transition temperature of 25 ± 4 °C, and latent heat ranged between 140 and 213 kJ/kg. Experiments were carried out using four different cell-size PV-PCM systems at three different values of solar incident irradiance ranging from 500 to 1000 W/m^2, and the ambient temperature was 20 ± 1 °C. Their results showed that using calcium chloride PCM in an aluminum based PV-PCM system maintained a lower PV temperature for a prolonged period at 1000 W/m^2, (up to 30 min at 18 °C below the reference system and 10 °C for 5 h). Biwole et al. (2013) reported that adding a PCM with a transition temperature of 26 °C on the back of the PV panel could maintain the panel temperature to less than 40 °C for 80 min and result in improved efficiency. Maiti et al. (2011) investigated the integration of paraffin wax PCM with a melting temperature ranging from 56–58 °C into the back of V-through PV module for thermal regulation. The temperature of the PV module with PCM could be maintained at 65–68 °C for 3 h at 2300 W/m^2 solar irradiance. However, the temperature of the PV module without PCM reached 90 °C within 15 min. Sharma et al. (2016) experimentally investigated the effect of using PCM on the cell electrical efficiency. They concluded that the relative electrical efficiency improved by 1.15%, 4.20%, and 6.80% when the irradiance was 500, 750, and 1200 W/m^2 respectively.

A few experiments were performed under actual outdoor climatic conditions. Park et al., 2014 compared the performance of a PV-PCM module installed on a vertical wall surface with that of a reference PV module without PCM under real outdoor climatic conditions. Their results showed that the optimal melting temperature was 25 °C regardless of installation direction, whereas the optimal thickness of the PCM slightly varied according to the installation direction of the PV-PCM module. In addition, the electric power generation from the PV-PCM module was increased by 1.0–1.5% compared to that of the reference PV module. Hasan et al., 2015 evaluated the PV-PCM system in different outdoor climatic conditions by using Calcium chloride hexahydrate $CaCl_2$-$6H_2O$ or Eutectic of Capric-Palmitic acid. They concluded that both systems achieved a higher temperature drop and power saving compared to the reference PV without the PCM.

A novel photovoltaic-thermal system with PCM (PV-T-PCM) was examined under outdoor conditions in Dublin, Ireland by (Browne et al., 2016). This system combined a PV module with a heat exchanger embedded in PCM and heat was removed from the system through a thermosiphon flow. The thermal behavior of the PV-T-PCM system was compared with that of three reference systems (a) the same system without PCM, (b) the same system without heat exchanger and PCM, and (c) the PV module alone.