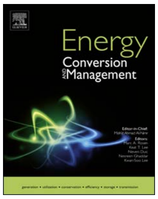
Energy Conversion and Management 158 (2018) 298–314

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman



Cooling concentrator photovoltaic systems using various configurations of phase-change material heat sinks

Mohamed Emam, Mahmoud Ahmed*,[1]

Department of Energy Resources Engineering, Egypt-Japan University of Science and Technology (E-JUST), Alexandria 21934, Egypt

ARTICLE INFO

Keywords:
Concentrator photovoltaic
Cooling
Phase change materials

ABSTRACT

A new hybrid concentrator photovoltaic-phase change material system is developed to attain rapid thermal dissipation by enhancing the typically low thermal conductivity of phase change materials. The developed system includes four different configurations of phase change material heat sinks: single cavity, three-parallel cavity, five-parallel cavity, and three-series cavity configuration. Furthermore, nine different pattern arrangements of phase change materials are studied. A comprehensive two-dimension model of photovoltaic layers integrated with phase change material heat sink is developed to predict the transient temperature variation at different concentration ratios of 10 and 20. The model is numerically simulated and validated with the available experimental data; the heat sink configurations with three and five parallel cavities are found to significantly reduce the solar cell temperature compared to the single cavity and three-series cavity heat sink configurations. Furthermore, the use of a five-parallel cavity heat sink is found to greatly enhance temperature uniformity of the solar cell. Substantial enhancement in temperature uniformity is also observed with different pattern arrangements of the phase change materials using the three-parallel cavity configuration. These findings can help identify the optimal configuration of heat sinks and pattern arrangements of phase change materials in order to achieve higher performance with concentrator photovoltaic systems.

1. Introduction

Concentrator photovoltaic (CPV) systems are widely recognized as the most efficient form of photovoltaic (PV) power generation due to high solar energy gain and low capital cost. In CPV systems, relatively inexpensive materials such as plastic lenses or mirrors are usually used to capture the incident solar irradiance on a large surface area and concentrate that energy into small solar cells [1]. Furthermore, the risk to investors is reduced due to a lower capital investment need, arising from the decreased use of expensive semiconductor materials compared with other types of PV. Rather, the capital investment for CPV tends to be distributed between the cell, lens or mirrors, tracker, and other supplies. CPV systems can be installed in sizes ranging from kilowatts to megawatts. Therefore, CPV systems are a promising alternative power source and can be widely used in industry in the foreseeable future. However, due to high concentration ratios (CRs), a significant increase in solar cell temperature occurs in these systems, which reduces the electrical conversion efficiency and increases the risk of damage to the CPV systems [2]. Therefore, thermal regulation of CPV systems is of great importance.

Extensive research has been conducted to develop an effective cooling system to reduce the impact of excessive temperature rise on the electrical conversion efficiency of CPV systems. An effective cooling method would attain higher performance, a prolonged lifetime, and provide the possibility of using concentrators. One such effective cooling method integrates phase change materials (PCMs) with PV systems for thermal management. Phase change materials absorb a significant amount of thermal energy as latent heat during the solid-liquid phase transition at approximately constant phase change temperature [3]. Thus, the electrical conversion efficiency increases by preventing the overheating of the PV cells during the daytime. In addition, the use of PCMs has added the advantage of storing heat energy that can be utilized for other purposes or directly used in buildings [4]. Consequently, the overall efficiency of the system will increase. Shukla et al. [5] reviewed various cooling methods of PV systems such as natural and forced air cooling, hydraulic cooling, heat pipe cooling, cooling with PCMs and thermoelectric cooling. They concluded that cooling with PCMs is the most promising and effective cooling technique for PV systems due to its higher energy density per unit volume. Furthermore, another comprehensive review on PCMs with specific

---

* Corresponding author.
E-mail addresses: mahmoud.ahmed@ejust.edu.eg, aminism@aun.edu.eg (M. Ahmed).

[1] On leave from Mechanical Engineering Dept., Assiut University, Assiut 71516, Egypt.

https://doi.org/10.1016/j.enconman.2017.12.077
Received 7 June 2017; Received in revised form 16 December 2017; Accepted 23 December 2017

Nomenclature

A_{mush}	mush zone constant [$kg/m^3 \cdot s$]
C_p	specific heat [$J/kg \cdot K$]
CR	concentration ratio
g	gravitational acceleration [m/s^2]
G(t)	concentrated solar irradiance [W/m^2]
G	reference solar radiation, 1000 [W/m^2]
h	convection heat transfer coefficient [$W/m^2 \cdot K$]
h_1	sensible enthalpy [J/kg]
H	total enthalpy of the material [J/kg]
H_1	solar cell height [m]
K	thermal conductivity [$W/m \cdot K$]
L	latent heat [J/kg]
m	mass [kg]
P	pressure [N/m^2], Power per unit width [W/m]
Q	stored thermal energy [J/kg]
t	time [min]
T	temperature [°C]
V	velocity [m/s]
u, v	velocity in x and y-direction respectively [m/s]

Greek symbols

α	absorptivity
β	solar cell temperature coefficient [1/K]
β_1	thermal expansion coefficient [1/K]
ε	emissivity
τ	transmissivity
μ	viscosity [$Pa \cdot s$]
σ	Stephan–Boltzmann constant, 5.67×10^{-8} ($W/(m^2 K^4)$)
ρ	density [kg/m^3]
δ	thickness [m]
η	efficiency
λ	liquid fraction

Subscripts

amb	ambient
Al	aluminum
conv	convection
elec	electrical
E	EVA
g	glass
ini	initial
l	liquid
m	melting
PCM	phase change material
rad	radiation
refl	reflected
ref	reference
s	solid
sc	silicon cell
T	Tedlar
th	thermal
w	wind

focus on their solar applications has been carried out by Islam et al. [6]. They reported that using PCMs for photovoltaic thermal management is technically viable if the low thermal conductivity of PCM is properly managed. Park et al. [7] compared the performance of a PV-PCM module installed on a vertical wall surface with a reference PV module without PCM under real outdoor climatic conditions. They concluded that the energy generation efficiency of the PV-PCM module increased by about 3.1% compared to the reference PV module. Hasan et al. [8] evaluated the performance of a PV-PCM system in two different outdoor climates of Dublin, Ireland and Vehari, Pakistan using two PCMs; Calcium chloride hexahydrate $CaCl_2$–$6H_2O$, and Eutectic of Capric-Palmitic acid. They reported that both systems achieved a higher temperature drop and power savings (compared to the reference PV system without the PCM) in warm and stable weather conditions of Vehari than the cooler and irregular weather conditions of Dublin. Recently, Hasan et al. [9] conducted a numerical and experimental study to evaluate the yearly energy performance of a PV-PCM system in extremely hot environment of the United Arab Emirates (UAE). Their results showed that the PV-PCM system improved the annual PV power output by 5.9%. A detailed numerical study of the PV panel coupled with PCM at its back has been developed by Kant et al. [10]. The convection effect within melted PCM, the wind speed and inclination angle of PV panel were examined. They concluded that the use of the PCM is an effective cooling technique since it attains a significant reduction in solar cell temperature. Browne et al. [11] presented comprehensive review of PV thermal regulation using PCMs as a heat sink. The literature presented in this paper has shown that PCM is not only useful for non-concentrator PV but also has particular potential for cooling concentrator photovoltaic systems.

Sharm et al. [12] experimentally investigated the effect of using Paraffin wax (RT42) as the PCM on the electrical performance of low concentration, building integrated CPV systems. They concluded that the relative electrical efficiency improved by 1.15%, 4.20%, and 6.80% (compared to the non-PCM system) when the irradiance was 500, 750, and 1200 W/m^2 respectively. A theoretical study to mitigate the temperature fluctuation of the concentrator photovoltaic-thermoelectric (CPV-TE) system using PCM was conducted by Cui et al. [13]. Their results indicated that using PCM can suppress the effect of solar irradiance fluctuation on the CPV-TE system and maintain it to operate at the optimal operating temperature. Moreover, the performance of the CPV-PCM-TE system was enhanced compared to that of PV cells and PV-TE systems. For low concentration ratios (CRs) up to 20, Emam et al. [14] investigated the influence of concentrate or photovoltaic-phase change material's (CPV-PCM) system inclination angle on the solar cell temperature at varying concentration ratios and PCM thicknesses. Their results indicated that using CPV-PCM with an inclination angle of 45° achieves the minimum average cell temperature with a reasonable uniformity of local temperature, while the use of an inclination angle of −45° leads to a higher temperature and an unfavorable performance.

Further research is still needed to promote CPV-PCM systems. Key difficulties include the low thermal conductivity of most PCMs, which leads to a poor heat transfer rate from the CPV cell to the PCM [15]. Additionally, the low PCM thermal conductivity leads to a temperature gradient and stratification within the PCM container. This causes a noticeable non-uniform temperature distribution in the CPV cell, and eventually generates hot spots. Thus, different techniques have been utilized to improve the performance of PCMs in thermal energy storage and management systems. A comprehensive review of experimental and numerical studies to achieve high heat conductivity rates of the PCM and its container for latent thermal energy storage was introduced by Fan et al. [16]. Moreover, Jegadheeswaran et al. [17] reviewed different methods employed to enhance the PCM thermal conductivity such as using extended surfaces, impregnation of porous material, dispersing of high conductivity particles in the PCM, placing of metal structures and using high conductivity and low density materials. They indicated that the insertion of metal fins inside PCM is the most widely adopted technique for the thermal regulation of PV cells. Accordingly, Huang et al. [18] investigated the effect of fin spacing, width, and fin materials on the PV-PCM system performance. They noticed that the insertion of fins improved the heat transfer process in the PCM heat sink