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ScienceDirect
Solar Energy 124 (2016) 114–123
SOLAR ENERGY
www.elsevier.com/locate/solener

Development of a thermal model for a hybrid photovoltaic module and phase change materials storage integrated in buildings

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Received 9 October 2015; received in revised form 19 November 2015; accepted 25 November 2015
Available online 17 December 2015

Communicated by: Associate Editor Brian Norton

Abstract

The performance of building integrated photovoltaic modules (PV) situated outdoors suffers from attained high temperatures due to irradiation as a negative temperature coefficient of their efficiency. Phase change materials (PCMs) are investigated as an option to manage the thermal regulation of photovoltaic modules and, hence, enhance their electrical efficiency. In this study a transient one-dimensional energy balance model has been developed to investigate the thermal performance of a photovoltaic module integrated with PCM storage system. Possible all heat transfer mechanisms are described to have a basic and step by step fundamental knowledge to analyze and understand the complex heat transfer characteristics of the PV-PCM system. Finite difference scheme is applied to discretize the energy balance equation while fully implicit scheme is applied to discretize the heat balance in the PCM module. Three different PCM of different melting temperatures were investigated. The numerical result is validated with experimental studies from the literature. The result indicates that PCM are shown to be an effective means of limiting the temperature rise in the PV devices thus increasing the thermal performance up to 5%.

Keywords: Photovoltaic module; Phase change materials; Buildings; Efficiency enhancement; Finite difference scheme

1. Introduction

Depending on type and developed technologies of silicon photovoltaics (PV), the power drop of PV above 25 °C was found to be 0.3%/K to 0.65%/K subjected to the type of PV cells (Radziemska et al., 2003). Up to date, to describe the dependency of PV operating temperature on climate condition, various mathematical correlations have been developed and discussed (Skoplaki and Palyvos, 2009). It was seen that, the power drop and the temperature rise in the PV cell largely depends on the climate of the sites (Bücher, 1997; Amy de la Breteque, 2009). For example, in southern Libya (27.6°N and 14.2°E), 69% reduction in nominal power was reported for 125 °C maximum PV operating temperature (Nassar and Salem, 2007). Furthermore, the integration of PV into building has shown so much temperature rise that there is almost 9.3% power reduction from the PV cell (Krauter and Hanitsch, 1996). The favorable operating temperature limit for PV cells ranges from −40 °C to 85 °C (http://www.arcmansolar.com/products/53.aspx?cid=7-12-11). However in real situation in hot climate, the PV temperature exceeds

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http://dx.doi.org/10.1016/j.solener.2015.11.027
0038-092X/

Nomenclature

A	area of the PV module (m^2)
a	coefficients
C	specific energy (J/K)
d	thickness of PV layer (m)
f	liquid fraction (Dimensionless)
H	enthalpy (J/kg)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	latent energy (J/kg)
m	mass of PCM (kg)
Nu	Nusselt number
Pr	Prandtl number of air
q	power (J/s)
Ra	Rayleigh number
T	temperature (°C)
Δt	time step (s)
x	characteristic length (m)
Δx	space step (m)

Symbols

α	absorption factor
ρ	density (kg/m^3)
β	thermal expansion coefficient (1/K)
ε	transitivity
σ	Stefan–Boltzmann constant (W/m^2 K^4)
ϕ	irradiation (W/m^2)
μ	dynamic viscosity of air (kg/m s)
υ	kinematic viscosity (m^2/s)

Subscripts

amb	ambient
air	air
b	bulk
$cell$	PCM cell
m	PV module
PV	photovoltaic cell
PCM	phase change material
$PV\text{-}PCM$	photovoltaic integrated with PCM module
sky	sky
n, P, E, W	cell identifier
p	black body

Superscripts

^{0}	previous/initial

the upper range (Nassar and Salem, 2007). The rise in PV temperature is mostly responsible for PV cell delamination, power failure and rapid degradation of the PV cell (Ružinsky and Redi, 2001). This situation presents the need for building integrated photovoltaics (BIPV) temperature regulation to maximize both panel power output and life. Until present, different passive and active heat removal technique has been investigated for non BIPV system to maintain the PV temperature. Heat removal due to buoyant circulation of air in a duct behind the PV were investigated by Yang et al. (1994) and (Brinkworth, 2000a, 2000b). It was seen that heat removal depends on the ratio of length to internal diameter of the duct (L/D) and maximum heat removal occurred at L/D of 20 (Brinkworth and Sandberg, 2006). For BIPV system, similar to non BIPV, the heat removal also depends on the buoyant circulation of air in an opening or air channel instead of a duct behind the PV. A theoretical analysis of buoyancy driven air flow in such an opening behind a façade integrated PV showed a maximum of 5 °C temperature reduction in averaged monthly temperature resulting in a net 2.5% increase in yearly electrical output of the PV (Yun et al., 2007). But the major problem of such cooling system is the temperature reduction is very low. To improve the heat removal much further for such system, suspending metal sheets and inserting fins as well as optimizing the air channel spacing were also investigated (Tonui and Tripanagnostopoulos, 2007; Fossa et al., 2008).

Optimum cooling of PV depends on the air or water flow on the front or back of the PV cell surface. To understand the effects of different inlet velocity of air with different air gaps in the front, side and back of PV cell was conducted by Mallick et al. (2007) and found that a maximum of 34.2 °C of temperature drop can be achieved by air inlet velocity of 1 m/s in front and back air gap of 20 mm. Similarly water as coolant of PV was investigated by Krauter (2004) and found that the electrical power output of PV can be increased by 8–9%. Water flow on the back of a façade integrated PV has theoretically shown optimum electrical and thermal performance at a water flow rate of 0.05 kg/s for a particular system in the weather conditions of Hefei, China at solar radiation intensities of 405 and 432 W/m^2 (Ji et al., 2006).

The history of thermal regulation of PV using PCM is not so old and first assessed experimentally for BIPV in 2004 by Huang et al. (2004). An aluminum box container contained the PCM having a coating of solar selective absorbing material with its front surface to mimic a PV cell attached to its front. 2D and 3D finite volume heat transfer simulation models were developed to study PCM performance for BIPV thermal regulation. Model predictions were found in good agreement with experimental results (Huang et al., 2006a, 2006b). Similar to the experiment described above, Hassan et al. (2007) got 10 °C temperature reduction for 6 h at 415 W/m^2 while using eutectic mixture of capric–lauric acid in an aluminum box container.