Solar Energy 135 (2016) 605–617

Contents lists available at ScienceDirect

Solar Energy

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

Experimental performance evaluation and modeling of jet impingement cooling for thermal management of photovoltaics

Haitham M.S. Bahaidarah

Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:
Received 2 January 2016
Received in revised form 28 May 2016
Accepted 6 June 2016

Keywords:
Photovoltaics
Cooling
Modeling
Jet impingement
Experimental
Thermal management

ABSTRACT

Thermal management of PV systems is one of the most important factors that affect the overall performance especially in hot climate regions. In this paper, the viability of jet impingement cooling for PV panels subjected to the climatic conditions of Dhahran region of Middle East has been discussed. Experimental and numerical performance evaluation was carried out for two configurations, an uncooled PV system and an impingement cooled PV system. The complete cooling model incorporates optical, radiation, thermal, geometric and electrical model for the overall performance analysis of the PV system. Jet impingement geometric model for PV was developed to carry out the heat transfer analysis for single nozzle for analyzing the cell temperature, power output and conversion efficiency of PV strings. For precise prediction of the performance of the PV cell, seven parameters electrical model is employed, whereas for absorbed radiation calculation isotropic sky model is adopted. Temperature measurements revealed cell temperature as high as 69.7 °C and 47.6 °C for an uncooled system for June and December, respectively. By applying jet cooling, average cell temperature was reduced to 36.6 °C for June and 31.1 °C for December. Power output and conversion efficiency was enhanced by 51.6% and 66.6% by employing jet cooling for June, respectively. Similarly, December results revealed performance improvement by 49.6% in power output and 82.6% in conversion efficiency. Simulation carried out reveals that jet cooling with optimum parameters has not only significantly increased the electrical power output and cell efficiency but has reduced the cell temperature while keeping it uniform for each cell.

1. Introduction

Thermal management of photovoltaic (PV) systems plays a key role for low and high concentration systems. The overall performance of solar panels is strongly dependant by the affect of PV cells' operating temperature. Commercially existing PV modules generally converts 13–20% of incident solar radiation to electricity (Usama Siddiqui et al., 2012). The remaining component of radiation absorbed in the cell transforms into thermal energy which causes the temperature of the cell to be increased. This further causes the panel efficiency to decrease as the open circuit voltage and fill factor is reduced with rising temperature (Amin et al., 2009; Bahaidarah et al., 2013; Du et al., 2013; Erdil et al., 2008; Kumar and Rosen, 2011; Ling et al., 2014; Micheli et al., 2013; Radziemska and Klugmann, 2002; Radziemska, 2003; Teo et al., 2012; Yadav et al., 2013). With an increase in the PV cell temperature, the open circuit voltage and fill factor is reduced, which decreases the conversion efficiency of the PV system (Royne et al., 2005). Hence, the cooling technique is desirable to maintain the cell at the operating temperature and should be such that it keeps the average cell temperature at its minimum with a uniform distribution (Bahaidarah et al., 2014; Chenlo and Cid, 1987; Du et al., 2013; Royne et al., 2005).The temperature distribution in PV panels generally depends on the PV cell material, PV cell type, the panel configuration, the electrical load attached to the PV system, the prevailing environmental conditions and in case of cooling, the characteristics of the heat dissipation technique (Baig et al., 2012). The main reasons for non-uniform flux distribution this issue are the PV cell material, geometry of the concentrator, optical properties of concentrators, design, and manufacturing method (Baig et al., 2012).

In this paper a cooling technology is presented to investigate the optimum geometry which would result in the best global performance with uniform temperature profile and low cell temperature so that the entire string could be operated under similar temperature values to avoid current mismatching and hotspot problem. In a non-uniform temperature distribution, PV cell in a string operates at different power points and results in a faulty mode thereby reducing the performance of PV with reduced efficiency (Gokmen et al., 2013) and increased thermal stresses

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E-mail address: haithamb@kfupm.edu.sa

http://dx.doi.org/10.1016/j.solener.2016.06.015
0038-092X/

Nomenclature

a	modified diode ideality factor (V)
A_c	area of PV string (m^2)
C_d	discharge coefficient of nozzle
CPV	concentrated photovoltaic
d	diameter of nozzle
e	elementary charge, 1.60218×10^{-19} (C)
F	Reynolds number parameter in jet model
G	total horizontal radiation (W/m^2)
G_b	horizontal beam radiation (W/m^2)
G_d	horizontal diffuse radiation (W/m^2)
G_{ref}	reference condition (STC) incident radiation (W/m^2)
h	heat transfer coefficient (W/m^2 K)
h_w	wind heat transfer coefficient (W/m^2 K)
G_T	total tilted incident radiation (W/m^2)
I	PV output current (A)
I_L	light current (A)
I_o	diode reverse saturation current (A)
k	thermal conductivity, (W/m K)
K	extinction coefficient
$K_{\tau\alpha,b}$	incidence angle modifier for beam radiation
L	thickness of front glass layer (m)
m	irradiance dependence parameter for I_L
M	air mass modifier
N	number of nozzles
n	temperature dependence parameter for ideality factor
Nu	Nusselt number
P	electrical power (W)
P_{net}	net power (W)
P_{pump}	pumping power (W)
ΔP	pressure drop (Pa)
q	heat transfer (W)
Q	flow rate (m^3/s)
r	equivalent radius of cooled plate
R_{beam}	geometric factor for beam radiation
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
$RMS\%$	root mean square percent deviation (%)
R_{top}	top loss thermal resistance (K/W)
R_{bottom}	bottom loss thermal resistance (K/W)
Re	Reynolds number
S_{pv}	absorbed solar radiation at operating conditions (W/m^2)
S_{ref}	absorbed solar radiation at STC (W/m^2)
T	temperature (°C)
T_{amb}	ambient temperature (°C)
S	plane-of-array absorbed solar radiation at operating conditions (W/m^2)
$T_{f,in}$	inlet water temperature (°C)
T_{cell}	cell temperature (°C)
V	voltage (V)
V_w	wind speed (m/s)
z	nozzle to plate spacing

Greek symbols

β	slope of PV string
δ_W	uncertainty of variable "W"
η_{mp}	electrical efficiency of PV at maximum power point
ρ	reflectivity of ground
θ	incidence angle of solar radiation
θ_r	refracted angle of solar radiation
σ	Stefen–Boltzmann's constant
$(\tau\alpha)$	Transmitivity–Absorptivity product

Subscripts

0	reference condition
al	aluminum
amb	ambient
avg	average
b	beam radiation
bs	backsheet
c, cell	PV cell
conv	convection losses
diff	diffuse radiation
exp	experimental
mod	modeled
martin	martin model
mp	maximum power point
n	normal
oc	open circuit point
opt	optimum condition
ref	reference cell condition
rad	radiation losses
sc	short circuit point
string	parameter for PV string
tot	total
uniform	uniform temperature distribution

(Royne et al., 2005). Moreover this effect further aggravates the performance of PV systems in the case of concentrated systems where the effect of non-uniformity is much pronounced. Non-uniform temperature across the PV string has been found to affect the cell efficiency and overall system performance in a negative way (Baig et al., 2012; Chenlo and Cid, 1987; Luque et al., 1998; Mathur et al., 1984; Royne et al., 2005; Sanderson et al., 1980). Non-uniformity in temperature distribution affect the PV system performance in two ways: (1) Cells experience efficiency loss due to loss in power output; (2) Temperature variation induces thermal fatigue because of large amount of thermal cycles and stresses. This further cause the irreversible damage to solar cell due to excess localized heating across the region and reduces the reliability of the system (Royne et al., 2005). Due to the non-uniform temperature distribution, hot spots occurs on the cell resulting in reduction of life and safety of PV systems (Royne et al., 2005).

Series connected PV cells faces greater damage as current directly varies with light, so the current in an array of series of identical PV cells will be restricted by the solar cell with the maximum temperature. This failure is called as the 'current matching problem'. This issue can be solved by using bypass diodes or by keeping a uniform temperature across each series connection. Moreover conventional cooling mechanism like rectangular channel cooling in simple PVT systems result in temperature variation along the length of PV string because of the effect of constant heat transfer increase at the wall. Therefore, the cooling method should be such that it keeps the average cell temperature at its minimum with a uniform distribution (Baig et al., 2012; Royne et al., 2005).

Therefore the viability of jet impingement cooling, with its high heat transfer capability and uniform cooling characteristics, has been considered in this study to avoid the failure modes of current mismatching and structural damage due to thermal stresses. The proposed study is full scale real time PV setup which has been tested under climate conditions of Dhahran and is an extension from the laboratory scale setup developed by Royne and Dey (2007). Moreover, the PV system model developed by coupling five sub-models shows a good agreement between experimental and simulation results. Electrical model employed is seven parameters model which estimate precise module parameters even for low irradiance and high temperature (Siddiqui and Abido, 2013).