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Experimental and numerical performance analysis of a converging channel heat exchanger for PV cooling

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ABSTRACT

An experimental and numerical investigation of a cooling technique called as converging channel cooling intended to achieve low and uniform temperature on the surface of PV panel is presented in this paper. Experimental evaluation for an uncooled PV system and a converging channel cooled PV system was carried out subjected to the hot climate of Saudi Arabia for the month of June and December. Detailed modeling was performed using numerical analysis to investigate the effect of changing the converging angle on the thermal characteristics of the PV system. Based on the developed model, two degrees angle showed the best performance in terms of temperature distribution and average cell temperature with a standard deviation of 0.91 °C. A comprehensive system model was developed to assess the performance of PV systems numerically by coupling the optical, radiation, thermal, computational fluid dynamics, and electrical model. Thermal measurements for an uncooled PV showed cell temperature as high as 71.2 °C and 48.3 °C for the month of June and December, respectively. By employing converging cooling, cell temperature was reduced significantly to 45.1 °C for June and to 36.4 °C for December. Maximum percentage improvement in power output was 35.5% whereas maximum percentage increase in the conversion efficiency was 36.1% when compared to the performance of an uncooled PV system. For cost feasibility of an uncooled and cooled PV system, levelized cost of energy (LCE) analysis was performed using the annual energy yield simulation for both systems. LCE was found to be 1.95(€/kW h) for an uncooled PV system which was reduced to 1.57(€/kW h) for converging cooled PV system with a relative percentage decrease of 19.5%, hence making it economically viable.

1. Introduction

Photovoltaic (PV) cells are renewable energy devices, which convert sunlight directly into electrical energy. During this energy conversion process, these cells only convert part of the incoming solar radiation into useful power output while the remaining is lost as waste heat. Consequently, this waste heat raises the cell temperature. 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 [1–11]. 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 [6,12–14]. The primary criteria for the evaluation of heat exchanger considered in this study is 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 hot-spot problem. Non-uniform temperature across the PV string has been found to affect the cell efficiency and overall system performance in a negative manner [12,14–18]. 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 [12]. Due to the non-uniform temperature, hot spots occurs on the cell resulting in reduction of life and safety of PV systems [12].

Many investigations have been carried out experimentally and numerically to analyze the effect of the temperature on PV systems using cooling systems [19–28]. In some of these cases, the operating cell temperature for a typical PV cell was found out to be as high as 80 °C well beyond the typical 40 °C, the Nominal

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Nomenclature

a	ideality factor
A_c	area of the PV module (m^2)
C_p	specific heat capacity (kJ/kg K)
CELF	constant-escalation levelization factor
CFD	computational fluid dynamics
CRF	capital recover factor (%)
C_{Inv}	investment cost (€)
$C_{O\&M}$	annual operation and maintenance cost (€)
E_{annual}	annual electricity production by system (kW h)
h_w	wind heat transfer coefficient (W/K m^2)
i_{eff}	effective discount rate (%)
I	current at load (A)
I_T	amount of incident radiation (W/m^2)
I_L	light current (A)
I_{mp}	maximum power point current (A)
I_{sc}	short circuit current (A)
I_o	diode saturation current (A)
k_f	thermal conductivity of fluid (W/m K)
k_w	thermal conductivity of solid (W/m K)
LC_{Fuel}	levelized cost of fuel (€/kW h)
LCE	levelized cost of energy (€/kW h)
n	life time of system (years)
P	pressure (N/m^2)
P_{outlet}	outlet pressure (N/m^2)
PV	photovoltaic
P_{mp}	maximum power point electrical power
Q	flow rate (m^3/s)
Q	amount of heat transfer (W/m^2)
r_n	nominal escalation rate (%)
RMS %	root mean square percent deviation
R_{beam}	geometric factor
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
S_{PV}	amount of energy absorbed by PV (W/m^2)
T_{amb}	ambient temperature (°C)
T_{bs}	back surface temperature (°C)
T_{cell}	cell temperature (°C)
$T_{f,in}$	fluid inlet temperature (°C)
V_w	wind velocity (m/s)
V	voltage at load (V)
V_{pvcell}	volume of cells in a string
V_{oc}	open circuit voltage (V)
V_{mp}	maximum power point voltage (V)

Greek symbols

Ø	converging angle (°)
Θ	angle of incidence of surface for beam radiation (°)
ρ_g	ground reflectance
η_{mp}	conversion efficiency of cell (%)
$\tau\alpha$	product of transmittance absorbance product of solar cell
δ_W	uncertainty of variable W
μ	viscosity (Pa s)
β	slope of PV panel (°)

Operating Cell Temperature (NOCT) [29]. It is commonly found in literature that the maximum power output for a typical crystalline silicon panel decreases as the temperature increases [30]. At elevated temperatures, reduced power output has been reported for crystalline silicon solar cells with a power reduction coefficient of 0.5–0.65% °C^{-1}[10]. As indicated by Jiang et al. [31], more than 18% decrease in the maximum power was observed when a PV panel of 240 W was irradiated by solar radiation equivalent to 1000 W/m^2 as the operating temperature of the cell was changed from 0 °C to 75 °C.

Bahaidarah et al. [7] carried out an analysis of back surface cooling of a PV panel subjected to hot climatic conditions of the Middle East. It was concluded via the experimental setup that active cooling of rear surface resulted in a temperature drop of about 20% that led to an increase of efficiency by 11% for the climate of Saudi Arabia. Gang et al. [21] performed analysis of heat pipe photovoltaic/thermal (HP-PV/T) systems on annual basis for three locations in China. They developed a mathematical model of the HP-PV/T system for domestic hot water and electricity production. It was concluded that for the systems without auxiliary heat source, the annual electrical output and thermal energy were lower than the system with the auxiliary heat source. In a different study, an experimental setup was constructed for the cooling of a photovoltaic panel by Rahimi et al. [22]. The fabricated experimental apparatus was a laboratory scale cooling device based on a conic wind collecting tunnel. They observed that the combined electrical output was increased by 21% as compared to the simple cooling system. An experimental study was conducted on the cooling of hybrid micro channel PV cells using two phase flow by Valeh-e-Sheyda et al. [32]. The experiments were carried out at indoor conditions using air and water as the two phase fluid at different superficial velocity ranges. The two phase cooling was compared with that of a single phase; and it was concluded that the proposed hybrid system improves the performance of the PV cells.

In this paper, an experimental and a numerical assessment for PV systems were performed for a cooling technique called converging channel heat exchanger subjected to the hot climate of Saudi Arabia. primary aim is to manufacture and model a cooling technique which can attain uniform temperature profile while keeping the cell temperature to its minimum. Numerical analysis was performed to examine the effect of varying the converging angle on the temperature profile of the PV surface. Ambient data required for the analysis had been measured for the month of June and December, 2014 on site where the two systems were installed. Detailed analysis was carried out for the PV system comprising of Computational Fluid Dynamics (CFD) model, optical, radiation, thermal, and electrical models. This PV system model is then used to assess the overall performance of the converging channel cooled PV string and the uncooled PV string. Results obtained from the experiments are compared with the model for the thermal and electrical parameters. For the economic viability of cooled and uncooled PV systems, LCE analysis was carried out using annual energy yield simulations.

2. Experimental setup and measurements

2.1. Experimental setup

This experimental test facility has been designed to investigate the effect of the temperature on the performance of the PV systems. The performance of this heat exchanger is compared with an uncooled PV string subjected to the real time extreme climate of Saudi Arabia. The PV strings employed were manufactured by connecting eight solar cells in series with bottom contacts and have the dimensions as shown in Fig. 1. The active area of each solar cell is 125 mm by 125 mm and the system considered is flat PV. Maximum Power Point Tracker (MPPT) device was used during operation to extract maximum current and maximum voltage. The