Experimental Assessment of Flat-type Photovoltaic Module Thermal Behavior

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Abstract

The electrical performance and reliability of flat-type photovoltaic (PV) modules can be severely affected by elevated cell operating temperature in regions benefiting from high yearly solar irradiation levels, due to elevated ambient temperatures. In this work the potential of active cooling solutions to enhance flat-type PV module electrical performance, consisting of forced air- and water-cooling, is experimentally explored on laboratory-scale prototypes operated indoors under different light source illuminance levels. Forced-air and water-cooling are implemented using a duct-axial fan configuration and chilled water channel, respectively, both attached to the module non-active surface. In both cooling configurations, the cooling fluid directly wets the module non-active surface, thereby eliminating thermal contact resistance.

Forced air-cooling is found to improve module peak output power by approximately 10% relative to passive cooling, in an ambient temperature of 21°C. The output power of water-cooled modules increases by 48% using unchilled water at a temperature 21°C, and by 66% and 69% using chilled water at 14°C and 5°C, respectively, relative to passive cooling. The experiments conducted therefore provide an order-of-magnitude assessment of the technical feasibility of different active cooling strategies before characterizing commercial modules under solar irradiation conditions.

1. Introduction

The share of photovoltaic (PV) power generation is presently growing in the Middle East and developing countries having high yearly solar irradiation levels and sky clearness index. However, its implementation in extremely hot, dusty (i.e., desert) or humid (i.e., tropical) climates is accompanied by technological difficulties, which have been insufficiently considered to date. Thus, the efficiency and reliability of PV modules is severely affected by elevated cell operating temperature. Typically, commercially-available flat-plate (i.e., non-concentrating) PV modules only convert 4 to 18% of the solar irradiation to electrical energy, depending upon cell type and operating conditions, with the remainder being primarily converted to thermal energy [1,2]. Furthermore, PV cell efficiency (i.e., percent of incident solar irradiance that is converted into electricity) typically degrades by 0.2% to 0.5% per °C rise in ambient temperature [1,3]. This is essentially attributable to a reduction of the semiconductor material band gap [1]. Augmenting heat dissipation to the environment in order to prevent electrical and thermo-mechanical performance degradation, poses challenges at elevated ambient temperatures, which yearly average 29°C in for example Abu Dhabi, with daily maximum and monthly average temperatures peaking at approximately 51°C and 36°C, respectively [4]. Thermal issues are compounded by high humidity in coastal regions and sand fouling. As the introduction of PV technology in the Middle East and certain developing regions is still recent, insufficient experience exists on the long term performance and reliability of PV technologies in hot climates.

A recent review of previously reported PV module thermal analyses [5] highlighted that few studies have attempted to integrate liquid cooling schemes in flat-type PVs. Although liquid cooling designs have been found to offer promising electrical output improvements over passively-cooled designs, the environmental conditions encountered in the Middle East or extremely hot climates have not been fully considered [5]. The objective of this study is to explore the potential of active cooling solutions, consisting of forced air- and water-cooling, to enhance PV module electrical performance by indoor experimentation on laboratory-scale prototypes under artificial lighting conditions.

2. Experimentation

The PV module electrically and thermally characterized is a laboratory-scale 4-cell 0.15 m by 0.12 m module, having a rated maximum output voltage of 3 V. The PV module was characterized indoors using a 200 W incandescent light source. These characterization conditions do not comply with either standard IEC60904-3 [6] or IEC 60904-9 [7] for outdoor and indoor characterization of terrestrial flat-plate PV devices, respectively. IEC60904-3 specifies the spectral distribution of the irradiance known as AM1.5G spectrum. IEC 60904-9 defines solar simulator performance requirements used for indoor testing of PV devices in conjunction with a spectrally matched reference device. As the output of a PV cell is a strong function of the wavelength of the incident spectral irradiance distribution, the latter standard specifies the acceptable match to the reference spectral irradiance distribution. Although non-standard, the characterization approach employed here provides a simple means of evaluating the effectiveness of active cooling strategies, before assessing commercial PV module performance in outdoor conditions.

The PV module was oriented horizontally, with its active surface normal to the light source, as illustrated in Figure 1. The light source was placed at a distance of either 80 or 130 mm from the module, which resulted in

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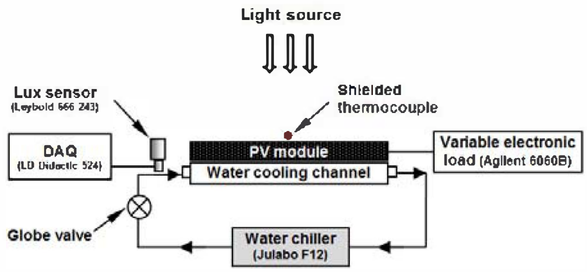
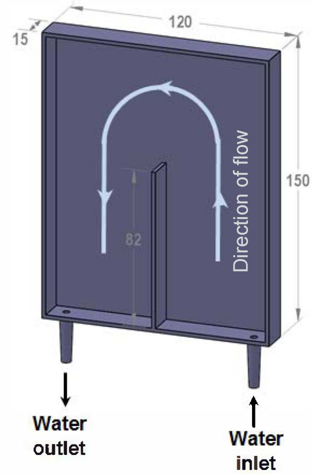


Figure 1. Schematic representation of experimental test set-up for water-cooled PV module.



Note: All dimensions are in mm.

Figure 2. Schematic representation of PV module water-cooling channel geometry.

measured light illuminance levels of 56 and 22 klux, respectively.

The PV module was characterized in both passive and active cooling conditions to assess the power output improvements obtained with active cooling. In passive cooling conditions, the module is cooled by free air convection and radiation to the surroundings. Active cooling consists of either forced air- or water-cooling, with the cooling fluid directly wetting the module surface, thereby eliminating thermal contact resistance. In all cooling configurations the module active surface was shielded from extraneous laboratory drafts.

The forced air-cooled design comprises an aluminum duct of transverse cross sectional area 120 mm x 60 mm, which is attached to the module non-active surface. Two 60 x 60 x 25 mm, 12 V, 1.56 Watts axial DC fans (Kingsky FD6025D12MS) are mounted in parallel at the duct inlet, that operate in push mode to generate a mean measured airflow velocity of 1.7 m/s.

The water-cooled design is illustrated in Figure 2, and consists of a Plexiglas U-channel of internal depth 15 mm, attached to the non-active surface of the module. Chilled water at inlet temperatures ranging from 1°C to 21°C (i.e., ambient air temperature), was pumped at a mean velocity of 0.5 m/s through the cooling channel. This study being exploratory, the cooling channel design and water flow rate were not formally optimized, but permitted an effective assessment of the technical feasibility of water cooling.

PV module surface temperature was measured using type-K thermocouples having an accuracy of ±1°C, attached to the module active surface. All module surface temperature measurements were made by ensuring that steady-state conditions were reached. The module current-voltage characteristics were recorded using a 300 W Agilent 6060B DC electronic load. The test matrix is summarized in Table 1.

Table 1. PV module test matrix.

Cooling Configuration		Irradiation (klux)
Passive, T_a = 21°C		22 56
Forced air-cooled, T_a = 21°C		22 56
Water-cooled	T_w = 5°C, 14°C, or 21°C	22
	T_w = 1°C, 9°C, or 21°C	56

Note: T_a and T_w refer to ambient air and water temperature, respectively.

3. Results

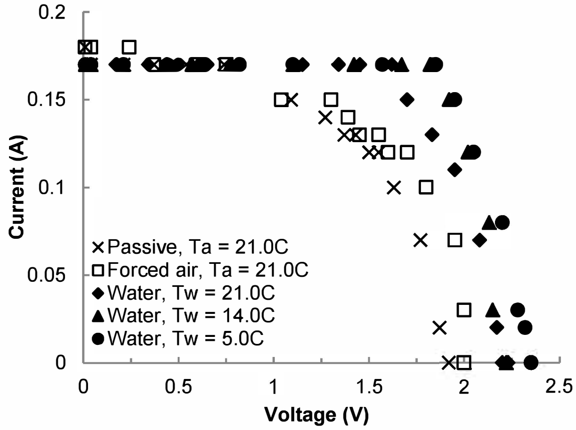
The measured current-voltage (I-V) and output power characteristics of the laboratory-scale PV modules operated under light source illuminances of 22 and 56 klux are presented in Figures 3 and 4, respectively, for passive, forced air and water-cooling conditions. Measured module peak power output as a function of operating temperature and light source illuminance is presented in Figure 5.

At an illuminance of 22 klux (Figure 3b), forced air- and water-cooling (T_w = 5°C) result in 11.4°C and 32.9°C reduction in module operating temperature relative to passive cooling, respectively, with power output increased by approximately 10% and up to 69%, respectively. This highlights the effectiveness of water cooling in improving PV module output power, while forced air-cooling results in much smaller performance improvements. The same trends are observed at an illuminance of 56 klux (Figure 4b), with higher power output levels obtained.

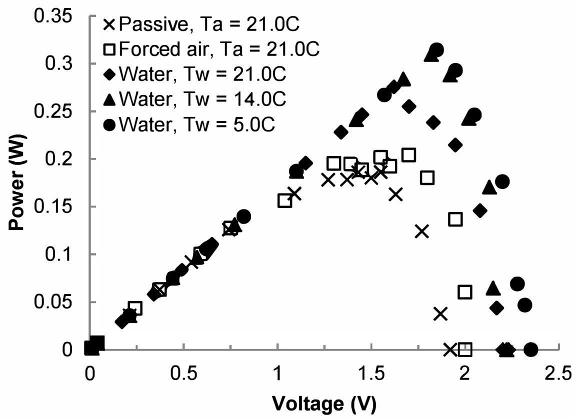
As shown in Figure 5, for an illuminance of 22 klux, peak output power increases by 0.123 W (66%) from passive to chilled water-cooled conditions (T_w = 14°C), with an accompanying module operating temperature reduction of approximately 19°C.

For a light source illuminance of 56 klux, peak output power increases by 0.089 W (19%) from passive to chilled water-cooled conditions (T_w = 9°C), with an accompanying module operating temperature reduction of 47.5°C.

The results suggest that forced air-cooling would be ineffective in hot climates, such as in the Middle East, where ambient air temperatures typically reach 45°C in



a) Current-voltage characteristics

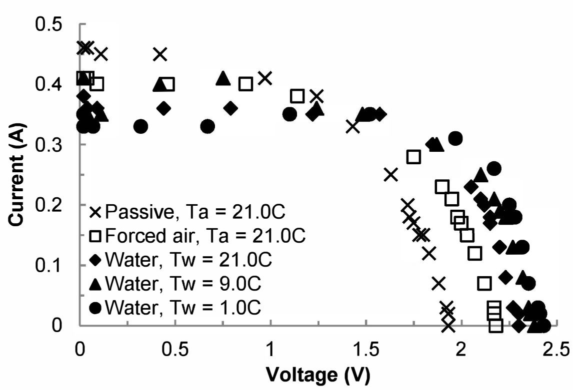


b) Output power

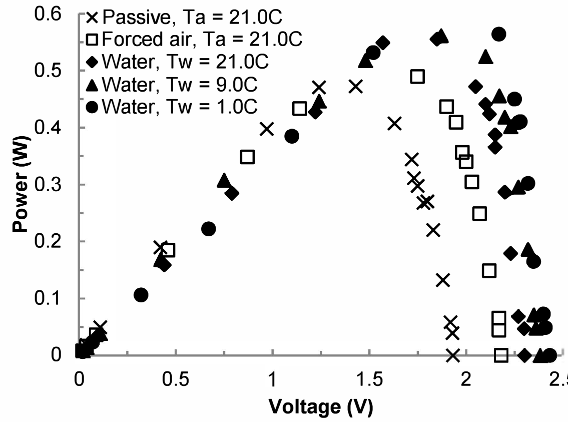
Cooling Configuration	T_p (°C)	T_a (°C)	T_w (°C)	P_{max} (W)
Passive	42.8	21.0	---	0.186
Forced air-cooled	31.4	21.0	---	0.204
Water-cooled	26.3	21.0	21.0	0.275
	23.9	21.0	14.0	0.309
	9.9	21.0	5.0	0.315

Note: T_p, T_a, and T_w refer to module, ambient air and water temperature, respectively. P_{max} refers to module peak electrical power.

Figure 3. Comparison of measured electrical characteristics for passively cooled, forced air-cooled and water-cooled PV module indoors at a light source illuminance of 22 klux.



a) Current-voltage characteristics



b) Output power

Cooling Configuration	T_p (°C)	T_a (°C)	T_w (°C)	P_{max} (W)
Passive	71.0	21.0	---	0.472
Forced air-cooled	44.3	21.0	---	0.490
Water-cooled	26.3	21.0	21.0	0.555
	23.5	21.0	9.0	0.561
	10.0	21.0	1.0	0.564

Note: T_p, T_a, and T_w refer to module, ambient air and water temperature, respectively. P_{max} refers to module peak electrical power.

Figure 4. Comparison of measured electrical characteristics for passively cooled, forced air-cooled and water-cooled PV module indoors at a light source illuminance of 56 klux.

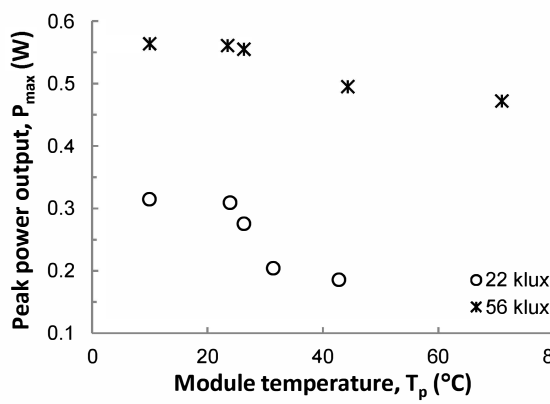


Figure 5. Measured module peak power output as a function of operating temperature and light source illuminance.

summer. In addition, there is an optimum range of refrigeration intensity to enhance power output, which could be analyzed further in future work using coefficient of performance (COP) and economic analyzes.

The analysis methodology employed here has been extended to commercial modules (e.g., 100-140 W rated power) operated under actual solar loading conditions [5]. The trends observed in this study for the effectiveness of forced air- and water-cooling strategies were found to hold, highlighting the value of exploratory experimentation on mock-up cooling prototypes.

4. Conclusions

The thermal and electrical performance of passively-, forced air- and water-cooled laboratory-scale PV modules was experimentally characterized indoors under different light source illuminance levels. At an illuminance of for example 22 klux, peak output power is found to increase by 10%, 48% and 66% from passive to forced-air, water-cooling at ambient air temperature (T_w = 21°C), and chilled water-cooling conditions (T_w = 14°C), respectively.

Future work will focus on coefficient of performance (COP)-based design optimization in conjunction with an economic payback period analysis for commercial modules operated outdoors. In addition, experimentation will be extended to a complete year in hot desert environments.

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