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Experimental study on direct-contact liquid film cooling simulated dense-array solar cells in high concentrating photovoltaic system

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ABSTRACT

This paper presented a new method of cooling dense-array solar cells in high concentrating photovoltaic system by direct-contact liquid film, and water was used as working fluid. An electric heating plate was designed to simulate the dense-array solar cells in high concentrating photovoltaic system. The input power of electric heating plate simulated the concentration ratios. By heat transfer experiments, the effect of water temperatures and flow rates on heat transfer performance was investigated. The results indicated that: the average temperature of simulated solar cells was controlled well below 80 °C under water temperature of 30 °C and flow rate of 300 L/h when concentration ratio ranged between 300X and 600X. The maximum temperature difference among temperature measurement points was less than 10 °C, which showed the temperature distribution was well uniform. The heat transfer coefficient reached up to 11.91 kW/(m^2·K) under concentration ratio of 589X. To improve heat transfer performance and obtain low average temperature of dense-array solar cells, lower water temperature and suitable water flow rate are preferred.

1. Introduction

Solar energy is one source of renewable energy which draws attention from all over the world. Concentrating photovoltaic (CPV) with high efficiency multi-junction photovoltaic cells is a photovoltaic technology that generates electricity from sunlight. Efficiency of multi-junction photovoltaic cells developed in research is upward of 44% today, with the potential to approach 50% in the coming years [1]. Contrary to conventional photovoltaic systems, CPV requires less photovoltaic material which is often the most expensive part of solar operation. However, the solar energy which is not fully utilized for generating electricity is converted to thermal energy which results in tremendous temperature increasing of solar cells, reducing the power efficiency and even threatening the running life of PV cells if not dissipated timely and efficiently [2–4]. Therefore, it is urgent to find a highly-efficient cooling method to manage the solar cells temperature, especially in high concentrating photovoltaic (HCPV) systems.

Cooling methods reported in the literature and reviewed for cooling of photovoltaic and electronics are: jet impingement, microchannels, heat pipes, hybrid microchannels and impingement jet cooling, as well as direct liquid immersion [5]. Royne and Dey [2] designed an impingement jet device for the cooling of densely packed solar cells under high concentration ratio ranged between 200X and 500X. It was concluded that for 200X, the cell temperature decreased approximately to the value of 30 °C from 60 °C whereas for 500X, cell temperature dropped from 110 °C to 40 °C at maximum power point and average heat transfer coefficient in the range of 105 W/(m^2·K) was achieved for the four nozzle array. In addition, the pump power consumed almost 30% of the total power generation under fixed experimental conditions. Yang and Zuo [6] designed a multi-layer manifold microchannel cooling system to effectively lower the cell surface temperature and improve the uniformity of surface temperature distribution. The results showed that the surface temperature difference of the CPV cells was below 6.3 °C and the multi-layer manifold microchannel had a heat transfer coefficient of 8235.84 W/(m^2·K). Huang et al. [7] presented a novel hybrid-structure flat plate heat pipe for a concentrator photovoltaic and examined its performance. About 65% reduction in the thermal resistance has been realized compared to the design without supporting structure. Moreover, the electrical efficiency of CPV is enhanced by

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Nomenclature

A	surface area, m^2
h	heat transfer coefficient, W/(m^2·K)
I	current, A
q	heat flux, W/m^2
Q	water flow rate, L/h
T	temperature, °C
ΔT	temperature difference, °C
U	voltage, V

Subscripts

avg	average
i	number of measurement point
in, out	inlet, outlet
LTMD	logarithmic mean temperature difference
w	water

Abbreviation

CPV	concentrating photovoltaic
EHP	electric heating plate
HCPV	high concentrating photovoltaic
IR	infrared
PV	photovoltaic
PCM	phase-change materials
Re	Reynolds number

3.1% in comparison with aluminum substrate. Barrau et al. [8] studied in deep the performance of a new hybrid jet impingement/microchannel cooling scheme for densely packed PV cells under high concentration ratios. It was found that the hybrid system provided thermal resistance as low as 2.18×10^{-5} m^2·K/W and the temperature variation of 2.01 °C was obtained. However, the main problem of above cooling methods is that the existence of the thermal resistance between solar cells and heat sinks impeded the improvement of heat transfer performance. Fortunately, liquid immersion cooling proposed by Russell [9] indicated that PV cells directly immersed in the circulating coolant could minimize or eliminate the thermal resistance and the heat was absorbed by the circulating coolant from both the front and back surface of solar cells. Sun et al. [10] investigated the cell temperature distribution and long-term stability of mono-crystalline concentrator silicon solar cells immersed in dimethyl silicon oil at an energy flux ratio of 9.1 suns. Han et al. [11] described that the degradation mechanism of silicon solar cells immersed in de-ionized water and the results showed that the cells were not damaged after long-time de-ionized water immersion. Xin et al. [12] studied the electrical characteristics of GaInP/GaInAs/Ge triple-junction solar cells immersed in dimethyl silicon oil of 1.0–30.0 mm thickness and the results showed that the efficiency and the maximum output power of the cell have become less than those without liquid-immersion when the silicon oil thickness exceeds 6.3 mm. Zhu et al. [13] investigated the liquid immersion cooling technique for solar cells in CPV system. A 250X dish concentrator with two-axis tracking was utilized to evaluate a new CPV system using de-ionized water for immersion cooling. The results showed that the PV module temperature decreased up to 45 °C with inlet water temperature of 30 °C and the calculated amount of heat transfer coefficient was found to be around 6000 W/(m^2·K) under an insolation level of 940 W/m^2.

Generally, liquid film evaporation is an effective latent heat transfer technology widely utilized in industrial fields because of its advantages, such as simple structure, high heat transfer efficiency and low energy consumption [14,15]. In the process of liquid film flowing, a lot of heat can be taken away through water evaporation. Experimental researches on falling film evaporation were reviewed by Ribatski and Jacobi [16], Thome [17], Fernández-Seara and Pardiñas [14], and Abed et al. [18]. In addition, a lot of theoretical analysis was carried out in terms of the falling film flow pattern and the heat transfer performance [19,20]. Chien and Tsai [21] investigated heat transfer performance on horizontal copper tubes with refrigerant of R-245fa, finding that the heat transfer coefficient of falling film vaporization increased with an increase of heat flux and fluid temperature, and increased slightly with increase in flow rate before dry-out occurred. Huang et al. [22] studied the falling film evaporation in a large scale rectangular channel and the results showed that the evaporation heat transfer coefficient increased with an increase of air Reynolds number (Re) and had little relation with the variation of film Re and film temperature. Abdellatif [23] presented and analyzed three cooling systems: film water cooling, direct contact back water cooling and combining film-back cooling. The results show that the daily output power of the PV cooling module increased up to 22%, 29.8% and 35% for film cooling, back cooling and combined film-back cooling module, respectively compared to non-cooling module. Kordzadeh [24] studied the effects of nominal power of array and system head on the operation of system by using a thin film of water and this increased the panel and total efficiency. Overall, the liquid film evaporation is an effective heat dissipation method and the heat transfer performance is dependent on the operation conditions.

To enhance heat transfer and obtain a lower temperature of dense-array solar cells, direct-contact liquid film evaporation technology was firstly adopted in this paper for thermal management of simulated dense-array solar cells worked under high concentration ratios. The feasibility of direct-contact falling film cooling method applied in temperature control and temperature distribution was investigated.

2. Experimental setup and approach

The facility consists of test section, water supply and distribution system, as well as the measurement system, and the schematic of the experimental setup is shown in Fig. 1. The detailed description of the system parameters was given in Table 1.

2.1. Test section

The test section consists of an EHP and alumina ceramics plates. In order to decrease the experimental complexity and cost, an EHP was designed to simulate the dense-array solar cells worked in HCPV system. The structure of EHP is shown in Fig. 2a. The central part was four stainless steel (resistivity is 7.3×10^{-7} Ω·m) plates in parallel. To avoid the other part was overheating, three copper (resistivity is 1.68×10^{-8} Ω·m) plates were welded to connect the four stainless steel plates end to end. Another two copper plates with 1/4 circle ring of 20 mm inner diameter and 30 mm outer diameter were welded with the stainless steel in order to link with the heating electrodes. The thickness of stainless steel plates and copper plates were both 0.2 mm.