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Experimental and numerical optimization of direct-contact liquid film cooling in high concentration photovoltaic system

Yiping Wang[a,b,1], Liqun Zhou[a,1], Xue Kang[c], Qunwu Huang[a,*], Xusheng Shi[a], Chen Wang[d]

[a] School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, China
[b] School of Architecture, Tianjin University, Tianjin 300072, China
[c] School of Chemical Engineering and Technology, North University of China, Taiyuan 030051, China
[d] School of Environment and Safety Engineering, North University of China, Taiyuan 030051, China

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ABSTRACT

Thermal management is a critical issue for normal operation of dense-array solar cells in high concentration photovoltaic system. A cooling method of direct-contact liquid film was experimentally and numerically investigated. In the experiments, deionized water was adopted as coolant and an electric heating plate was optimal designed to simulate dense-array solar cells. A two-dimension model was derived to present the temperature distribution on the surface of the simulated solar cells and flow characteristic of liquid film. The effect of various inlet parameters such as water temperature, inlet width and velocity had been numerical studied. The experiment results suggest that the surface temperature is well controlled under 120 °C at corresponding conditions, with concentration ratios ranging from 300 to 500X. The numerical results show that inlet width has a crucial effect on the liquid film thickness. The subcooled boiling state is a necessary condition to ensure cooling effect. High water inlet temperature is preferable for better heat transfer performance and temperature uniformity. The best optimizing inlet velocity, width and temperature are 1.06 m/s, 0.75 mm and 75 °C, respectively.

1. Introduction

Concentrating photovoltaic technology (CPV) is an effective way to implement photoelectric conversion. The high concentration photovoltaic (HCPV) technology, which obtains energy by concentrating sunlight hundreds times through an optical system onto solar cells, becomes a very prospective market with indefinite value. Recently, the power generation efficiency of multi-junction solar cells has reached up to 46%, allowing for significant future module and system cost reductions for HCPV [1]. Talavera [2] estimated that in 2020 the cost of electricity will be able to reach values for HCPV systems from 0.035 to 0.080 €/kWh in Spain. On high concentration ratios, thermal management becomes a challenge for large-scale popularization of HCPV system. For instance, increasing operating temperature leads to negative influences on the efficiency, maximum power point, short circuit, open voltage and fill factor of multi-junction solar cells. A rise of 10 °C in cell temperature will reduce the cell efficiency by a half percentage. Moreover, higher operating temperatures will reduce the cell lifetime [3]. Rodrıguez's results showed that certain types of solar cells can operate at a relatively high temperatures (100–170 °C) [4]. Lower solar cell temperature and higher uniform temperature distribution are desirable cooling results in HCPV system [5].

Many useful literatures have been made of various cooling method that have been studied, and of their practical applications. The techniques reported in literatures and reviewed for cooling of photovoltaic and electronics are: jet impingement, micro channels, improved heat exchanger designs, heat pipes, combined microchannel-jet impingement, heat sinks and spreader, phase change material for cooling and dielectric cooling by direct immersion. A comprehensive review had been published by Royne et al. [6], which indicated that for densely packed cells under high concentration ratios (≥150 suns), an active cooling system was necessary, with a thermal resistance of less than 10^{-4} K·m^2/W. Only impinging jets and micro-channels have been reported to achieve such low values. Two-phase forced convection would also be a viable alternative. Jakhar [7] summarized various cooling technologies available for CPV systems. Applicable environment for different cooling methods under various concentration ratio and photovoltaic models were analyzed. Bahaidarah et al. [8] systematically expounded the uniform cooling of photovoltaic in recent years. This review paper highlighted the importance of uniform PV cooling by exploring the possible causes and effects of non-uniformity. Cooling techniques with low average cell temperature and uniform temperature

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[*] Corresponding author.
E-mail address: huangqw@tju.edu.cn (Q. Huang).
[1] These authors contributed equally to this work.

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Nomenclature

A	heating area of EHP, m^2
H	surface heat transfer coefficient, $W/(m^2 \cdot K)$
I_{in}	input current, A
P_{in}	input power, W
q	heat flux, W/m^2
S	standard deviation of temperature
T	temperature, °C
$\triangle T$	maximum temperature difference on EHP, °C
U	voltage, V
V	velocity, m/s
X	concentration ratio

Subscripts

A	average
End	end section of EHP
in, out	water inlet, water outlet
Ini	initial section of EHP
L	liquid
LTMD	logarithmic mean temperature difference

Greek symbols

α	phase fraction
λ	thermal conductivity, $W/(m \cdot K)$
μ	viscosity, Pa·s
ρ	density, kg/m^3

Abbreviations

CPV	concentration photovoltaic
EHP	electronic heating plate
HCPV	high concentration photovoltaic

distribution were interpreted. The review also pointed out that passively cooling CPV was insufficient for dissipation of heat even when a large heat sink was used relative to cell size. Active cooling by micro-channels, impingement cooling and hybrid micro-channel impingement cooling were found to be most effective in dissipating high heat flux from PV surface. Most researches focus on the cooling method of concentration under 300X. Nevertheless, for HCPV thermal management, the studies are insufficient. Min et al. [9] studied metal heat sinks for 400X PV system and performed experiments in outdoor environment. They concluded that for a stable average temperature of 37 °C, area of heat sink was required to be 700 times more than the area of solar cell. Cheknane [10] compared the water and acetone as the working liquid in the gravity-dependent heat pipe on cooling of concentrator solar cell up to 500X. Tan et al. [11] analyzed the thermal performance of multiple-channel heat sink in application of ultra-high CPV system via CFD simulation. By optimizing the average water velocity at 0.6 m/s, the heat sink with the configuration of 1 × 20 mm can maintain the CPV cells operating at 91.4 °C under solar concentration ration of 1800 suns. Micheli [12] reported the design of a natural convective micro-finned heat sink for HCPV via numerical simulation, and found that micro-fins were a suitable solution for passive cooling at concentrations up to 500X. Xu et al. [13] conducted a numerical investigation on the natural convection combined with radiative heat transfer underneath inclined heat sink cooling. Theristis et al. [14] set a three-dimensional finite model to quantify the effect of each atmospheric parameter on the thermal performance. It was shown that a heat transfer coefficient greater than 1300 $W/(m^2 \cdot K)$ was required to keep the solar cell under 100 °C. Cui et al. [15] proposed a novel PV-PCM-TE hybrid system. The incorporation of the PCM can suppress the influence of the solar irradiance fluctuation on the PV-PCM-TE system and maintain the PV-PCM-TE system to operate at the optimal operating temperature, when the concentration ratios ranged from 1X to 1000X Suns. The published literatures mainly based on the numerical simulation approach and lack of experiment data. In additional, whether microchannel or heat pipe cooling method caused a rising cost of HCPV system.

The wall thermal resistance between solar cells and heat sinks is the main barrier that limits the heat transfer performance. The direct-contact cooling is an effective way to overcome the above disadvantages. Russell [16] patented a long cylinders filled with dielectric liquid, which had concentrating action and cooling the system. Zhu et al. [17] investigated a 250X dish concentrator with two-axis tracking that was utilized to evaluate a new CPV system using deionized water for immersion. Kang et al. [18] built a self-running system to study the feasibility of temperature control and the effect of bubbles generated by ethanol phase change using direct liquid-immersion method under high concentration ratios. The surface heat transfer coefficient of electric heating plate was up to 23.49 $kW/(m^2 \cdot K)$ under 398.4 K. Xin [19] studied electrical characteristics of GaInP/GaInAs/Ge triple-junction solar cells immersed in dimethyl silicon oil of 1.0–30.0 mm thickness under 500 suns and 25 °C. However, the liquid immersion cooling methods generated bubbles, which reduced the cell efficiency and higher sealing quality was required. Therefore, a new heat dissipation method of

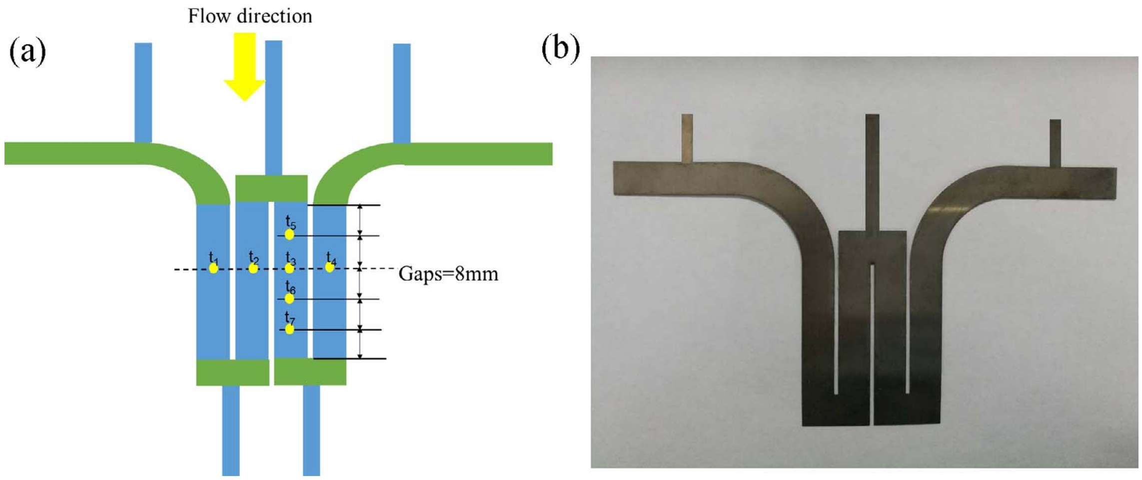

Fig. 1. Details of the EHP (a) the design sketch, (b) the material object photo.