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Performance comparison between ethanol phase-change immersion and active water cooling for solar cells in high concentrating photovoltaic system

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ABSTRACT

This paper presents an optimized ethanol phase-change immersion cooling method to obtain lower temperature of dense-array solar cells in high concentrating photovoltaic system. The thermal performances of this system were compared with a conventional active water cooling system with minichannels from the perspectives of start-up characteristic, temperature uniformity, thermal resistance and heat transfer coefficient. This paper also explored the influences of liquid filling ratio, absolute pressure and water flow rate on thermal performances. Dense-array LEDs were used to simulate heat power of solar cells worked under high concentration ratios. It can be observed that the optimal filling ratio was 30% in which the thermal resistance was 0.479 °C/W and the heat transfer coefficient was 9726.21 W/(m^2·°C). To quantify the quality of energy output of two cooling systems, exergy analysis are conducted and maximum exergy efficiencies were 17.70% and 11.27%, respectively. The experimental results represent an improvement towards thermal performances of ethanol phase-change immersion cooling system due to the reduction in contact thermal resistance. This study improves the operation control and applications for ethanol phase-change immersion cooling technology.

1. Introduction

The energy demand of world is continuously rising due to the increasing global population and industrialization. At present, solar energy is one of the renewable energies that has obtained the widest attention. High concentrating photovoltaic (HCPV) technology is a fastest growing solar energy technology with higher photoelectric conversion efficiency. HCPV technique is generally based on the use of multi-junction solar cells in which each junction absorbs a particular region of spectrum to increase the overall conversion efficiency. The highest cell efficiency recorded for multi-junction GaInP/GaAs/Ge solar cell is 46.0% (AM1.5D, 500 suns) [1]. The rest of solar radiation absorbed is converted into heat and causes the cell temperature risen. The photovoltaic cells are negatively affected by operating temperature increasing, which maybe cause drops in electrical efficiency [2]. Furthermore, non-uniform temperature distribution and long-term high operating temperature also lead to an irreversible degradation of solar cells. Therefore, the system needs to be cooled during operation.

Several cooling methods have been presented: jet impingement, heat pipes, microchannels, active cooling by attaching water/fin and dielectric cooling by direct immersion. A comprehensive review of cooling methods for concentrator photovoltaic systems were published by Royne et al. [3]. Besides, Royne and Dey [4] proposed a jet impingement device for cooling densely packed cells under 200X to 500X concentration ratio. Based on jet device, cell temperature was controlled below 50 °C and heat transfer coefficient achieved at 30,000 W/(m^2·K). Meanwhile, the non-uniform temperature distribution had a negative effect on electrical output of HCPV system. Heat pipe is a device to transport heat by two phase flow of working fluid from evaporation to condensation section. Due to effective heat transfer with minimal energy loss, heat pipes have been studied in thermal management. Huang et al. [5] investigated a novel hybrid-structure flat plate heat pipe (NHSP heat pipe) with a sintered metal structure and a supporting structure for CPV systems. This NHSP heat pipe can reduce thermal resistance by 65% and enhance electrical efficiency by approximately 3.1%, showing a relatively good cooling performance. In addition, microchannel cooling method receives wide attention of researchers as a novel technique. Yang and Zuo [6] designed a novel multi-layer manifold microchannel for CPV cells. The multi-layer structure enlarged contact area between microchannels and cell surface, resulting in a higher heat transfer coefficient and a uniform temperature distribution. Reddy et al. [7] performed a design and

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Nomenclature

A	substrate surface area of dense-array LEDs, m^2
C_p	specific heat, kJ/(kg·°C)
Ex_{LED}	exergy of dense-array LEDs, W
Ex_{th}	exergy of coolant, W
h	enthalpy, kJ/kg
$\dot{m}$	mass flow rate, kg/h
K	heat transfer coefficient, $W/(m^2 \cdot °C)$
q	heat flux, W/m^2
P_{heat}	heat power of dense-array LEDs, W
P_{pump}	heat power of pump, W
R_{th}	thermal resistance, °C/W
s	entropy, kJ/(kg·°C)
T_c	temperature of coolant, °C
T_j	junction temperature of dense-array LEDs, °C
$T_{substrate}$	substrate temperature of dense-array LEDs, °C
ΔT	temperature difference, °C
ρ	density, kg/m^3
η	exergy efficiency

Abbreviation

CPV	concentrating photovoltaic
FR	filling ratio
LED	light emitting diode
EPCI	ethanol phase-change immersion
EQE	external quantum efficiency
HCPV	high concentrating photovoltaic
HCPV/T	high concentrating photovoltaic/thermal
PV	photovoltaic

numerical analysis of heat sink with micro-channels for high concentration photovoltaic cells using CFD software ANSYS 13. At the optimized geometry (0.5 mm width and aspect ratio of 8), the results predicted over less than 10 K rise in temperature of CPV module with a pressure drop of 8.8 kPa along a single channel. The overall load was calculated to be 4 W which is approximately 0.2% of the electric power generated by CPV module. In the majority of HCPV systems, active cooling techniques by attaching water or fin on the backside of modules are widely used to minimize cells temperature. Tarabsheh [8] investigated the performance of PV modules with active cooling fluid flowing through pipes underneath module backside. The efficiencies of modules using different fluid pipes design were 15%, 16.4% and 16.25% that were higher than without cooling only 14%. Xu [9] et al. carried out electricity and heat performance analysis based on a point-focus fresnel lens HCPV/T system. The grooved water tube on the rear side of triple-junction solar cells was used to cool cells and collect thermal energy generated from system. The results showed that the electricity efficiency of system was 28% and a high thermal efficiency of 54% under concentration of 1090X, indicating a compatible cooling ability.

However, the main problem of above mentioned methods is the existed contact thermal resistance between heat sinks and solar cells, which hinders the cooling performance. Russel [10] firstly invented and patented a cooling system in which photovoltaic cells were immersed in non-conductive liquid inside a tube. The ideas similar to direct liquid immersion cooling were also reported by Abrahamyan [11] and Tony [12]. Zhu et al. [13] applied de-ionized water immersion cooling for a 250X dish CPV system to keep solar cells working temperature. The cell modules temperature decreased to 45 °C and the uniformity of temperature distribution was less than 4 °C with DNI above 900 W/m^2. The total heat transfer coefficient was calculated about 6000 $W/(m^2 \cdot K)$ which showed a high cooling capability. Moreover, the electricity efficiency of HCPV system used GaInP/GaAs/Ge triple-junction solar cells was studied [14]. Cells were immersed in dimethyl silicon oil with 1.0–30.0 mm under 500X concentration ratio and the experimental results showed the efficiency and maximum output power of system were less than that without liquid-immersion when the silicon oil thickness exceeds 6.3 mm.

Whereas, in all immersion cooling systems described above, high flow rate is always required to obtain a higher single-phase convective heat transfer due to the high concentration ratio and temperature, which leads to a high load power consumption. To enhance the economic and heat transfer performances, a novel phase-change liquid immersion cooling method was proposed by Kang [15]. Ethanol was chosen as phase-change liquid to cool solar cells. It was found that cell temperature can be controlled between 87.3–88.5 °C under 219.8X to 398.4X. Meanwhile, the highest surface heat transfer coefficient was 46.98 $kW/(m^2 \cdot K)$ under 398.4X. According to the results, phase-change

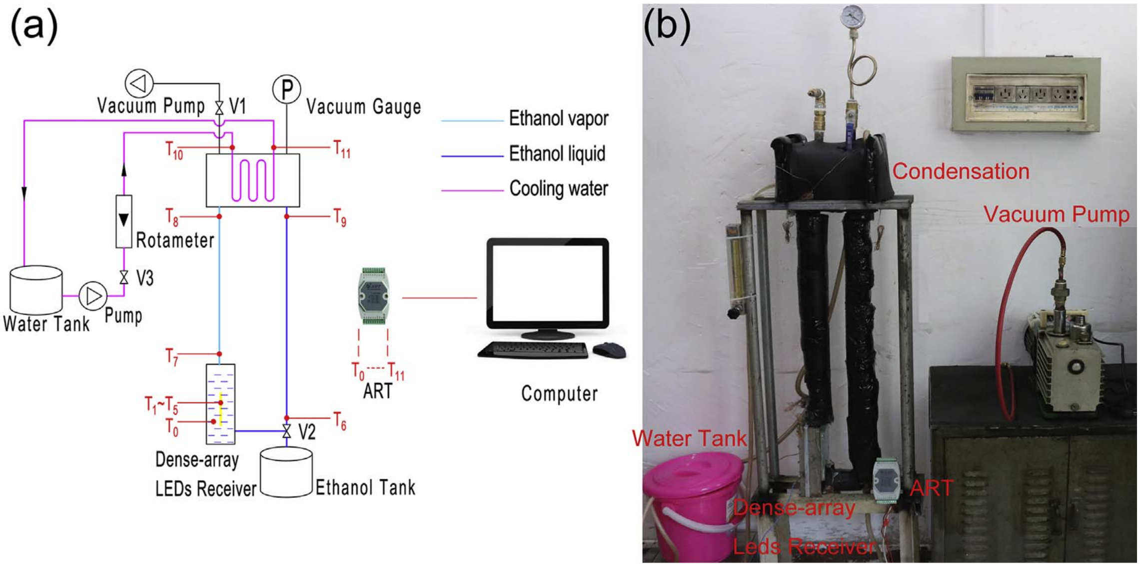

Fig. 1. Experimental set-up of ethanol phase-change immersion cooling system. (a) Schematic of the facility and (b) photograph of the facility.