Energy Conversion and Management 128 (2016) 95–103

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Study on direct-contact phase-change liquid immersion cooling dense-array solar cells under high concentration ratios

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ARTICLE INFO

Article history:
Received 1 June 2016
Received in revised form 22 September 2016
Accepted 23 September 2016

Keywords:
Direct-contact phase-change liquid immersion cooling
Heat transfer performance
Bubble effect
Electrical performance
Interface function

ABSTRACT

A new cooling method by directly immersing the solar cells into phase-change liquid was put forward to cool dense-array solar cells in high concentrating photovoltaic system. A self-running system was built to study the feasibility of temperature control and the effect of bubbles generated by ethanol phase change under concentration ratio ranged between 219.8× and 398.4×. The results show that the cooling system is self-regulating without consuming extra energy and ethanol flow rate reaches up to 180.6 kg/(s·m^2) under 398.4×. The temperature of solar cells distributes in the range between 87.3 °C and 88.5 °C, the surface heat transfer coefficient of electric heating plate is up to 23.49 kW/(m^2·K) under 398.4×. The bubble effect on electrical performance of triple-junction solar cells is reported and the results show that I_{sc} and P_{max} decline 10.2% and 7.3%, respectively. A model based on bubble images illustrates that light loss at the interface between ethanol and bubble is the main reason to cut down the electrical performance.

1. Introduction

Concentrating photovoltaic (CPV) with high efficiency multi-junction solar cells is considered as a cost-effective and promising power generation technology using solar energy. The main advantages of CPV systems are high efficiency and relatively low system cost for getting more photovoltaic (PV) power output by using less expensive material for the same output [1]. An increase of temperature decreases the solar cells efficiency and system output power even threaten the running life of solar cells [2]. Therefore, thermal management is an important issue for both single and dense-array solar cells under high concentration ratios [3]. Significantly, for high concentrating photovoltaic (HCPV) system, large amount of heat need to be dissipated timely and effectively, so a highly efficient cooling method is necessary.

There had been some methods developed by researchers [4] to solve heat dissipation issues of HCPV systems. Royne proposed a cooling device based on jet impingement for cooling densely-packed photovoltaic cells under high concentration and the results showed the inherently non-uniform heat transfer distribution existed [5]. Rahimi designed a self-adjusted jet impingement system for cooling photovoltaic cells and introduced a hybrid jet cooling device which is a combination of wind and photovoltaic cell to generate electrical energy from both wind and solar cell simultaneously [6]. Yang proposed a novel multi-layer manifold micro-channel cooling system for concentrating photovoltaic cells and the results indicated that the surface temperature difference of the CPV cells was below 6.3 °C, heat transfer coefficient was 8235.84 W/m^2 K and pressure drop was lower than 3 kPa [7]. Ho proposed two-phase flow cooling in the back surface of densely-packed solar cells and analyzed the heat transfer performance under different conditions [8]. Then, he further investigated the impact of two-phase flow cooling on cell temperature and the practical solar concentration limits of eight working fluids for photovoltaic. Finally, he found that water and ammonia exhibited greater limits of concentration because they possess greater values of sensible and latent heats compared with the organic fluids [9]. Xu analyzed computationally Al_2O_3-water nanofluid cooling of high concentration photovoltaic cells and optimized the working parameters based on minimizing the system's entropy generation [10]. Karami investigated experimentally Boehmite nanofluid used for heat transfer enhancement for PV cells [11]. Meanwhile, the combination of above cooling approaches was also performed for photovoltaic solar cells cooling. Valeh-e-Sheyda studied the integration of jet impingement/micro-channel cooling and found that

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http://dx.doi.org/10.1016/j.enconman.2016.09.073
0196-8904/© 2016 Published by Elsevier Ltd.

Nomenclature

A	surface area, m^2
b	liquid thickness, mm
d	diameter of pipe, mm
g	acceleration of gravity, m/s^2
L	length of pipe, mm
I	light intensity, W/m^2
I_{in}	input current, A
I_{sc}	short circuit current, A
K	the absorption coefficient, m^{-1}
Ks	surface heat transfer coefficient, $W/(m^2{\cdot}K)$
m	bubble-ethanol interface amount
n	refractive index
ΔP	pressure drop, Pa
q	heat flux, W/m^2
R	reflection
t_{avg}	average temperature, °C
t_{cell}	temperature of solar cell, °C
t_i	temperature of EHP, °C
t_{in}	inlet temperature, °C
t_{out}	outlet temperature, °C
Δt	temperature difference, °C
U_{in}	input voltage, V
u	velocity in downward pipe, m/s
u_1	velocity in receiver, m/s
ρ	density, kg/m^3
λ	friction coefficient
μ	viscosity, Pa·s
Θ	the incident angle of light

Abbreviation

AC	alternating current
ARC	anti-reflection coating
CCA	concentrator cell assembly
CPV	concentrating photovoltaic
EHP	electric heating plate
EQE	external quantum efficiency
FS	full scale
HCPV	high concentrating photovoltaic
I-V	current-voltage
PV	photovoltaic
Re	Reynolds number
UV	ultraviolet

the percent of increase in maximum output power of PV cell was about 38% in comparison with conventional reference solar cell [12]. Barrau investigated the performance of a new hybrid jet impingement/micro-channel cooling scheme for densely packed PV cells under high concentration and found that the net PV output of the receiver was higher when cooled by the hybrid design than by the micro-channel one [13]. However, lower system thermal resistance requirement is difficult to satisfy because of the contact thermal resistance existed at the interface between solar cells and the heat sinks using above cooling methods. But for direct liquid immersion cooling put forward by Wang [14], the bare solar cells were directly immersed in the insulation liquid, the contact thermal resistance between solar cells and the cooling system was minimized or eliminated. Moreover, the massive heat could be taken away from both front and rear surfaces, enhancing the heat transfer area [15]. Much effort had been done about direct liquid immersion cooling and valuable results were obtained. The solar cell efficiency is dependent on immersion liquid type, stability and thickness under direct liquid immersion cooling. Abrahamyan found the solar cell efficiency improved when immersed in liquid electrics [16]. Krauter found that the electrical output increased when water flew over the front of photovoltaic panels [17]. Tanaka found that a shallow layer of liquid-gel could also improve the efficiency of solar cells [18]. It was concluded the solar cell efficiency would improve with a layer liquid immersed. And the performance of solar cells varied with different types of insulation liquids immersed [14]. For example, Zhu found that the temperature of solar cells kept well in de-ionized water under 250× concentrating solar system [19]. However, Han found the stable electrical performance was difficult to achieve using de-ionized water as immersion liquid [20]. Then, Han also found that solar cells showed best performance in non-polar silicon oil [21]. Further, the durability of dielectric liquids for CPV system was researched and turned out that the most stable liquids were paraffin and silicon oil after a UV dosage equivalent to 3 years of AM1.5D radiation [22]. In depth, the III–V multi-junction solar cells immersed in 1.0 mm to 30.0 mm thickness dimethyl silicon oil under 250× was studied and the results illustrated the efficiency of the solar cell was less than those without liquid-immersion when the thickness of silicon oil exceeded 6.3 mm [23]. In summary, a layer of silicon oil with suitable thickness existed in front of the solar cells can improve the power generation efficiency.

However, in HCPV system, higher flow velocity is needed to obtain large single-phase convective heat transfer immersing solar cells directly in silicon oil, which results in parasitic energy consumption of the whole system increasing. There were reports of phase-change liquid cooling method applied in electronic elements revealed that the air-lifting driving force generated by liquid phase-change could drive the system run without consuming parasitic energy [24]. Meanwhile, it was also found that the solar cells immersed in phase-change liquid could be cooled significantly [25]. Therefore, using phase-change liquid to direct contact immerse cooling may be a potential solution to solve the heat dissipation issue of dense-array solar cells in HCPV system.

Feasibility of direct-contact phase-change liquid immersion cooling method using in temperature control and the effect of bubbles generated by liquid phase-change on light are two important issues when the proposed cooling method is applied in HCPV system. In this paper, an electric heating plate (EHP) was designed to simulate the dense-array solar cells in HCPV system and ethanol was used as phase-change immersion cooling liquid. The bubble effect on light was identified by electrical performance changing of a triple-junction solar cell.

2. Experimental

As shown in Fig. 1, the experimental device mainly consists of a circulation system, a rectangular channel receiver and a measurement system.

2.1. Circulation system

The circulation system worked at atmospheric pressure. The heat flux of simulated dense-array solar cells operated under high concentration ratio was adjusted by changing the input powers of EHP by a transformer. Ethanol with temperature near the boiling