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Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver

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ABSTRACT

Direct liquid-immersion cooling of solar cells using dimethyl silicon oil is proposed as a heat dissipation solution for linear CPV (concentrating photovoltaic) systems. To reduce the liquid holdup, a narrow rectangular channel receiver was designed and its heat transfer performance was investigated experimentally at an energy flux ratio of 9.1 suns. Long-term stability of mono-crystalline concentrator silicon solar cells immersed in dimethyl silicon oil with viscosity of 2 mm^2/s was monitored under real climate conditions. Experimental results show that the liquid-immersion cooling capacity in the designed receiver is favorable. The cell temperature can be controlled in the range of 20–31 °C at a 910 W/m^2 DNI (direct normal irradiance), 15 °C silicon oil inlet temperature and *Re* numbers (Reynolds) variation from 13,602 to 2720. The cell temperature distribution is quite uniform, and a general correlation of *Nu* number (Nusselt) was obtained. The electrical performance of the cells immersed in the silicon oil is stable and no obvious efficiency degradation was observed after immersed for 270 days.

1. Introduction

Energy generation from PV (photovoltaic) technology is simple, reliable, available everywhere, in-exhaustive, almost maintenance free, clean and suitable for off-grid applications [1]. CPV (concentrating photovoltaic) systems concentrate solar radiation on the solar cells. In CPV, lens or mirrors are used to concentrate solar radiation on solar cell. The main advantages of the CPV systems are high efficiency and relatively low system cost for getting more PV power output by using less expensive semiconducting PV material required for the same output [2]. Cooling of solar cells is an important consideration when designing CPV systems. Cell efficiency, and therefore system output power decreases with increasing cell temperature [3]. Characteristics of heat dissipation and heat transfer performance of flat photovoltaic systems by air cooling or back surface water cooling has been investigated in work [4–6] recently. Tina et al. propose a different PV cooling solution based on a submerged PV system in shallow water and found that the annulment of thermal drift and the lesser reflection increase the photovoltaic efficiency conversion by about 15% at water depth of 4 cm [7]. Significant researches have been dedicated to CPV cooling systems, as reviewed by Royne et al. [8]. Anderson et al. [9] determined the optimum fin dimensions and pitch of a heat-pipe based cooling system for CPV systems. Natarajan et al. [10] numerically investigated the solar cell temperature for a CPV system of 10X with and without passive cooling arrangements and optimized the fins configurations. Ahsan et al. [11] developed a CFD (computational fluid dynamics) model of the Amonix system which is a point focus Fresnel lens array arranged in a parallel plate assembly. Du et al. [2] developed an active water-cooling CPV system and the experimental results show that the operating temperature of the CPV module under water cooling is reduced under 60 °C. Calise et al. investigated the energetic and exergetic performance of a parabolic trough photovoltaic/thermal collector using a finite-volume model [12]. With conventional cooling approaches for CPV, it has been shown that low system thermal resistance requirements are difficult to satisfy because of the presence of thermal contact resistance at the interface between cells and the heat sink.

Direct liquid-immersion cooling of CPV cells shows significant advantages compared with passive cooling and conventional active cooling. With direct liquid-immersion cooling, bare CPV solar cells are immersed in a circulating liquid. Thus the contact thermal resistance between the solar cell and the cooling system is minimized or eliminated, and heat is taken away from both the front and rear cell surfaces instead of just the rear surface, as in conventional active cooling. Its efficient heat transfer performance in CPV system has been demonstrated in work [13,14]. Results

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Nomenclature

A_a	front surface area of the cell array, m^2
A_e	active area of ANU silicon solar cell, m^2
D_h	hydraulic diameter of the narrow rectangular channel, m
E	average energy flux ratio
g	acceleration of gravity, 9.8 m/s^2
H	height of the rectangular channel, m
ΔH	height difference in the inverted U-tube manometer, m
I_{sc}	short circuit current, A
L	distance between two pressure measuring points, m
L_1	upper part width of the channel, m
L_2	lower part width of the channel, m
ΔP_{f0}	pressure loss per unit length of the receiver, Pa/m
P_{max}	maximum output power, W
Q	effective thermal load of the receiver, W
t_{avg}	average cell array temperature, °C
t_i	cell array temperature on measuring point I, °C
t_{in}	temperature of the silicon oil at receiver inlet, °C
t_{out}	temperature of the silicon oil at receiver outlet, °C
Δt	heat transfer temperature difference, °C
u	flow velocity in the channel, m/s
V_{oc}	open circuit voltage, V
Greek	
α	convective heat transfer coefficient, W/m^2 K
ρ	density of dimethyl silicon oil, kg/m^3
λ	thermal conductivity of dimethyl silicon oil, W/m K
μ	viscosity of dimethyl silicon oil, mm^2/s
η	conversion efficiency of solar cells
Abbreviations	
ANU	Australian National University
CPV	concentrating photovoltaic
DNI	direct normal irradiance
Nu	Nusselt number
PV	photovoltaic
Re	Reynolds number

reported by Zhu et al. [15] and Xiang et al. [16] show that the cell temperature in a dish CPV system can be cooled to lower than 45 °C by water immersion cooling under 250 suns, and the heat transfer coefficient can be higher than 6000 W/m^2 K. Han et al. [17,18] modeled a rectangular liquid immersion solar receiver for a linear trough CPV system. The simulation results show that low and uniform cell temperature can be maintained in the receiver. Furthermore, several patents based on direct liquid-immersion cooling concepts for solar cells have been applied in recent years. Tanaka [19,20] suggested using a shallow liquid layer or a gel layer surrounding solar cells to provide light trapping and cell surface-wetting functions. In addition, phase change liquids have been proposed for direct liquid-immersion cooling of solar cells by Koehler [21]. Victoria et al. [22] studied durability of dielectric fluids that might be used for immersing optics in CPV system, and found that the most stable fluids were paraffin and silicone oils whose transmittances remained practically unaltered after a UV (ultraviolet) dosage equivalent to 3 years of AM1.5D radiation.

Many researchers also studied the possible optical or electrical effects of liquid on the cells. Ugumori and Ikeya [23] found that the photocurrent of solar cells operated in liquids increases with the increase in the permanent dielectric moment of liquid molecules. Abramyan et al. [24,25] reported that a dielectric liquid thin-film increased the efficiency of common silicon solar cells by 40–60%. Zhu et al. [26,27] reported that there was no electrical degradation for silicon solar cells immersed by silicon oil, which could be a suitable candidate liquid for liquid-immersing CPV system, but alcohols liquid is unsuitable as an immersion liquid. Han et al. [28] found that the electrical performance of silicon CPV cells can be improved when immersed in de-ionized water, isopropyl alcohol, ethyl acetate and dimethyl silicon oil, arising from improved light collection and reduced cell surface recombination losses from surface adsorption of polar molecules. However, further studies by Han et al. [29,30] show that the stable electrical performance was difficult to be achieved by long-time de-ionized water immersion, and the investigation on the degradation mechanism indicated that galvanic corrosion occurred on cells.

In the present work, a small-scale experimental linear CPV system with liquid-immersion cooling was constructed and to reduce the liquid holdup, a narrow rectangular channel receiver was designed. Dimethyl silicon oil with viscosity of 2 mm^2/s was chosen as an immersion liquid because of its high transmission, good stability, good electrical insulating ability and acceptable viscosity. Heat transfer studies were performed, and long-term stability of the silicon solar cells immersed by the silicon oil was monitored under real climate conditions.

2. Experimental

The liquid immersion linear CPV system by liquid-immersion cooling mainly consists of a narrow rectangular channel receiver, a linear flat mirror concentrator, one-axis tracker and other components.

2.1. Narrow rectangular channel receiver

As shown in Fig. 1a, the receiver is composed of a cell array with 10 cells in series, a glass cover, a rubber gasket and an aluminum substrate. The glass cover was tightened together with the gasket and the substrate by bolts to form a narrow rectangular channel with 20 mm in height, and the solar cell array was placed in the middle of the channel. The channel width of the upper and lower parts is 60 mm and 50 mm respectively, and two bulges in the lower parts are used for supporting the tabs of the solar cells. The overall length of the receiver and the cell array is 1060 mm and 509 mm respectively. The performance of the receiver was investigated on the one-axis tracking linear flat mirror concentrator, and Fig. 1b shows the receiver on sun. The optical performance of the concentrator was simulated using TracePro software (Lambda Research Corporation, Littleton, MA, USA), and the spectral reflectivity of the flat mirror, the transmittance of the glass cover and the silicon oil were all considered into the simulation. The result of TracePro simulation of energy flux profile on the receiver with width and length of 60 mm is shown in Fig. 2, it can be seen that the uneven distribution of the flux on the focus is mainly on the width direction but not on the length direction. The cell array is located between −20 mm and +20 mm on the width direction, and the average energy flux ratio on cells surface is calculated as 9.1 suns.

The solar cells used in this experiment are mono-crystalline concentrator silicon solar cells provided by the ANU (Australian National University) with an efficiency of about 19% at 25 °C [31]. The dimension of the cell is 50 mm by 40 mm with an active area of 19.5 cm^2. As shown in Fig. 3, each cell is connected to four tabs, two for the back contact and two for the front. The tabs are used not