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A novel multi-layer manifold microchannel cooling system for concentrating photovoltaic cells

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Using concentrating photovoltaic (CPV) cells is an effective method for the low-cost photovoltaic conversion. However, higher temperature and non-uniform surface temperature distribution will result in the electrical output decline of CPV cells and shorten their life time. To obtain higher net output power of CPV cells and prolong their life time, we designed a novel multi-layer manifold microchannel cooling system to effectively lower the cell surface temperature and improve the uniformity of surface temperature distribution. Thermal image analysis indicated that the surface temperature difference of the CPV cells was below 6.3 °C. The multi-layer manifold microchannel had a heat transfer coefficient of 8235.84 W/m^2 K and its pressure drop was lower than 3 kPa. The results show that the hybrid CPV cells have a satisfactory net output power due to their lower pumping power and the higher electrical output of CPV cells.

1. Introduction

CPV technology is an effective way to reduce the cost of the solar cells because a smaller area of photovoltaic material is required. However, under concentration, increasing temperature will lead to a decrease in electrical output of CPV cells due to solar-to-electrical conversion losses. Moreover, long-term high operating temperature can cause irreversible degradation of CPV cells. Therefore, cooling of CPV cells is quite important when designing CPV systems. Royne et al. published a comprehensive review about the cooling technologies of CPV systems in 2005 [1]. Among these technologies, only impinging jets and microchannels achieved low thermal resistances for satisfactory cooling performance. Subsequently, impinging jet [2,3] and microchannel cooling [4,5] applied to the CPV cells have better thermal resistance coefficients. These studies concluded that low thermal resistances can be reached, but it is difficult to reduce the temperature non-uniformity inherent to impingement distributions. It is a challenge to achieve more uniform temperature distribution.

Uniform temperature distribution and net output power for CPV cells are two important factors which should be considered simultaneously. However, only a few studies investigated the effect of temperature uniformity on the efficiency and longevity of CPV cells, or the effect of pumping power on net output power of CPV cells. Some studies have shown that cell efficiency declines due to the non-uniform temperature across the cell [6–9] and that the lack of uniformity in temperature causes reverse saturation current, reducing the life of solar cell [10]. Other studies have shown that the maximum net output power was obtained by cooling under the minimum power required to drive the pump [11–13]. The pumping power is related to the flow rate and pressure drop [14].

Several cooling methods for CPV cells have been developed. Good results were obtained using manifold microchannels [15] or hybrid jet impingement/microchannels [16]. However, compared to microchannels, jet immpingement/microchannels enhance the uniformity of temperature distribution and reduce the pumping cost, but sacrifice the heat transfer coefficient.

A simple way to increase the uniformity of temperature distribution and decrease the pressure drop is the mal-distribution method. This technique has been applied to fuel cells and CPV cells [17,18]. Although this method achieved the uniformity of temperature distribution, it caused a relatively large pressure drop and low cooling surface utilization for CPV cells [19].

In this study, we designed a novel multi-layer manifold microchannel cooling system for CPV cells. The designed cooling system contains three layers. The as-designed multi-layer manifold microchannel cooling system can effectively lower the surface temperature, improve surface temperature distribution, reduce the pressure drop, and increase the heat transfer coefficient,

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resulting in a lower pumping power and a higher net output power of CPV cells. Meanwhile, the effective utilization of the cooling surface makes the as-designed multi-layer manifold microchannel cooling system more suitable for the requirements of other types of CPV devices such as single cell, linear geometry and densely packed module devices [1].

2. Experimental

2.1. Experimental design and cell modules

A schematic overview of the multi-layer manifold microchannel testing unit is given in Fig. 1. The working fluid goes into an inlet plenum chamber with a diameter of 8.5 mm, a length of 98 mm, and a wall thickness of 1 mm through a circular inlet. This entrance tube was welded onto the side plate. The ducts were parallelly arrayed as two lines on the plenum chambers. The inlet plenum chamber was filled with water and then the water turned 90° at ducts into manifolds. Owing to a large pressure drop of microchannels, water was completely filled in the manifolds, and then was forced to flow into microchannels by the subsequent water driving. The heat was taken away from the microchannels connected with heat sources by forcing water in the microchannels to flow through the lower surface of the heat sink. The water then returned to the outlet manifolds through ducts into the outlet plenum chamber, and finally reached the outlet.

The designed testing unit contains three layers, the microchannels, the manifolds, and the plenum chamber with ducts. Commonly, the fabrication technologies of microchannels include microelectronic discharge machining, micro ultrasonic machining (micro USM), excimer laser machining, and etching. In these technologies, the wire electrical discharge machine can easily manufacture the long microchannels. For fabricating the long microchannels with the wire electrical discharge machine (WEDM (DK 7740b)), we adopted an electrode of Φ 0.18 mm (molybdenum wire). The microchannel length was 98 mm, it is width was 220 μm [0.18 mm + 2 × 0.02 mm (discharge gaps)], and it is depth was 1.5 mm. Owing to the width of the silicon solar cells being 17 mm, the upper layer consisted of 41 parallel microchannels, each with a length of 98 mm, a width of 0.22 mm, and a depth of 1.5 mm. To account for the upwind coefficient, the middle layer consisted of 12 inlet manifolds and 11 outlet manifolds, each with a length of 17 mm, a width of 2 mm, and a depth of 2 mm. 12 inlet ducts and 11 outlet ducts, each with a length of 2 mm, and a width of 2 mm, were used to connect the manifolds and plenum chambers. The bottom layer consisted of an inlet plenum chamber and an outlet plenum chamber, each with a diameter of 8.5 mm and a length of 98 mm. In the process of manufacturing, in order to reduce the contact heat resistance of the welding areas, we processed the three-layer structure as two units. One unit contained the microchannels and manifolds, and the other unit contained the ducts and plenum chambers. The microchannels were fabricated on copper with a thickness of 4 cm using a WEDM. The manifolds were fabricated on the back of the copper using a CNC machine. The ducts and plenum chambers were fabricated on the stainless steel block with a thickness of 4 cm using the CNC machine. Finally, soft soldering was adopted to connect the two parts.

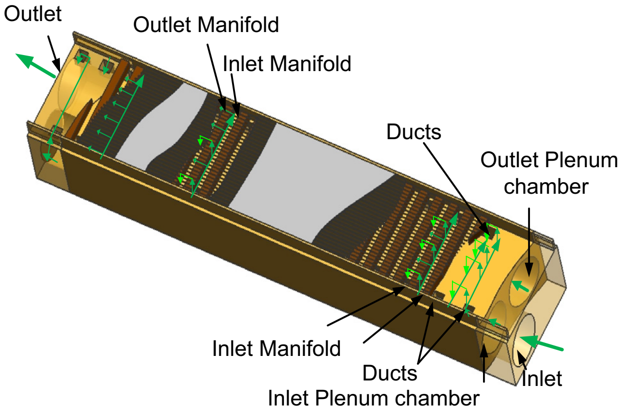

Fig. 1. Schematic diagram of the multi-layer manifold microchannel testing unit.

Because of the shortage of concentrated solar cells in china, common silicon solar cells (17 mm × 17 mm, Shanghai YangYuan new energy technology co., LTD) were used in the experiment. The CPV cells testing module had 3 cells connected in series so that the testing area was 1152 mm^2. Below the CPV panel, a thermal conductive silicon grease was adopted as the electrical insulator on the back of the CPV cells.

2.2. Simulated illumination and cooling system

A 6 kW long-arc xenon lamp (Chang zhou Yuyu Electronic–optical) was selected as a solar simulator. The electrode distance of the lamp was 250 mm. According to the light intensity uniformity distribution, about l/4 to 3/4 of the electrode distance was selected and the cell module was only installed in this range, as described by Zhu [20]. The concentration ratios (Cs) used in the experiment was 28, 36, 74, and 98 suns, which corresponded to 58, 44, 23, and 17 mm of the height from the long-arc lamp to the CPV cells, respectively.

The cooling system consisted of a gear pump, piping, an inlet, an outlet and CPV cells backed with microchannels. The water was pumped from a liquid reservoir through a 15 μm filter to prevent any solid particles from blocking the microchannels. After exiting the filter, the water then entered into the microchannels of the CPV cell testing module where the generated heat from the CPV cells was removed by the water. Leaving the test module, the water flowed into the outlet. In the by-pass loop, the water flowed through the pass valve to enter into the long-arc lamp, and flowed through a heat exchanger to return to the by-pass loop.

2.3. Data measurement

The surface temperature of the CPV cells was measured by using the thermocouples in the back of the CPV cell [4,20]. In order to visualize the surface temperature distribution, we adopted an IR Flex Cam Thermal Image (20 mm/F0.8, Ti 45FT) to exhibit the cell surface temperature.

The temperatures of water at the inlet and outlet were also measured by a Pt 100 temperature sensor (OD 5 mm; ID 2 mm, OMEGA), with an accuracy of 0.15 K. Pressure drop was measured by a pressure transmitter (FKCX-AII, Fujinon with sensitivity 8 mA/k Pa) with a response time of 1.0 ms and an accuracy of 0.07% F.S. The temperature and pressure drop data were collected by an Adam Data Acquisition Modules-4019+(ADAM 4019+) [wiring method: series connection, measuring range: 4–20 mA, power supply: 24(DC)] and then the real-time data output was viewed by the king-view configuration software.

The short-circuit current was tested indirectly by a sampling resistor ($R = 0.01\ \Omega$) and then the open-circuit voltage across the resistance was measured by using a Fluke 175 multimeter.

2.4. Experimental procedure

Prior to the experiment, a hood was placed in front of the long-arc lamp. The height from the long-arc lamp to the CPV cells