高倍率集光型太陽電池冷却用相変化冷却器に関する研究（Study on two phase cooling unit applied for high concentration solar cell)

47-176823 Zhang Bohan

Supervisor: Prof. Dang Chaobin

Photovoltaic power generation is a growing renewable primary energy source, expected to play a major role as we strive toward fossil fuel free energy production. Hybrid systems extend the functionality of high concentrating photovoltaics (HCPV) system from simply generating electricity, to providing simultaneously electricity and heat. However, the extreme high heat flux makes the temperature of PV cell very difficult to control. Thus, in this article, a new-type radial expanding micro-channel heat sink is designed to cool the solar cell and also the two-phase flow generated by HE would elevate the overall system efficiency and boosts the economic value of the generated power output. The thermal characteristics and instability of heat exchanger are investigated both theoretically and experimentally.

Key words: Photovoltaics, energy efficiency, heat transfer, micro channel, orientation, two-phase flow, flow instability.

1 Introduction

The energy demand of the world is continuously rising due to ever increasing global population and industrialization[1]. Harvesting solar energy is a promising technology for renewable power generation with the potential to meet a significant proportion of the world's energy needs. In high concentrating photovoltaic (HCPV) systems the sunlight is collected by concentrating optics and focused onto a considerably smaller photovoltaic receiver. Thus, solar cell requires strict temperature control because of the strong influence of the operation temperature on the photovoltaic conversion process. In order to realize the appropriate cooling of solar cell while concentrating. A radial expanding micro-channel heat sink was designed and thermal characteristics were studied.

2 Experiment on thermal characteristics of radial expanding micro-channel heat exchanger

2.1 Conception of radial micro-channel heat sink

Novel heat sink utilizing two-phase cooling attracts increasing attentions owing to the high heat transfer capacity and convenient assembly[2]. However, the application of two-phase heat sinks in engineering field confronts intricate issues of flow maldistribution and flow instability. Attributed to the enhanced effect of surface tension in small scaled space, isolated bubble flow, elongated bubble flow and annular flow are the main flow patterns observed in microchannels. Bubbles inside channels evaporate fast and elongate towards both sides, interim vapor blockage and succeeding pressure peak are induced, which causes reverse flow or even local dry-patch. Violent fluctuations in wall temperature, inlet mass flux and pressure caused by flow instability have been reported in previous researches.

To relieve the instability of two-phase flow, a redial expanding micro-channel heat sink is designed for HCPVT system, as seen in fig.1. The diameter of channel is 80mm.

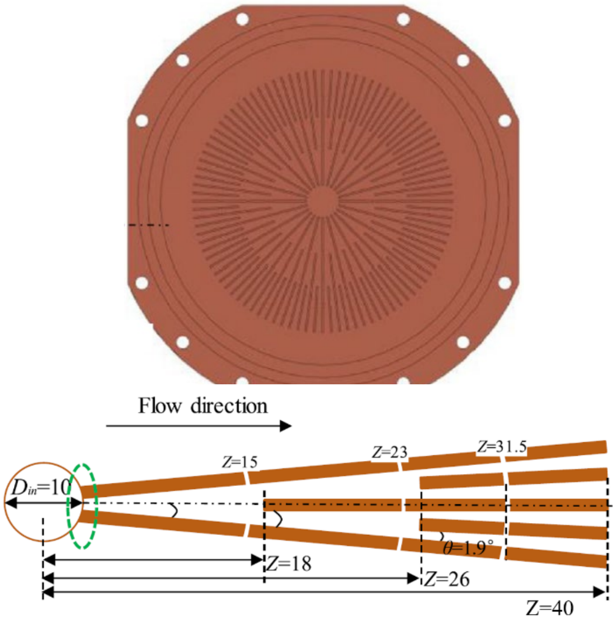


Fig.1: Sketch of radial microchannel heat sink

Compared to conventional array micro channel heat sink, the expanding channel gives a flatter space for bubbles to grow. And also, the cut-off in the middle of channel, as seen in fig.2, can break up the long bubble into several pieces. In that way, the flow instability could be greatly relieved and the heat transfer would be more stable and efficient.

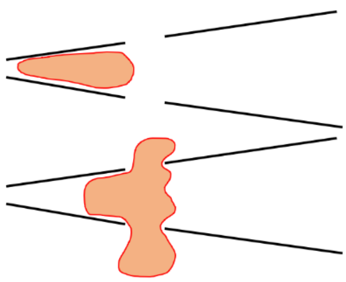
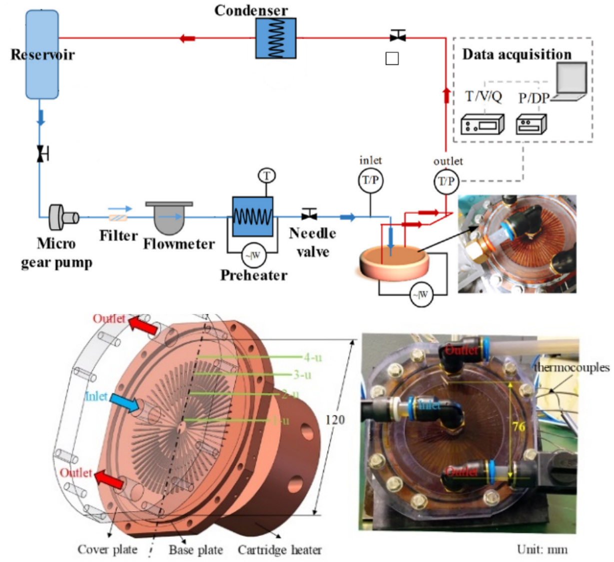


Fig.2: Sketch of cut-off in microchannel

2.2 Experiment setup

The schematic diagram of experimental loop is shown as Fig. 3(a). Deionized water was used as the working fluid. The inlet liquid was supplied by a micro gear pump (MICROPUMP GJ-DB380.A), and the flowrate was measured by a mass flow meter (OVAL ALTI mass II CA001) before flowing into test section. The needle valve in the loop was used to adjust the inlet mass flowrate. The temperature of inlet subcooled liquid was regulated at 84.7 ± 0.5 ℃ by a thermostatic bath preheater. The two-phase flow outflowed the test section was cooled down by a plate heat exchanger type condenser.



(a) Experimental loop

(b) Test section and thermocouples' location

Fig.3: Schematic diagram of experimental set-up

Two copper rods were used as an independent heat source for heat exchanger, and the heating load was measured by a power meter (Hioki 3333). The area of heater top surface is the same as HE. The test section was kept horizontal. The test section and all connecting pipes were wrapped with thick asbestos fabric for thermal insulation. The temperatures at the inlet and outlet were measured by K-type thermocouples. The pressures at the inlet and outlet were measured by pressure sensor switch gauge (NAGANO KEIKI KP-15), the outlet pressure was maintained at 107.2 ± 1 kPa by the test bench, and the corresponding saturation temperature was within 101.5 ± 0.5 _C. The inlet/outlet pressure were recorded in a frequency of 500 ls with a high-speed analog measurement unit (NR-HA08). The input heat load Q varied from 1000 to 1850 W, and the inlet mass flowrate m ranged from 120g/min to 300 g/min.

2.3 Heat transfer

In order to figure out the relationship between heat flux and heat transfer coefficient, the thermal performance of the proposed radial expanding micro-channel heat exchanger under various working conditions is evaluated. Saturation temperature is calculated by outlet pressure and inlet temperature is controlled by preheater to be 82±1℃. Heat flux was changed from 220,106 to 422,424 W/m², mass flow rate was 300g/min.

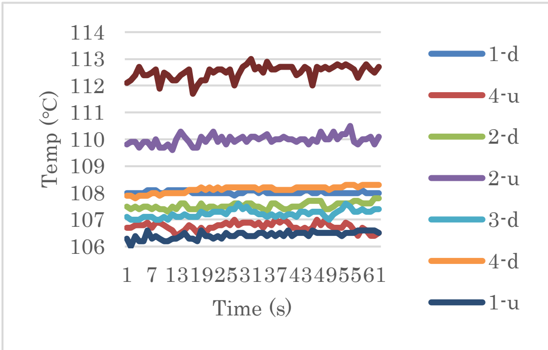
As shown in fig.4. The highest wall temperature is about 112℃, however T 4-u is almost located at the outlet, it is unfair to judge the performance of heat sink with that, on the contrary T 3 is a good measurement point.

The heat transfer capacity of HE is evaluated with the average saturated boiling heat transfer coefficient haver, defined as Eq. (1), where q_{eff} is the effective heat flux in terms of the footprint heating area, defined as Eq. (2). $T_{w,aver}$ is the average wall temperature in saturated region, and T_{sat} is the saturated temperature of working liquid under the outlet pressure.

$$h_{aver} = \frac{q_{eff}}{T_{w,aver} - T_{sat}} \tag{1}$$

$$q_{eff} = \frac{Q}{\pi \cdot L^2} \tag{2}$$

Where Q is the energy from heater, L is the radius of heated surface.



q_{eff}: 42 W/cm^2, Average x_{out}: 0.13, T_{in}: 84.7℃, T_{sat}: 101.8℃

Fig.4. Temperature distribution of HE at mass flow: 300g/min,

As seen in the figure 4, the heat transfer coefficient reaches as high as 85,000W/m²K when heat flux is 42W/cm²K. Besides, this thermal characteristic is ideal for solar system use.

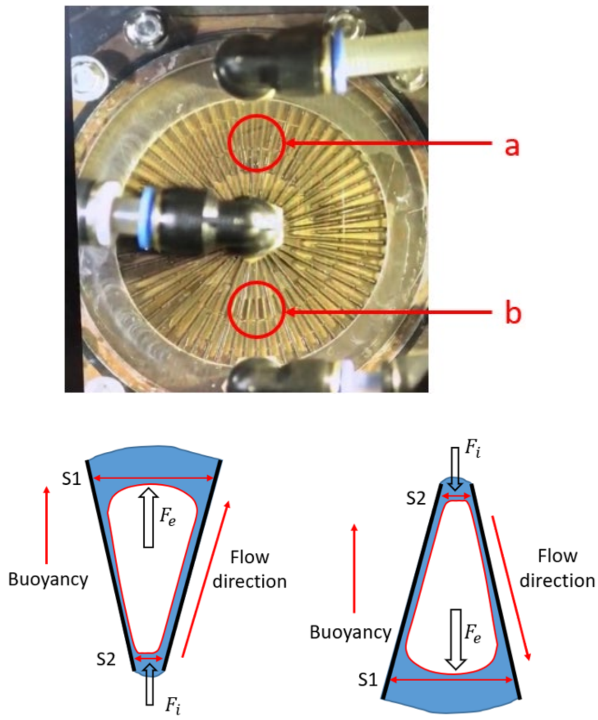
3 Experiment of effect of gravity on radial micro-channel heat exchanger

3.1 Theoretical analysis on the effect of gravity and improvement

Fig.5 is a force analysis of a single channel, illustrating how flow boiling instability occur and exploring the solution.

Bubble growth in the microchannel is the main cause of reverse flow instability of the two-phase flow. If the saturation liquid continues to be heated, the bubble expands rapidly. The pressure inside the bubbles increases and may become larger than the pressure of the inlet fluid, pushing the fluid back to the inlet and causing a reverse flow. And reverse flow is fatal to the heat transfer performance.

Parabolic dish concentrator tracks the sun at a low orientation about 11.74 degrees in winter, which means heat exchanger is working more like a perpendicular condition at that time. Compared two position of microchannel heat sink, as seen (a) and (b) in fig.5, when bubble is heated and inflates, in the upper part of HE buoyancy contributes to accelerate the vapor escape the channel, however, in the lower part of HE the buoyancy prevents bubble inflate and make vapor float upward to the inlet. Thus, dry-out probably occurs in the (a) region of HE because of lacking liquid.



(a) In the upper part of HE (b) In the lower part of HE

Fig.5: Sketch diagram of force analysis in a single micro-channel

Where F_i is represented inertia force, F_e is force of evaporation.

The effect of orientation on radial heat exchanger also was verified by visualization, as seen in fig.6.

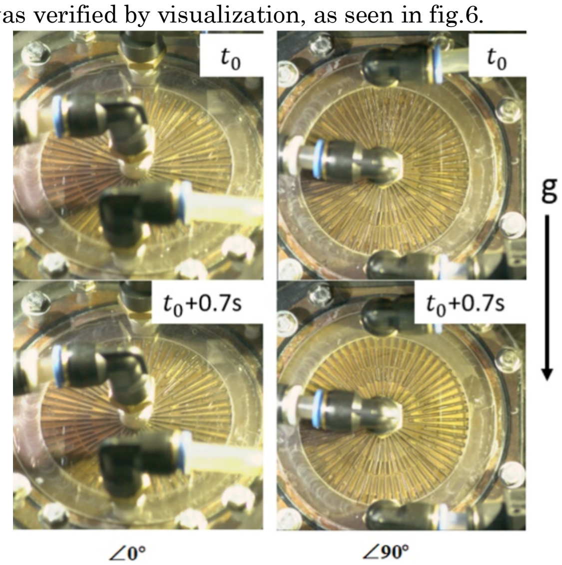


Fig.6: Visualization of various orientations

When ∠0°, the flow distribution was almost uniform in each micro-channel, both upper and lower region of heat sink were filled with fluid. Bubbles were growing up along with the flow direction and escaping successfully. However, as seen in the visualization of ∠90°, vapor was almost aggregating at the upper of HE and prevented fluid flowing into the channel. As a result, the upper region of microchannel was filled with high vapor quality two-phase flow and it was evaporated in a short time. Thus, dry-out occurred.

3.2 Experiment of thermal characteristics of improved heat exchanger

The improvement is to plant a porous metal in front of each micro-channel in order to elevate the total pressure drop to relieve the effect of static pressure drop in micro-channel heat exchanger, as seen in fig.7.

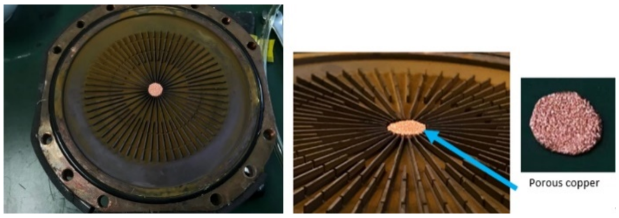


Fig.7: Porous copper placed in front of each channel

The experiment setup is the same as the loop as above, the only difference is planting a porous copper. The testing condition is shown in table.1,

Angle °	G[kg/m²s]	Q_{in}[W]	q_{eff}[kW/m²]	T_{in} [°C]
90	71	800	177.6	80.1±0.3

Table.1: Testing condition

As the thermal performance is the worst in vertical condition, only ∠90° is tested during experiment. As seen in fig.6, which is the temperature distribution on the surface of heat exchanger, after planting the porous copper in front of the micro-channel, the temperature oscillation was eliminated and also kept a good heat transfer characteristic as before. That is to say, planting porous copper to elevate total pressure drop could relieve the effect of gravity on micro-channel heat sink with a diameter of 8cm.

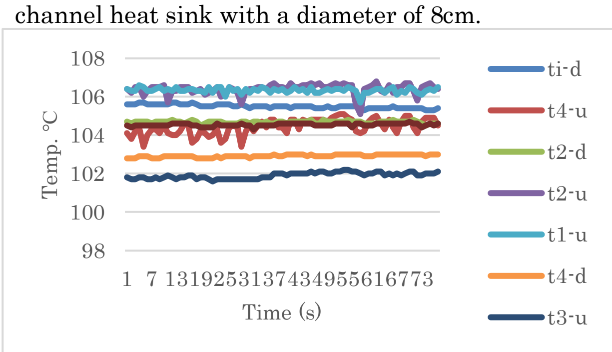


Fig.8: Thermal characteristic of improved heat sink at vertical

4 Experiment of thermal performance on HCPVT system with improved microchannel heat exchanger

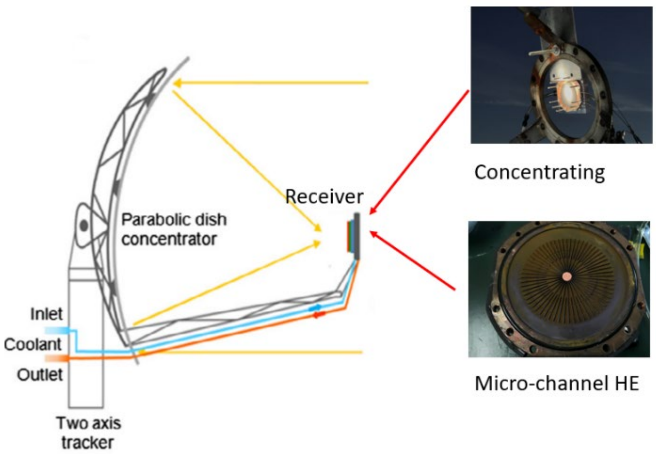
All over the work introduced in this article serves for an ultimate goal that is to realize the co-generation of HCPVT system. From the point view of heat transfer, ultimate is to carry out the thermal control of solar cell while concentrated with a huge heat flux. After solving the heat transfer performance and the effect of gravity, it is time to apply radial micro-channel heat exchanger on the parabolic concentrator and investigate the overall performance of HCPVT system.

Fig.9: Concentrator and receiver of HCPVT system

Thermal performance was experimented almost the same as before, apart from three temperature measurement points beneath the surface of micro channel heat exchanger, as seen in fig 10, the parameters of inlet temperature, outlet temperature, direct solar radiation and total solar radiation were conducted in the test. The working condition is introduced as table.2,

Angle	G[g/min]	T_{in} [°C]	Q_{in}[W]	$Tsat$ [°C]
64	163	84±3	800	102.2±0.5

Table.2: Testing condition



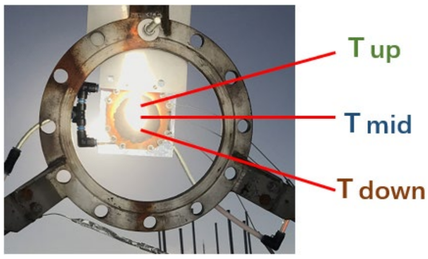


Fig.10: Three temperature measurement points by thermocouples

Fig.11: Thermal characteristics of radial micro-channel heat sink in HCPVT system

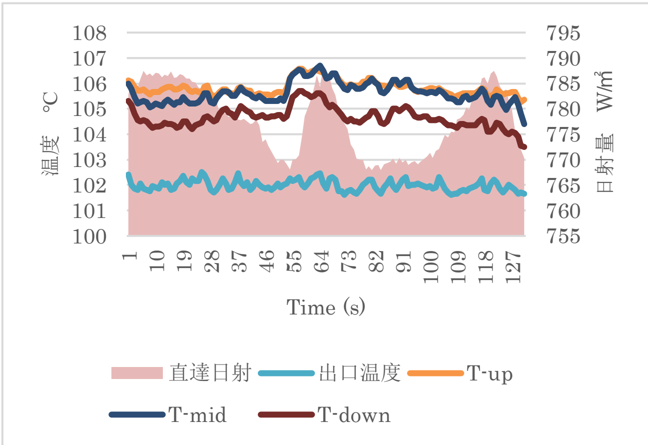


Fig.11 shows the wall temperature and solar radiation as a function of time, for an average of temperature, $T_{up}=105.7$°C, $T_{mid}=105.2$°C, $T_{down}=104.3$°C. The difference between T_{up} and T_{down} is only 1.4℃, it means the temperature distribution of surface is uniform.

5 Conclusion

The flow instability caused by gravity was relieved successfully. More importantly, the maximum of surface temperature is only 106.7℃ under the heat flux of $82.4W/cm^2$, concentration ratio of 1060 $xsuns$. And the heat transfer coefficient would be as high as $235{,}428W/m^2K$. For 3-junction solar cell which usually could work below 150℃, the heat transfer performance is capable to sustain it in HCPVT system. Although in particle, the thermal resistance of solar cell and solder or silicon grease is evitable to create a temperature elevation during concentrated, the thermal characteristics of heat sink successfully meet the requirement of cool the solar cell.

Reference

1) C. Wolfram, O. Shelef, P. Gertler, How will energy demand develop in the developing world?, J Econ. Persp. 26 (1) (2012) 119-138.

2) 123S.G. Kandlikar, Review and projections of integrated cooling systems for three dimensional integrated circuits, Trans. ASME, J. Electronic Packag. 136 (024001) (2014) 1-11.