THERMAL EFFECTS OF MICRO-FIN GEOMETRY ON A SILICON RECEIVER FOR CPV COOLING PURPOSES

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ABSTRACT: Temperature rising negatively affects all the photovoltaic technologies. This problem becomes particularly relevant for concentrating photovoltaic (CPV), where the sunlight density is increased up to thousands of suns and the exchange surfaces are inversely reduced. Furthermore, multijunction cells, most commonly used in CPV applications, intensely suffer the increasing in temperature. Several technologies, mainly active ones, have been tested so far to solve this problem. Micro- and nano-technologies can represent a cheap and effective passive solution for CPV cooling: in particular the application of a micro-fin array leads to a strong improvement of the exchange surface area. In this work, it has been developed onto a silicon backplate of a 4-cells CPV receiver: different designs have been developed and tested in a solar simulator and then the results have been compared to those of a flat silicon wafer. This paper investigates for the first time the effect of geometry of a micro fin array on natural convection on a silicon backplate of a CPV receiver, in order to minimize the thermal gradient between the solar cell and the cooling plate. It reports the improving in efficiency related to the application of a micro-fin array replacing a flat wafer. The correlation among the micro-fins geometric parameters (such as fins spacing and fins thickness) and the cooling efficiency of the array has been sorted out as well.
Keywords: concentrators, thermal performance, design, multijunction solar cell

1 INTRODUCTION

Although the efficiency of any photovoltaic device decreases as the temperature raises, the flat photovoltaic modules usually operates without cooling systems. This is true even for low concentrating photovoltaic systems. This is due to a large module surface that is able to naturally exchange the waste heat produced by the low-density solar energy flux.

Due to the large amount of incoming sunlight, concentrating photovoltaic (CPV) requires cooling solutions: the rise in concentration results in an increase in waste heat and, thus, in temperature. Moreover, the multijunction cells, commonly applied in CPV systems, are particularly sensitive to temperature rise, with efficiency possibly dropping up to 0.05% for every ºC increase [1].

Given a 500x CPV system operating under standard conditions (AM 1.5d solar insulation of 850 W/m^2), an optical efficiency of 80% and a cell efficiency of 35%, the cooling system needs to dissipate a heat power of 221 kW/m^2. While several active cooling technologies have been tested so far for CPV cooling [2], only a little effort has been made to test and design passive cooling systems.

The development of micro- and nano-technologies offers new perspectives for both active and passive CPV cooling. A lot of papers have been published on this subject: micro- and nano-technologies are particularly interesting for electronic devices, which can require heat removal flux up to thousands of W/cm^2. Among all the possible solutions, micro-fin array offers a simple, suitable solution for improving passive cooling system [3].

Natarajan et al. [4] numerically studied the application of aluminum macro-fins in a 10x CPV system. Unfortunately, as demonstrated by Kim et al. [5], the heat transfer correlation for macro-fin arrays is inadequate for the accurate estimation of the heat transfer rate in micro-scale systems, which, on the other hand, have been studied by Mahmoud et al. [6]. The authors investigated the thermal effect of micro-fin geometry on a copper device. Shokouhmand H. and Ahmadpour A. [7] presented a numerical investigation about heat transfer from a micro-fin array heat sink, but without taking into account the effect of fin thickness on the thermal exchange.

The present work took into account the effect of the different dimension on the performances of the arrays. Moreover, a couple of samples equipped with micro-pillars have been studied, to compare their performances with those of the micro-fin arrays. The application of micro fin for CPV purposes represents a novelty. In this work, the cooling of a 10x CPV system has been considered. In particular, different arrays of micro-fin have been developed on the 1.3mm-thick silicon backplate of the assembly. The silicon wafer has a similar thermal expansion coefficient as III-V materials, which will play an important role of dissipating heat from the solar cell. Different designs have been developed and tested to experimentally investigate the effect of silicon micro-fin array geometry on natural convection.

2 MATERIAL AND METHODS

A simple, low-cost densely packed receiver has been developed. Undoped silicon wafers have been used as base layer, due to their good thermal conductivity and high electrical resistance. Silicon can help reducing the thermal stress on the assembly. Compared to copper, another good thermal conductor commonly used for heat sink purposes in CPV applications, silicon match better the germanium coefficient of thermal expansions. That is an important issue, since the solar assembly is usually subject to uneven temperature gradient. Being a dielectric material, silicon can even work for electric insulation purposes. All these characteristics made him a good candidate for being used as backplate material in the CPV assembly.

Table I: Proprierties of germanium, copper and silicon

Material	Thermal conductivity (W/mK)	Electrical resistivity (nΩ*m)	CTE (ppm/°C)
Germanium	60	10^9	5.8
Silicon	150	10^10	2.6
Copper	390	16.78	16.7

The micro-fins arrays have been firstly designed using CAD and then fabricated through a common dicing machine. Seven different designs have been tested: the first sample uses a flat silicon wafer, the others employ micro-fins arrays.

Table II: Dimensions of the fabricated micro-fins array (in mm)

	Type	W	L	t
#1	Flat	49.85	49.86	-
#2	Single array	49.82	49.87	0.79
#3	Single array	50.04	49.86	0.39
#4	Single array	49.89	49.89	0.35
#5	Single array	49.78	49.84	0.18
#6	Crossed arrays	50.23	49.95	0.39
#7	Crossed arrays	49.84	49.75	0.19

	Type	H	t_b	S
#1	Flat	-	-	-
#2	Single array	0.62	0.76	0.81
#3	Single array	0.60	0.72	0.81
#4	Single array	0.56	0.76	0.46
#5	Single array	0.79	0.53	0.22
#6	Crossed arrays	0.56	0.78	0.41
#7	Crossed arrays	0.55	0.74	0.21

The fins dimensions have then been measured using a measuring microscope: they are reported in Table II, according with the nomenclature shown in Figure 1 and Figure 2.

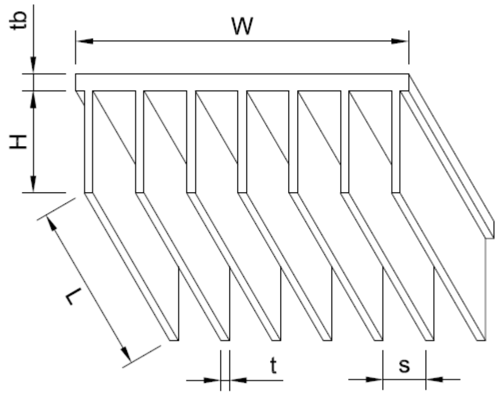

Figure 1: Geometric parameters in the developed plate fin array

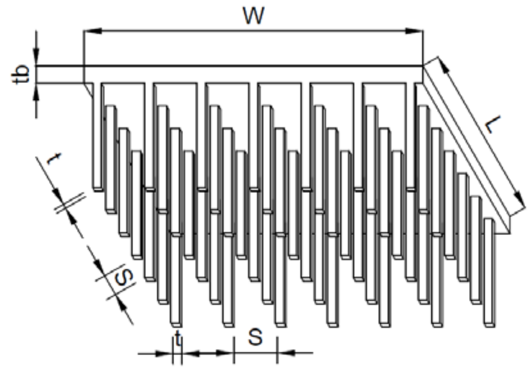

Figure 2: Pin fin array design (referred in the text even as “crossed array”)

The setup has been tested in a solar simulator. An Abet Technologies Sun 2000 Solar Simulator has been used for experiments requiring the use of a controlled sunlight. It is equipped with Xenon Arc Lamps and its AM1.5G spectral match is grouped as Class A. The 6x6-inches-wide illuminated area has a non-uniformity lower than 5%.

A geometric concentration of 17x has been achieved, which corresponds to an effective optical concentration ratio of 10x, thanks to a Fresnel lens made of PMMA. It has been calculated analyzing the current output of a trusted receiver provided by Azurspace. The experimental short-circuit current (Isc) has been compared with the expected one, corrected by the coefficients reported in the datasheet and shown in Table III

Table III: Cell’s temperature coefficients (25-80°C, beginning of life)

Parameter	Value
Δ Isc / ΔT	1,596 mA /°K
Δ Voc / ΔT	- 4,130 mV/°K
Δ Pmpp / ΔT	- 6,194 mW/°K
Δ η/ ΔT	- 0,034 %(abs.)/K

The output values of current and voltage have been measured through multimeter. The temperature was monitored by a thermocouple located on the top of the silicon sample but hided from the sunlight.

Each setup has been tested for five minutes under the solar simulator. The temperature values has been collected each 0.2 seconds and stored into a database. In order to avoid temperature floating, the temperature data have been averaged out each 10 seconds. No solar cells were placed on the silicon backplate: all the temperatures have been reduced by 30%, to keep into account the quote of sunlight which should be successfully converted into electricity by the cell.

3 RESULTS AND DISCUSSION

This work aims to study the thermal performances of a 5x5cm silicon backplate under a 10x concentration, equipped with different micro-fins arrays. The micro-fins allow to increase the surface of the backplate and, then, to increase the thermal exchange, reducing the temperature.

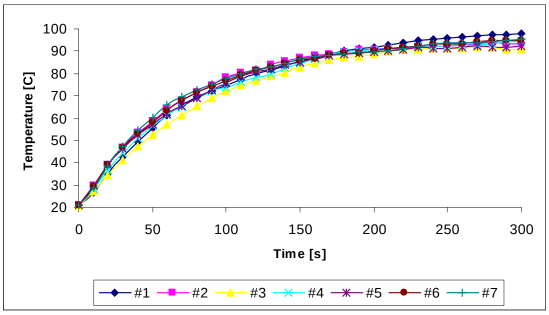

Figure 3: Thermal behaviour of the samples

In Fig. 3, the temperature risings of the samples are reported. All the temperatures, after 300 seconds, range between 90 and 98 °C. As expected, the worst performing sample is obviously the flat backplate. The low exchange surface area led to a lower thermal exchange and then to a higher temperature. Developing a micro-fins array on the backplate of the sample means getting a reduction in temperature up to the 10%.

According to the shape of the lines in Fig. 3, the rising in temperature usually settles down after 160 seconds. This is the time when the sample#1 curve's increasing drops below 2%. Thus, an average of the last 140 seconds values has been taken into account for further considerations. They are reported in Fig. 4.

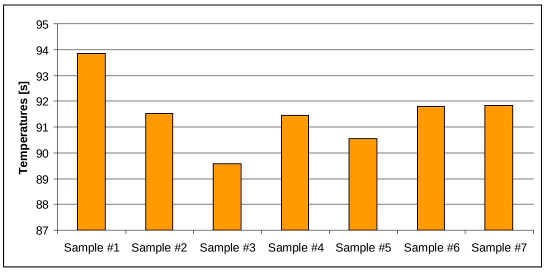

Figure 4: Last 140 seconds average temperatures

The best performing sample seems to be the sample#3. It assures a temperature reduction higher than 8% compared to the sample#1. It is interesting to analyze the geometric characteristics of the sample. First of all, this sample has one of the lowest exchanges surfaces: the total area is just one time bigger than the flat case one. The sample#5, which has a surface four times larger than sample#1 has anyway a good reduction in temperature, of about 7.3%. This means that the area of the thermal exchange surface is not necessarily the main issue for cooling a device. That's due to the viscous effects of the air between the fins: an higher number of fins led to a lower spacing between them and, then, to higher viscous forces. These forces led the air to act as an insulator, due to high resistance to thermal conduction of air. These results were indirectly confirmed by Mahmoud et al. [6]: they stated that the heat transfer coefficient decreases when the fin spacing decreases, which means that the performances are lower with a higher number of fins and, thus, with a larger exchange surface area.

The values of the heat transfer coefficients (h) have been calculated as well (Fig. 5). As reported even in previous literature [5,6] the highest values are obtained in the flat case. The reason of that is inside the definition of the heat transfer coefficient, which is inversely proportional to the temperature difference and to the heat exchange surface area. These cases, the temperature reductions affect less the coefficient of heat exchange comparing to the surface area enhancement, reported in Figure 6. Then, there are no correlations between the final temperatures and the heat transfer coefficients, since, in this work, this last parameter strongly depends on the surface area more than on the temperature drop.

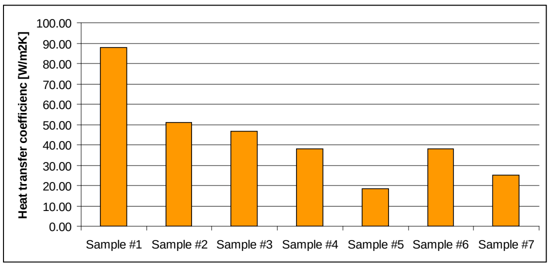

Figure 5: Heat transfer coefficients

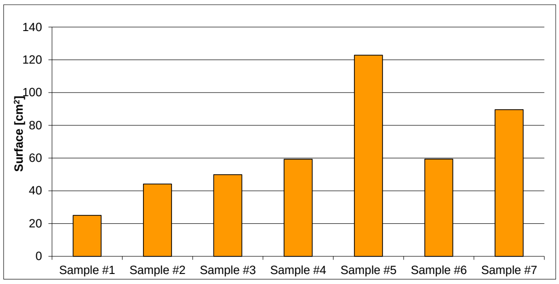

Figure 6: The surfaces of the samples

Kim et al. [5] overtook the heat transfer coefficient issue taking into account the fin effectiveness, ε_f. It can be calculated as the ratio of heat transfer rate of the microfin array to that of the flat plate, each one multiplied by the respective area.

$$\varepsilon_f = \frac{H_{sample\#} * A_{sample\#}}{H_{sample1} * A_{sample1}}$$

The fin effectiveness represents the enhancement in the heat transfer due to the extended surface. This case, the heart transfer enhancement of microfin doesn't exceed the 6% (Figure 7): it is in line with the previous tests. According to Kim et al. [5] this is due to the fact that conduction is dominant over the natural convection for microscale fins.

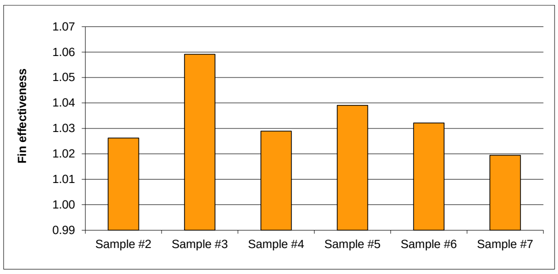

Figure 7: Fin effectiveness of the samples

As previously shown, sample#3 seems to be the most effective setup. It has the largest fins spacing among the arrays and report a fin effectiveness of 1.06. Sample#2 has the same spacing, but its lower performance is probably due to the large fins thickness, that leads to the lowest surface incensement among the samples. The high enhance in surface might be the cause of the performances of sample#5, which report the best effectiveness after sample#3.

The results show that the introduction of crossed setup doesn't give any great benefit to the performances. The fin effectiveness of sample#6 is similar to that of sample#4. The sample#7, if compared to the sample#5, shows a deterioration of the performances. A crossed array doesn't increase the exchange surface of the system. This might be explained with the dominance of the conduction compared to the natural convection in the micro-scale fins. New designs, for example involving non-vertical surfaces or different shapes of the fin basis, might introduce some enhancements in the crossed arrays performances.

4 CONCLUSIONS

Micro- and nano-technologies represent a reliable way for decreasing the temperature of a CPV system. In particular, the application of a micro-fins array on the backplate of the receiver represents a simple solution for a passive cooling system.

This work has experimentally studied for the first time the effect of the fins dimensions on the natural convection of a silicon micro-fins array for CPV cooling purposes. All the results have been summarized in Table IV. No correlation between thermal exchange surface and the temperature drop has been found: the geometry of the fins is more important than the total surface. In particular, the best performing sample was that one with one of the lowest thermal exchange surfaces. Since the heat transfer coefficients were not able to represent the effective drop in temperature related to the different micro-fins arrays, the fin effectiveness has been considered. It is a good way to understand how much a design is effective for cooling purposes.

Table IV: Summary of the geometric parameters and the results

	Type	W [mm]	L [mm]	H [mm]	tb [mm]
#1	Flat	49.85	49.86	0	0
#2	Single array	49.82	49.87	0.62	0.76
#3	Single array	50.04	49.86	0.60	0.72
#4	Single array	49.89	49.89	0.56	0.76
#5	Single array	49.78	49.84	0.79	0.53
#6	Crossed arrays	50.23	49.95	0.56	0.78
#7	Crossed arrays	49.84	49.75	0.55	0.74

	S [mm]	t [mm]	Surface [cm^2]	H [W/m^2K]	ε_f.
#1	0	0	25	87.66	1.00
#2	0.81	0.79	44	51.00	1.03
#3	0.81	0.39	50	46.52	1.06
#4	0.46	0.35	59	38.02	1.03
#5	0.22	0.18	123	18.54	1.04
#6	0.41	0.39	59	38.12	1.03
#7	0.21	0.19	90	24.94	1.02

Single and crossed arrays have been compared as well. The results show that the crossed setup doesn't give any great benefit to the performances if compared to the single array case.

Further investigations on the subject are needed. In particular, a software modeling of the phenomena should be useful to confirm and better explain the experimental results. Along with that, testing of more samples should help in understanding the importance that each geometric dimension has on the cooling performances of the fins. Design and testing new fin shapes are required to improve the performances of micro-fin arrays.

5 ACKNOWLEDGMENTS

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