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Plate micro-fins in natural convection: an opportunity for passive concentrating photovoltaic cooling

Leonardo Micheli[a],*, K. S. Reddy[b], Tapas K. Mallick[a]

[a]*Environment and Sustainability Institute; University of Exeter, Penryn Campus, Penryn, Cornwall TR10 9FE, UK*
[a] *Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering,*
Indian Institute of Technology Madras, Chennai 600 036, India

Abstract

The raise in temperature is a non-negligible issue for concentrating photovoltaics (CPV), where the sunlight is concentrated up to thousands of times and a large amount of heat is collected on the solar cells. Micro-fins have been identified as one of the most promising solution for CPV cooling: despite its potentials, the number of publications on this subject is still limited. The present paper resumes the state-of-the-art of the research on micro-fins, in order to identify the most convenient fin geometry for CPV applications. The results of the investigation conducted in this work show that, compared to a conventional heat sink, micro-fins can improve the thermal performance and, at the same time, lower the weight of a system. For this reason, they are particularly beneficial for tracked systems, such as CPV, where a reduced weight means a reduced load for the tracker. The heat transfer coefficients measured through an experimental setup are used to predict the performance of a micro-finned CPV system in natural convection: an optimized fin array is found able to enhance the mass specific power up to 50% compared to an unfinned surface.

Keywords: concentrating photovoltaics, micro-fins, natural convection, passive cooling.

1. Introduction

The temperature of any photovoltaic cell has to be minimized in order to enhance the electrical efficiency, to limit the thermal stresses, and to avoid mechanical damages [1]. In a concentrating

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* Corresponding author. Tel.: (+44) 01326259478.
*E-mail address:*l.micheli@exeter.ac.uk.

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photovoltaic (CPV) system, the sunlight is concentrated on a small cell up to thousands of times [2] and the temperature can easily raise above the safety operating range if the heat is not correctly dissipated. For this reason, the temperature of CPV cells working at concentrations above 300 suns is generally maintained within a 50 to 80°C range through the deployment of a cooling system [3,4]. Coolers are generally required to be simple, in order to have a limited impact on the CPV cost. Moreover, a reliable system is essential: any failure can cause damages to the cells and long stops to the power generation. Passive cooling systems have shown high reliability, due to their simplicity and to the employment of natural laws in place of mechanical or electrical power inputs, required instead by active systems. The heat transfer of a surface can be passively enhanced by increasing its extension through the introduction of fins, a widely used solution that has been investigated in numerous studies and are currently employed for many different purposes, such as electronic cooling, industrial processes, and power generation plants [5–7].

The price of cooling systems can be lowered by an increase in efficiency and a drop in volume and mass. Moreover, technologies such as CPV are tracked: a reduction in the weight of the heat sink means a subsequent reduction in load for the tracker and, thus, an increase in efficiency of the whole system. In this light, the micro-technologies represent an attractive solution for CPV cooling: among the present and potential micro-cooling technologies, the micro-fins have been considered as one of the most promising [8]. The present work resumes the outcomes of the previous researches and comments the benefits achieved so far by using the micro-fins in terms of thermal enhancement and mass reduction. The results of a previous experimental investigation are used in a3D model to predict the behavior of a micro-finned CPV system. The work is intended to highlight the recent progresses on natural convective micro-fins and to identity the future research directions towards the design of optimal fin geometries for passive CPV cooling.

2. Literature review

Fins are commonly used to enhance the heat transfer from a solid to the surrounding fluid by extending the thermal exchanging surface[7].It is known that the geometry and the surface temperature strongly affect the thermal behavior of fins in natural convention [9]. Natarajan and his colleagues [10,11]studied the application of fins for passive CPV systems and defined optimized number and geometry of the fins to maximize the heat transfer of a 10x CPV. They found that the fin thickness does not have a significant effect on the heat transfer because thicker fins increase the conduction heat losses and, at the same time, suppress the convection heat losses in between the fins. Bar-Cohen et al. [12] proposed a method to design a heat sink maximizing the heat transfer and minimizing the weight. A first investigation on tilted heat sinks has been reported by Mittelman et al. [13]. Five years later, Do et al. [14] proposed a correlation between the fin geometries, the tilt angles and the heat transfer coefficients.

In micro-fins, at least one of the dimensions is micro-scaled. Despite the wide literature available on fins, the studies on naturally convective micro-scaled fins are still limited. Kim et al. [15]investigated vertically orientated micro-fins and demonstrated the impossibility of using the macro-fin heat transfer correlations for micro-scaled systems. Shokouhmand and Ahmadpour [16]numerically demonstrated that the contribution of the radiative exchange cannot be neglected in a micro-fin array. In their study, radiation contributed to dissipate more than 20%of the heat exchanged by micro-fins. Recently, the correlations between the micro-fin geometries and the thermal behavior have been presented [17,18]: the heat transfer coefficients have been found to increase when the fin height decreases, the fin spacing increases and/or the fin thickness increases. Micro-fins are generally obtained by subtractivemanufacturing processes, such as dicing, etching or electrical discharge machining: Micheli et al. [19] experimentally demonstrated that the drop in weight, instead of an enhancement in heat transfer, is the most important benefit obtained by dicing micro-fins on a flat cooling surface. Additionally, the authors reported that the specific mass heat transfer increased when increasing the fin spacing and/or increasing the fin height. These results were then confirmed in [20]: a micro-finned silicon wafer was modelled to predict the thermal performance of a passively-cooled 500x CPV system. It was shown that micro-fins would be able to keep the CPV cell temperature within the operating range and enhance the mass specific power by more than 5 times compared to conventional macro-scaled systems.

3. Fin geometry and thermal model

It has already been demonstrated that the micro-fins can strongly reduce the heat sink weight [19,20]. In particular, a micro-fin geometry that maximizes the fin effectiveness can enhance the mass specific power by 25% compared to a flat surface. In the present work, instead, the fin geometry with the highest mass specific heat transfer coefficient among those studied in [19] is considered (Table 1), in order to further improve the mass specific power.

Table 1. Dimension of the fins considered in the present investigation.

Width[cm]	Length [cm]	Fin thickness[µm]	Fin spacing[µm]	Fin height[µm]	Base thickness[µm]	Number of fins
5	5	200	800	600	800	50

The fin array is applied to a500× CPV system, reproduced in COMSOL Multiphysics 5.0 using the same thermal model exploited in [20]. A single CPV cell is considered: the waste heat produced by it is transferred by conduction to the fin array. The heat is then dissipated into the surrounding media by convection(1) and radiation(2). The convective heat flux ($\mathbf{q_c}$) is modelled according to the Newton's law of cooling [7]:

$$\boldsymbol{q_c} = h \cdot (T_s - T_{amb}) \tag{1}$$

where h is the heat transfer coefficient, experimentally obtained in [19], T_s is the surface temperature and T_{amb} is the ambient temperature. The radiative heat flux from a surface to a media ($\mathbf{q_r}$) is instead expressed as[7]:

$$\boldsymbol{q_r} = \epsilon \cdot \sigma \cdot F_{i,j} \cdot (T_s^4 - T_{surr}^4) \tag{2}$$

where ε is the material's emissivity, σ is the Stefan-Boltzmann constant, and $F_{i,j}$ is the view factor between the fin surfaces and the ambient, calculated according to the equations reported in[21]. The methodology detailed in [18] has been used to calculate the contribution of radiation .In accordance to previous references [17,22], the surrounding medium temperature (T_{surr}) is considered to be equal to the ambient temperature, so that $T_{surr}=T_{amb}$. A 3mm×3mm cell produced by Azurspace is selected because of the limited volume and the high 42.5% peak efficiency [20]. The cell is placed on a 1.4mm-thick, 5cm×5cm-sized squared undoped silicon wafer. The fins are diced on the back of the wafer: an image of the geometries developed in COMSOL is shown in Fig. 1. A cross-sectional view of the micro-finned wafer is reported in Fig. 2. Taking into account the receiver's structure proposed in [23], a 0.125mm-thick solder paste layer and a 0.001mm copper layer are reproduced. The modelled CPV is tested under:

- Concentrator Standard Test Conditions (CSTCs): 1000W/m^{2}for direct-normal irradiance, an ambient temperature of 20°C and cell electrical efficiency of 42.5%.The cell produces 2.20W of waste heat.

- Worst Case Conditions (WCCs): 1000W/m^{2}for direct-normal irradiance, an ambient temperature of 20°C and cell electrical efficiency of 0%. In these conditions, the heat produced by the cell raises to 3.83W.

An optical efficiency of 0.85and a silicon emissivity of 0.78 are considered. The heat transfer coefficients measured by [19] are used: 2.44W/m^{2}K and 2.85W/m^{2}K under CSTCs and WCCs respectively.

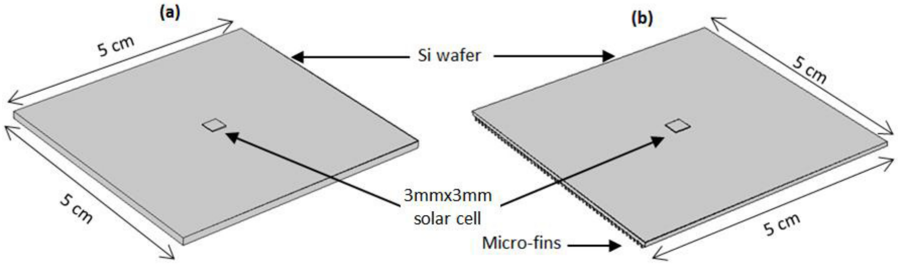


Fig. 1. The geometries reproduced in COMSOL: (a) unfinned silicon wafer; (b) micro-finned silicon wafer.

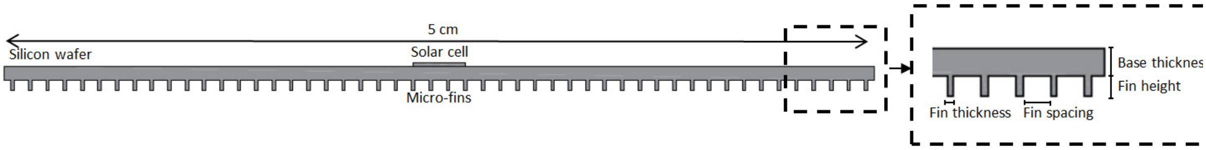


Fig. 2. Cross-sectional view of the micro-finned silicon wafer and zoom on the fins.

4. Results and discussion

The simulation is conducted using both a time-dependent and at stationary models. The time depend model is useful to understand the heating time required by the cell to achieve the steady-state conditions: both the operating and the worst case conditions (OCs and WCCs respectively, in Fig. 3) are modelled. The cell achieves steady state conditions in less than 1200s: maximum cell's temperatures of 73°C and 103°C are predicted under CSTCs and WCCs respectively (Fig. 4). Under both the conditions, the temperatures fall below the maximum limits required for CPV cells. The thermal performances of the fin array are compared with those of a flat silicon wafer and those of a micro-heat sink that maximizes the best fin effectiveness studied in [20]. The temperatures found in the present investigation are consistently lower than those registered for the flat plane silicon and, instead, as expected, slightly above those predicted for the best effectiveness array (Table 2**Errore. L'origine riferimento non è stata trovata.**).

CPV are usually tracked systems: the tracker uses part of the energy output to move the module and keep the direct sunlight always focused on cell. The largest part of any CPV module's weight is due to the heat sink [24]: the systems efficiency can be enhanced by reducing the heat sink weight and, thus, the tracker's load. In this light, the mass specific power is considered: this parameter expresses the ratio between the electrical output and the weight of the heat sink [20]. The mass specific power is refined taking into account the cell temperature's coefficient: a drop of 1.8mW in power output per degree of temperature has to be considered [25]. Fig. 5 shows the mass specific powers of different heat sinks for CPV applications [20,26,27]: compared to a macro-scaled heat sink, micro-fins are found to enhance the mass specific power by up to 625%. Among the micro-geometries analysed (Table 3), the fin array that maximizes the mass specific heat transfer coefficient shows the highest mass specific power. This parameter is enhanced by more than 50% compared to the flat surface and by almost 20% compared to the previous geometry.

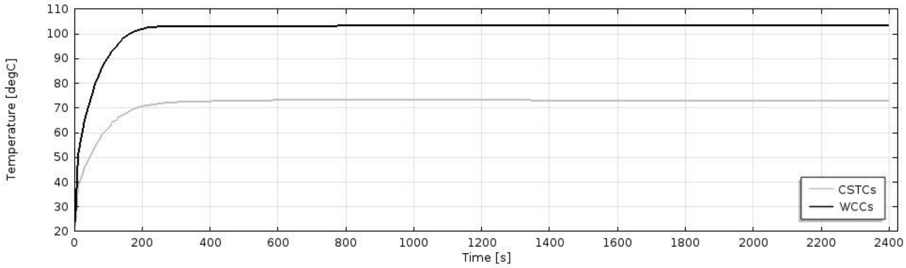


Fig. 3. Transient behavior of the modelled CPV cell temperatures under CSTCs and WCCs.

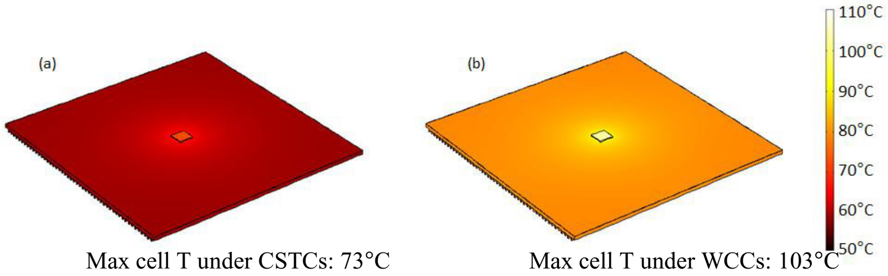


Fig. 4. Temperature distribution in the best mass specific heat transfer micro-finned array under (a)CSTCs (maximum cell's temperature: 73°C) and (b) WCCs (maximum cell's temperature: 103°C).

Table 2. Resume of the maximum cell' temperatures predicted by the thermal investigations.

Heat sink	**Maximum limits** [4]	**Unfinned silicon wafer** [20]	**Best effectiveness** [20]	**Best mass specific heat transfer**
CSTCs	80°C	78.8°C	70.4°C	73.0°C
WCCs	150°C	111°C	99.9°C	103°C

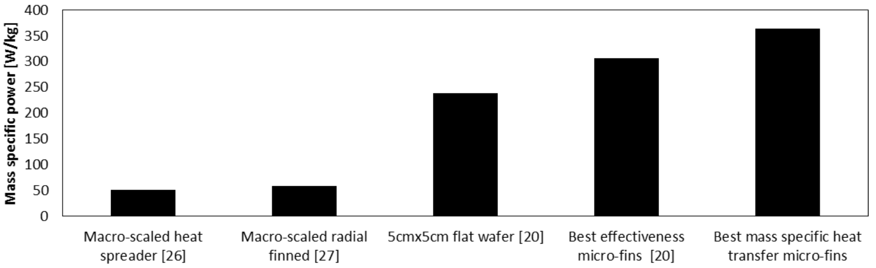


Fig. 5. Mass specific power: from macro-scaled CPV heat sinks to the present micro-finned array. Data sourced from [20, 26, 27].

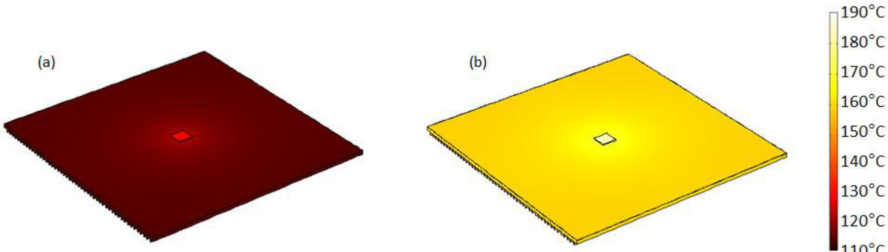
Table 3. Refined mass specific powers of passive cooled systems studied in [20] and in the present work.

Type of heat sink	Max predicted temperature	Refined max electrical power output at 500×	Weight of the heat sink	Mass specific power	Difference with the uncorrected values	Difference with the flat wafer
Flat [20]	78.8°C	$1.86W_p$	0.007798 kg	$238.52W_p$/kg	-5.10%	-
Best effectiveness [20]	70.4°C	$1.88W_p$	0.006126kg	$306.88W_p$/kg	-4.09%	+28.67%
Best mass specific heat transfer	73.0°C	$1.87W_p$	0.005135kg	$364.18W_p$/kg	-4.41%	+52.68%

These results confirm that a naturally convective micro-finned heat sink has the ability to manage the waste heat generated by CPV. It is proved that, instead of the fin effectiveness, maximizing the mass specific heat transfer would lead to lighter systems. These would benefit the CPV because of the reduced cell temperature achieved compared to a flat heat sink and the lower heat sink weight than any other micro-fin geometry. Deploying different fin geometries, such as pin fins or radial fins, is expected to further enhance these benefits and will be studied in future works.

5. The contribution of radiation

The present work takes into account the radiative heat exchange from the micro-fin array. The main heat sink metrics, instead, consider the convective heat transfer only [7]. Despite that, the non-negligible contribution of radiation has already been reported by some researchers [16,18,22]. In order to contribute to the discussion, a new simulation is conducted neglecting the material emissivity. The cell temperature dramatically raises to 131°C under CSTCs (Fig. 6), out of the acceptable CPV range. Similarly, the temperature under WCCs achieves 183°C, above the CPV limit. These results prove that the effect of radiation should not be neglected and that the investigations on the optimization of the micro-fin designing should considered the combined convective and radiative heat transfer.



Max cell T under CSTCs: 131°C

Max cell T under WCCs: 183°C

Fig. 6. Temperature distribution micro-finned array under (a) CSTCs (maximum cell's temperature: 131°C) and (b) WCCs (maximum cell's temperature: 183°C), neglecting the contribution of the radiative heat transfer.

6. Conclusions

The present research enhances the benefits expected by exploiting micro-fins for passive CPV cooling: it has been found that maximizing the mass specific heat transfer leads to an increase of 50% in mass specific power compared to a flat surface. This enhancement doubles that obtained by micro-fins with maximized fin effectiveness. The mass specific power is six times higher than that calculated for standard CPV heat sinks. Additionally, the importance of the radiative heat transfer has been proved: in this light, future works should consider the heat transfer due to radiation, in the light of developing a model to optimize the design of micro-finned heat sinks. The development of different geometries is expected to further benefit the thermal behavior and the weight reduction of micro-finned heat sinks.

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Corresponding author biography

Leonardo Micheli was born in Rome, Italy, in 1988. He completed a Master Degree in Renewable Energy Engineering in 2011 at Sapienza - University of Rome (Italy). He is currently a Ph.D. student at the University of Exeter’s Environment and Sustainability Institute (UK). His research interests include energy, solar technologies, heat transfer, manufacturing and assembling of electronic components.