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500× CPV Receiver With Integrated Micro-Finned Heat Sink

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Introduction

The main aim of concentrating photovoltaics (CPV) is reducing the amount of the expensive semicondutive material by replacing part of it with a reflecting optics and, thus, increasing the density of the sunlight hitting a smaller cell. Cell's temperature need to be minimized in order to enhance the electrical efficiency, to limit the thermal stresses, and to avoid damages. Common flat photovoltaic modules usually operates without cooling systems, whereas cooling is generally needed for concentrating photovoltaics, to manage the heat generated by concentrating the sunlight.

The low operating temperature is not the only achievement that a CPV cooling system needs to meet. The uniformity of the temperature has to be considered, both at single cell's and at series-connected cells' levels. Temperature gradients across the cell are generally due to non-uniform illumination on the active area, and cause power losses and may lead to the damages [1]. Series-connected cells working at different temperatures generate different currents: the overall series current is limited by the less performing cell. An optimal CPV cooling system should prevent the system from the occurrence of current-mismatch due to non-uniform temperature. Moreover, the cooler is generally required to be simple, in order to grant high reliability and not to strongly affect the CPV plant cost. A reliable system is essential: any failure could cause damages to the cells and long stops in the power generation.

Nowadays, fins are commonly used in many passively-cooled CPV installations [2,3]. The development of micro- and nano-technologies offers new perspectives for both active and passive CPV cooling. Among all the possible solutions, a micro-fin array offers a simple, suitable solution for improving a passive cooling system [4]. In the present article, the first investigation on the thermal performance of a 500x CPV receiver equipped with a micro-fins array is presented.

Governing equations and boundary conditions

A model developed in COMSOL Multiphysics 5.0 has been used to sort out the investigation. The simulation was conducted using the "Heat Transfer in Solids" module, taking into account the CPV standard reference conditions [5]: 1000W/m^2 DNI, and an ambient temperature of 25°C. An optic efficiency of 85% is accounted in the study as well.

The stationary pure conductive heat transfer equation is used to model the heat exchange between solids: it depends on the conductivity of the material (k) and on the temperature gradient between the opposite surfaces (∇T). The heat transfer in solids can be expressed through the Fourier's law [6]:

$$\rho \cdot c_p \cdot \frac{\partial T}{\partial t} = Q + k \cdot \nabla^2 \mathrm{T} \qquad (1)$$

where ρ the density, c_p the heat capacity, t the time, and Q the heat generated. ∇2 is the Laplace operator and k·∇2T expresses the heat fluxes in the three dimensions of an isotropic medium [7]:

$$\nabla^2 \mathrm{T} = \nabla \cdot (\nabla \mathrm{T}) = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \qquad (2)$$

In the steady-state conditions considered for this investigation, the temperature is not dependent on time and, then, ∂T/dt=0. So the (1) can be expressed as:

$$Q = -k \cdot \nabla^2 \mathrm{T} \qquad (3)$$

The heat generated (Q) by the source in this application corresponds to the sum of the heat generated by each cell (Q_{cell}). So, taking into consideration the number of cells on the plate (N_{cell}), it is expressed as:

$$Q = Q_{cell} \cdot N_{cell} \qquad (4)$$

All the media-facing surfaces were thermally insulated, with the exception of the backside of the receiver where a convective heat flux was introduced to model the action of the cooling system or of the natural convection.

Receiver's materials and structure

Among the different substrates employable in CPV, silicon wafers have been considered in the present study. Silicon has been preferred because easy to machine and because the receiver's layers can be directly sputtered onto it. Silicon based CPV receivers have already been presented in literature [8,9]. Avoiding any interface bonding material, generally characterized by low thermal conduction [10], would increase the thermal performance of the systems.

Any surface surrounded by a fluid exchanges heat by radiation and convection. Combining the contributions of this two heat transfer methods, it is possible to calculate the minimum area (S_{HS}) a flat silicon heat sink requires to work properly [11]:

$$S_{HS} = \frac{Q_{cell}}{h_c \cdot (T_s - T_{amb}) + \sigma \cdot F_{1-2} \cdot \varepsilon \cdot (T_s^4 - T_{amb}^4} \tag{5}$$

Where:

- h_c is the heat transfer coefficient,
- T_s is the temperature of the surface,
- T_{amb} is the ambient temperature,
- σ is the Stefan–Boltzmann constant ($5.67 \cdot 10^{-8}\ W \cdot m^{-2} \cdot K^{-4}$)
- F_{1-2} is the view factor, considered equal to 1,
- ε is the silicon emissivity, corresponding to 0.7 [12].

Assuming an optimistic heat transfer coefficient of 25 W/m^2K for natural convective air, a heat sink surface temperature of 60°C, and an ambient temperature of 25°C, a minimum dissipating surface of $0.0020m^2$ for the aluminum heat sink is required. It corresponds to a squared silicon wafer sizing 4.5cm per side. Because of the optimal conditions considered in the calculation and in order to introduce an adequate tolerance, a 5cmx5cm silicon wafer has then been considered in this application.

Cell's size and optics configuration

The thermal behavior of a CPV system does not rely only on the geometric concentration and the outdoor conditions. Factors, such as the geometry of the concentrators and the size of the cells have also an impact on the heat management that cannot be neglected.

In this work, the cell's available from Azurspace have been considered: their sizes range from 3.3mm to 10mm per side, with peak efficiencies at maximum power point (MPP) between 41.2 and 42.7% at 500x. Considering 15% optic losses and the datasheet efficiencies, these multijunction cells are expected to produce 25.1 W, 7.5W or 2.2W of waste heat at 500x under standard conditions if the they size 10, 5.5 or 3 mm per side respectively.

The heat generated by the cells depends on the second power of the cell's size. Moreover, the cells taken into account show peak efficiencies that increase inversely to the cells dimensions: the smaller the cell, the lower the amount of waste heat per unit of surface. For these reason, the smallest cell, sizing 3mm per side, has been taken into account in this application.

The geometry of the concentrators influences the orientation of the heat sink: the three most common configurations are shown in Figure 1. In reflecting systems without secondary, the receiver is usually located between the sun and the mirrors (Figure 1a) and creates shadows on the optics. For this reason, the extension of the receiver has to be minimized and active coolers are usually preferred because of their higher heat removal capacity. On the other hand, if a secondary reflector is employed (Figure 1b) or lenses are instead used to concentrate the light (Figure 1c), the dimension of the receiver does not represent an issue, because no risk of shadowing is present. Passive coolers can be exploited in these configurations, because a surface as large as that of the concentrator is generally available for cooling. In this configuration, the orientation of the heat sink becomes an issue, because the cooler is predominantly facing downwards, which is the worst orientation for natural convection [13].

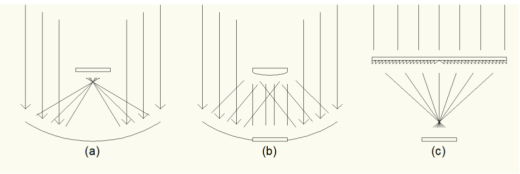

Figure 1 - Schematic of the most common CPV optics geometries: (a) primary reflector without secondary, (b) primary and secondary reflective concentrators, (c) Fresnel lens.

In the present 500x system, where the cell sizes 3mm per side, the primary optics has an extension of 67cm^2. In order to allocate a well dimensioned cooling system, it is important not have any shadowing on the optics due to the receiver. For this reason, the optics b and c in Figure 1 would be selected. This kind of geometries has been preferred because does not limit the size of the heat sink, even if it is known that the down-facing orientation causes a deterioration of the thermal performance of micro-finned heat sinks [7] that will be taken into account in the thermal model development.

Micro-finned heat sink

In this study, 0.2mm thick and 0.6 mm high fins have been considered. The fins are placed at a distance of 0.8mm. The 50mmx50mm heat sink is composed by 50 fins, milled on the back of a 1.4mm thick silicon wafer.

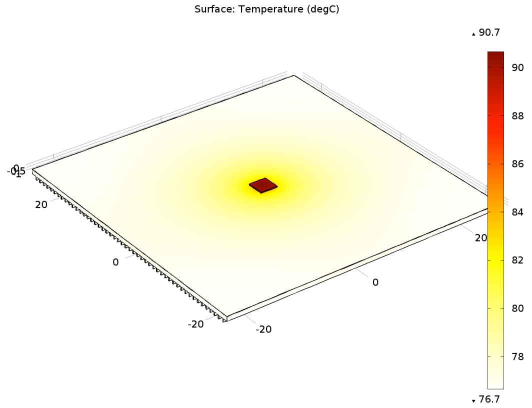

Figure 2 – Temperature distribution of the micro-finned CPV system in a real case scenario simulation. Temperatures in °C.

The heat transfer coefficient of the fins is set according to the results of an experimental investigation [14]. The results of the 3D simulation are reported in Celsius degrees, with a scale that ranges from red (highest temperature) to white (lowest temperature). The simulation predicts a maximum cell's temperature of 90.7°C, which falls within the range usually applied for CPV, when the system is working under operating conditions (Figure 2).

The cooling system is required to operate both in ordinary and extraordinary conditions: in particular, it has to be dimensioned to handle the CPV also in case of worst case conditions. The worst case scenario for a PCV happens at high irradiance and when the heat sink is in the less heat transfer conditions. Usually these conditions take place at mid-day, when the Sun reaches the highest tilt and the irradiance is high, and can be represented as 1000W/m^2 DNI, no wind, fins facing downwards. Moreover, in this case, an additional issue is considered: the solar cell in open circuit conditions. This means that all the incoming sunlight is converted into heat: a 3.825W heat input is considered. In these conditions, the temperatures should not overtake 150°C, the maximum temperature that the cells and the components of the system are able to face safely.

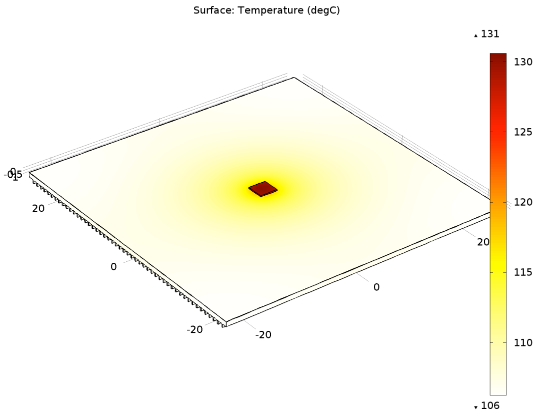

Figure 3 - Temperature distribution of the micro-finned CPV system in the worst case scenario simulation. Temperatures in °C.

A heat transfer coefficient of 3.79W/mK has been measured for the considered heat in input. In these conditions, the simulation reported a maximum temperature of 131°C (Figure 3): also in this case, the fin array shows the potential to handle the thermal management of a 500x CPV system.

Conclusions

The paper presents an investigation on the thermal behavior of a passive micro-finned silicon receiver for 500x CPV applications. For the first time the use of micro-scaled fins is considered for the passive cooling of a high concentrating photovoltaic system. Micro-fins have the potential to reduce the materials' cost and the system's weight, introducing multiple benefits to the CPV. The receiver is conceived to reduce the thermal interface materials, which usually deteriorates the thermal performance: the receiver's layers can be sputtered on the front surface and the micro-fins can be diced on the back one. The size of the solar cell and the silicon wafer are selected to minimize the heat production and thus to limit the cell's temperature. A model is developed to predict the thermal behavior of the receiver, taking in input the results of a preliminary experimental investigation. For the first time, it has been proved the ability of micro-fins to handle the thermal management of a 500x CPV system, both in operating and in worst case conditions. In future works, the receiver will be physically fabricated and experimental tested: this way, both the thermal and the electrical performance will be investigated.

Acknowledgments

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