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Assessment of the impact of non-uniform illumination and temperature profiles on a dense array CPV receiver performance

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ABSTRACT

The performance of dense array Concentrating PhotoVoltaics (CPV) receivers is reduced by the increase of average temperature and temperature non-uniformities which arise from illumination profiles and the characteristics of the cooling mechanism used. The magnitude of the impact of both illumination and temperature non uniformities depend on the electrical configuration of the CPV cell array. In this study, the impact of a cooling device, formed by a matrix of microfluidic cells with individually variable coolant flow rate, on the performance of a CPV receiver submitted to a non-uniform irradiance scenario is assessed and compared with microchannel cooling for three electrical configurations. The proposed cooling scheme tailors the flow rate distribution, and therefore the local heat extraction capacity, to the illumination profile, allowing the reduction of the temperature difference across the CPV receiver up to one third of the one obtained through microchannel cooling. This characteristic of the microfluidic cells cooling device, combined to its low pumping power, generates an improvement of the Net PV power of 3.83% for one of the configuration, the 6x8 matrix one.

1. Introduction

Concentrating PhotoVoltaics (CPV) is one of the most promising ways to reduce the levelized cost of energy (LCOE) of the solar energy technologies (Haysom et al., 2015). To reach this objective, apart from the system cost reduction, the global efficiency improvement is identified as a key factor (Ekins-Daukes et al., 2016). To reach this goal, the constant improvement of the CPV cells efficiency should be accompanied by the reduction of the gap between the efficiencies of cells and systems (Ekins-Daukes et al., 2016). CPV dense array receivers have a great potential for the system optimization as all the main components are mounted in a single receiver. However, this technology presents the drawback of requiring active cooling devices that must be efficient and maintain low and uniform receiver temperature (Jakhar et al., 2016).

Indeed, the non-uniformities of the temperature (Chemisana and Rosell, 2013) negatively affect the production of energy of PV cells. Some authors (Barrau et al., 2011; Barrau et al., 2014; Riera et al., 2014; Barrau et al., 2010) have focused their effort to generate uniform temperature profiles of the receiver by tailoring the distribution heat extraction capacity of the cooling device to the illumination profile and the coolant flow rate (Riera et al., 2015). They showed that this kind of cooling device is able to generate a temperature uniformity, expressed as the standard deviation of the temperature, of 0.7 K across the entire CPV receiver, improving both the system reliability and the PV production.

For a complete dense array CPV receiver, the usual concentrators, even with secondary optics, create non-uniform irradiance distributions which generate, among other drawbacks, mismatch losses between the PV cells in the array. The electrical connections between the PV cells play a relevant role for the reduction of these energy losses (Cooper et al., 2013). Vivar et al. (2010) demonstrated that the use of PV cells of different shapes and sizes in the receiver array, combined to the optimisation of the electric configuration, allow reducing drastically the mismatch losses. Other authors (Siaw and Chong, 2013; Siaw et al., 2014; Wong et al., 2015) proposed an algorithm to determine in each case and for each concentrator, the best cell array electrical configuration. Working with 1 cm^2 metamorphic multi-junction high efficiency cells, they identified, for several illumination profiles, the optimized electric configuration and demonstrated that this configuration can affect the global efficiency of the CPV receiver by more than 5%.

These works have the major drawback that they are done supposing the CPV array working under uniform temperature and constant illumination profiles, assumptions that are not exact in the field operation conditions. In this study, a cooling device (Azarkish et al., 2017; Laguna

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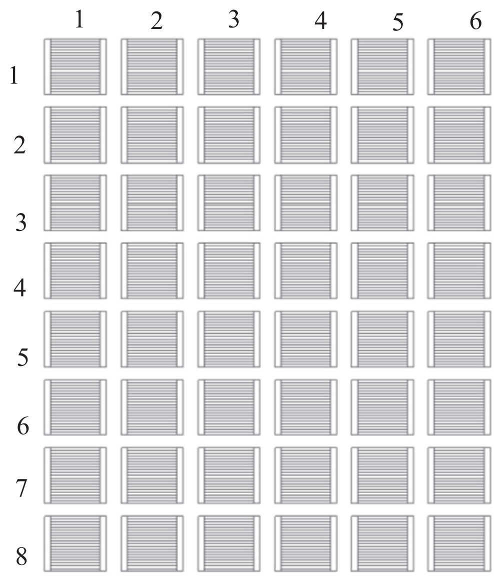

Fig. 1. Schematics of the placement distribution of the 48 PV cells (Ekins-Daukes et al., 2016). Total area: 6.7 × 8.9 cm^2.

et al., 2017), formed by a matrix of microfluidic cells with individually variable coolant flow rate, is presented as an alternative for dense array CPV receivers. This device tailors the distribution of the heat extraction capacity to the illumination and temperature conditions while minimizing the pumping power needed. The impact of this cooling device on the performance of a CPV receiver submitted to a non-uniform irradiance scenario is assessed and compared with microchannel cooling for several electric configurations.

2. Modelling

2.1. Global layout

For this study a CPV dense array of 6 × 8 cells has been selected (Fig. 1).

The PV cell used in this study is the triple-junction cell "C4MJ Metamorphic Fourth Generation CPV Technology" from Spectrolab (2011) (I-V curve in Fig. 2).

The 48 PV cells are connected in 3 different ways to observe the effect of non-uniform irradiance and temperature (Fig. 3).

As the main objective of this work is to assess the impact of the cooling device in the CPV receiver performance, a matrix configuration is compared to series and parallel configurations. The serial configuration was selected so that it produces the minimum currents of all possible configurations. The 6 × 8 matrix is the configuration reported by several authors as the best production output under non uniform radiation (Siaw and Chong, 2013.). The 8 × 6 electrical configuration

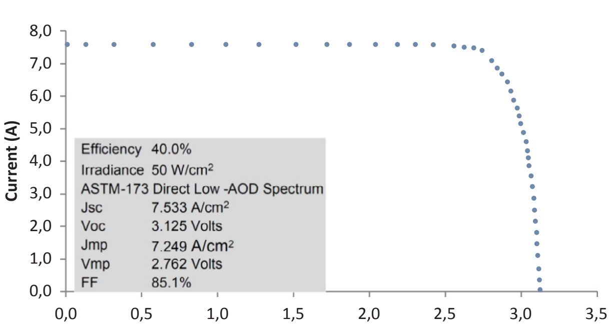

Fig. 2. SPECTROLAB triple-junction cell I-V curve Riera et al., 2015.

was also assessed and the power output was slightly lower than for the 6 × 8 one (difference lower than 0.6%). Finally the parallel one is by the moment the least practical connection due its high current output but serves as a reference model.

2.2. Cooling devices

In order to cool down the CPV dense array, two devices are studied. On the one hand, a conventional microchannels cooling system (Tuckerman and Pease, 1981), which consists of parallel channels with a hydraulic diameter below 1 mm, is applied. This cooling scheme is actually one of the most used for high heat flux applications due to its relatively low thermal resistance – lower than 10^{-4} K m^2/W – (Jakhar et al., 2016; Royne et al., 2005). However, this technology generates large temperature gradients along the coolant flow path and high pressure drops, that implies high pumping power. The global layout of this cooling solution applied to the CPV receiver is shown in Fig. 4.

The coolant flows through the microchannels in the direction of the longest side of the receiver (8.9 cm, the dimensions of 8 PV cells including the space between each other). Each microchannel is 0.4 mm wide and 0.3 mm deep.

On the other hand, the impact of using a microfluidic cells cooling system was investigated (Azarkish et al., 2017; Laguna et al., 2017). The cooling scheme (Fig. 5) consists in a matrix of microfluidic cells (dimensions 1.2 × 2.0 mm^2) with thermally activated microvalves (McCarthy et al., 2008), which tailor the local coolant flow rate to the local need of heat extraction capacity, avoiding overcooling and improving the temperature uniformity (Laguna et al., 2017).

A distribution layer provides coolant to the microfluidic cells. When the local heat flux augments, the temperature of the microvalve increases. The relatively high thermal expansion coefficient of the microvalves, with respect to the support, implies their buckling and, therefore, allows increasing the local coolant flow rate. Once the heat flux decreases, the microvalve turns back to its closed shape. This behaviour allows to increase the temperature uniformity and to reduce the pumping power (Laguna et al., 2017).

2.3. Thermal modelling

The main objective of the thermal modelling is to obtain the temperature distributions provided by microchannels and microfluidic cells cooling systems for a given irradiance profile. These data are used to assess the electrical performance of the CPV receiver as a function of the connection configuration.

An irradiance distribution, similar to measured illumination profiles used in previous studies (Siaw et al., 2014), has been adjusted to reach a mean irradiance of 800 suns (Fig. 6), varying from 225 to 1115 suns, with a standard deviation of 288 suns.

In order to isolate the effect of the temperature distribution on the electrical power, the water flow rate has been adjusted for the cooling devices so the mean temperatures of the CPV dense array are identical, equal to 86.1 °C, and the coolant inlet temperature (water) is fixed at 30 °C. The thermal analysis is carried out with a commercial finite element solver (COMSOL). For the microchannel cooling device, the longitudinal symmetries of the geometry have been used to simplify the model. In the case of the array of microfluidic cells, a spatial integration of steady-state results has been implemented, as explained in detail in (Laguna et al., 2017).

The microfluidic cells cooling device creates a more uniform temperature distribution than the microchannel one (Fig. 7). Indeed, the maximum temperature difference across the CPV receiver is reduced up to 1/3 of the one generated by the microchannel cooling device. Furthermore, while the microfluidic cells cooling device produces a temperature distribution pattern similar to the one of the irradiance distribution, the coolant temperature increase along the flow path of the microchannels which implies a displacement of the maximum