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CHP Efficiency of a 2000 × CPV System with Reflective Optics

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Abstract. In this work we have developed a combined heat and power (CHP) prototype that operates at 2000 × concentration based on reflective optics. The receiver consists of a InGaP/InGaAs/Ge triple-junction solar cell in thermal contact with an aluminium heat sink driving a forced water flow. This CHP system was tested both indoor (DNI of 650 W/m^2) and outdoor (DNI of 900 W/m^2) under different conditions of fluid parameters as the flow rate (ranging from 0.2 liters/min to 1.2 liters/min) and temperature (ranging from 25 °C to 60 °C). Electrical and thermal power were determined by acquiring IV curves and by measuring the heat subtracted from the cell while it delivered the maximum electrical power, respectively. The obtained results demonstrate that this CHP system achieves a total efficiency of about 80%, shared between the electrical (30%) and the thermal one (50%).

INTRODUCTION

The increase of the illumination level is a crucial requirement to the success of high concentration photovoltaics (HCPV) since it guarantees a reduction of components (cells, optics, heat exchangers) and costs [1]. On the other side, working at an extremely high solar concentration, exceeding 1000 suns, is also advantageous because of the adoption of a cooling system that captures the waste heat thus increasing the overall efficiency. Actually, many commercial systems use flat silicon plate collectors to obtain an electrical output with low efficiency (10-20%) and extract heat suitable for domestic water heating but inadequate for industrial uses or to drive absorption chillers for polygenerative applications [2]. In contrast, combined heat and power (CHP) hybrid solar systems are promising to exploit the concentrated solar power by collecting, in addition to the electric output of the multi-junction cells (efficiency larger than 40%), also the thermal (T) energy in the form of hot fluid (typically water) by heat exchangers behind the cells. This potentiality stimulates the effort to develop PV/T hybrid technology combining a high performance and reliability with a low cost of production [3]. In the framework of the FAE "Fotovoltaico ad Alta Efficienza" ("High Efficiency Photovoltaic") Research Project funded by the Sicilian Region under the program PO FESR Sicilia 2007/2013 4.1.1.1, we have realized and tested a CHP prototype [4]. In this work we report the analysis of its performances, both electrical and thermal, on varying the fluid parameters as the flow rate and temperature.

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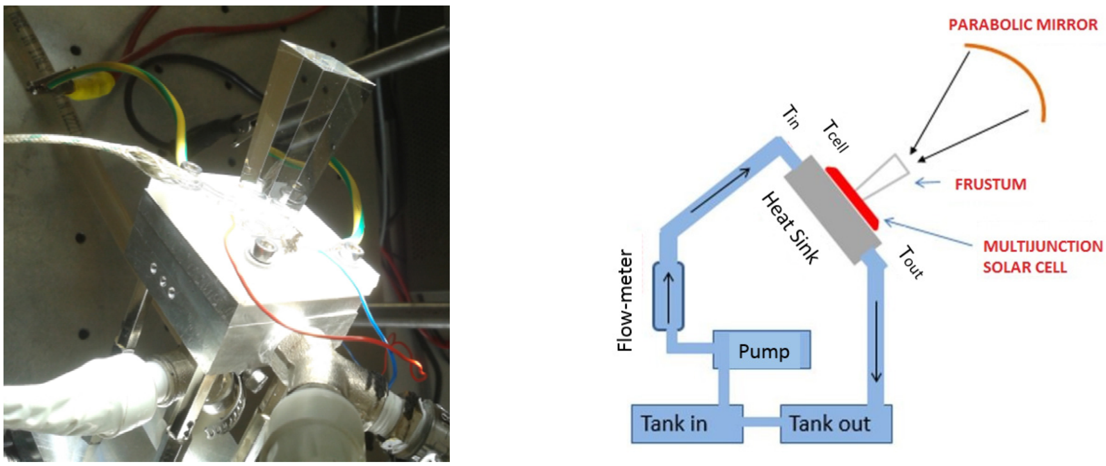
EXPERIMENTAL METHODS

The CHP system under test uses HCPV modules installed at Palermo (Italy), operating at 2000 suns on InGaP/InGaAs/Ge triple-junction solar cells provided by Taicrystal [5]. The concentration is based on a reflective optics consisting of an off-axis parabolic mirror with area $A_{conc} = 45\times45$ cm^2 that focuses the sunlight on the face of a BK7 glass frustum in optical contact (Wacker Semicosil 989 encapsulant) with the active area (107.9 mm^2) of the solar cell. A pyrheliometer measures the direct normal irradiance (DNI) incident on the mirror concentrator, then the solar power incident on the module is given by $P_{sun}^{inc} = DNI \times A_{conc}$.

The cooling system based on de-ionized water (flow rate in the range 0.2 ÷ 1.5 liters/min) passing across an aluminium heat sink with a slot nozzle and a planar output. When the water comes out from the slot nozzle, a sheet of water flows on the rear of the solar cell, with an effective heat transfer.



(a) (b)

FIGURE 1. (a) HCPV Solar receiver used for indoor and outdoor tests. (b) Schematic of the setup used for the characterization of solar receivers under concentrated sunlight.

Figures 1(a) and 1(b) show the solar receiver and the scheme of the experimental setup, respectively. The forced cooling is produced by a pump that moves the fluid from a tank with an heater in a closed circuit. Our test bench is equipped by a flow meter and PT100 platinum thermometers to detect inlet (T_{in}), outlet (T_{out}) fluid temperatures, while T_{cell} is estimated near the edge frustum. We observe that T_{cell} likely underestimates the real cell temperature because the majority of the heat should be conducted perpendicularly to the plane of the solar cell so inducing a temperature gradient [6].

The electrical power delivered by the cell is measured by a 300 W programmable DC electronic load controlled by a computer which is also interfaced with PT100 thermometers, as well as with the pyrheliometer. Electrical and thermal characterization of the system requires the cyclic execution of the following steps:

1. The data acquisition software communicates with the DC electronic load that performs a complete I-V scan in less than 10 ms.
2. The I-V curve obtained allows to determine the short-circuit current I_{sc}, the open-circuit voltage V_{oc}, the fill factor *FF*, the electrical peak power $P_{el}^{\max}$, the voltage V_{mpp} and the current I_{mpp} corresponding to the maximum power point (*MPP*). The DC electronic load is then set to *MPP* in less than 50 ms.
3. The software reads all the temperatures of the PT100 sensors, the value of the DNI and calculates the efficiencies of the system.

Because the time interval between two successive complete I-V scans is 1 s, we can assume that the vast majority of the time the cell operates at its *MPP*.

Recorded data allow calculate the extracted thermal power $\dot{Q}$ of the fluid by the following expression:

$$\dot{Q} = \rho c \dot{V} \Delta T \tag{1}$$

where ρ and c are the mass density and the specific heat, while the flow rate $\dot{V}$ and difference temperature $\Delta T = T_{out} - T_{in}$.

Then, normalizing to the incident solar power we can estimate the thermal and electrical efficiency of our CHP system:

$$\eta_{th} = \frac{\dot{Q}}{P_{sun}^{inc}} \tag{2}$$

$$\eta_{el} = \frac{P_{el}^{\max}}{P_{sun}^{inc}} \tag{3}$$

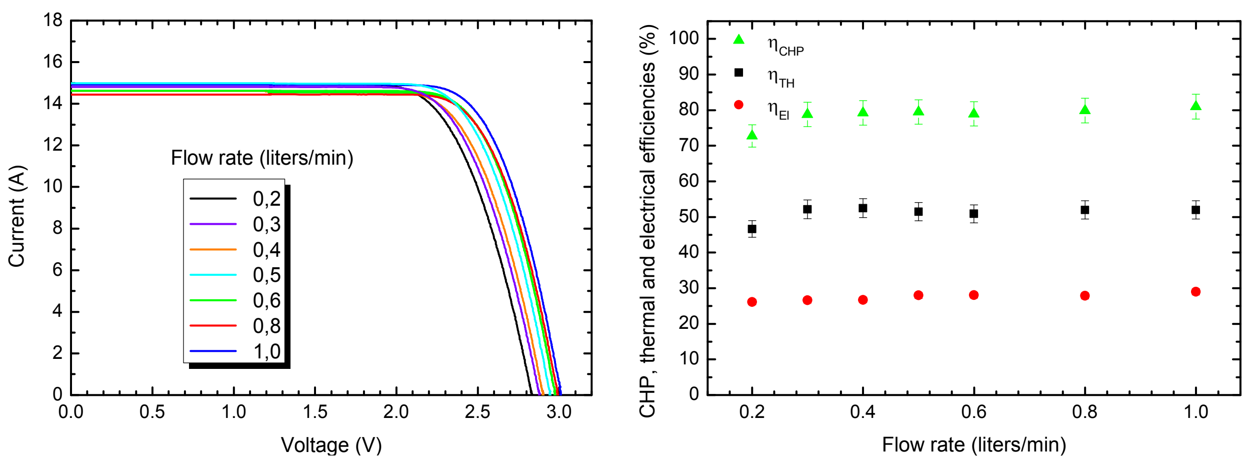
the total efficiency being the sum $\eta_{tot} = \eta_{el} + \eta_{th}$.

The tests were performed both indoor and outdoor. In the first case we used the facility for testing and research in HCPV [7], that is equipped with a dual-axis tracking heliostat (a high flatness extra clear glass mirror, coated with silver, its shape being a regular octagon circumscribed to a circle with diameter of 120 cm). In the field, the concentrator parabolic mirror is mounted on a 2 axis tracker composed by a N-S primary axis supporting a complete E-W secondary rotation.

RESULTS AND ANALYSIS

Indoor Tests

The aim of the experiments performed at the indoor facility is to evaluate the effect of the flow rate and the temperature of cooling fluid on the CHP performance. The tests were carried out under a DNI ≈ 650 W/m^2 corresponding to a P_{sun}^{inc} ≈ 130 W.



(a) (b)

FIGURE 2. Flow rate dependence of the CHP performance under a DNI of 650 W/m^2. (a) IV curves obtained with different flow rates ranging from 0.2 to 1.0 liters/min and at T_{in} = 25 °C. (b) Electrical, Thermal and Total CHP efficiencies as a function of the flow rate.

Figure 2(a) reports I-V curves recorded at a fixed T_{in}= 25 °C with flow rates $\dot{V}$ varying from 0.2 liters/min to 1.0 liters/min. We observe that on increasing $\dot{V}$, V_{oc} monotonically increases from 2.83±0.01 V to 3.01±0.01 V while I_{sc} varies from 14.90±0.05 A to 14.44±0.05 A, while the electrical peak power $P_{el}^{\max}$ increases from 34.2±0.1 W to 38.0±0.1 W . This result is consistent with the effectiveness of the fluid to make the cell colder [8]:

T_{cell} decreases from 90±1 °C ($\dot{V}$ = 0.2 liters/min) to 41±1 °C ($\dot{V}$ = 1.0 liters/min); hence, the difference temperature ΔT between inlet and outlet water in the heat sink decreases from 4.87±0.05 °C to 0.97±0.05 °C. From Eq. (1) we get the thermal power $\dot{Q}$ that is nearly constant (68±3 W) in the investigated $\dot{V}$ range. Figure 2(b) summarizes the electrical, thermal and total efficiencies as a function of the flow rate: it is observed that when $\dot{V}$ = 1.0 liters/min, η_{el} is close to 30%, η_{th} exceeds 50% and the CHP total efficiency η_{tot} is about 80%.

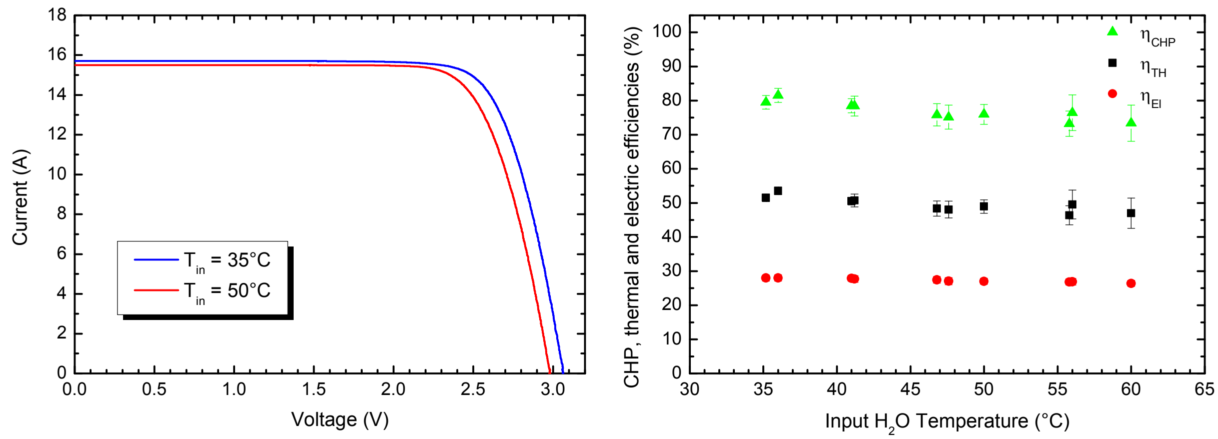


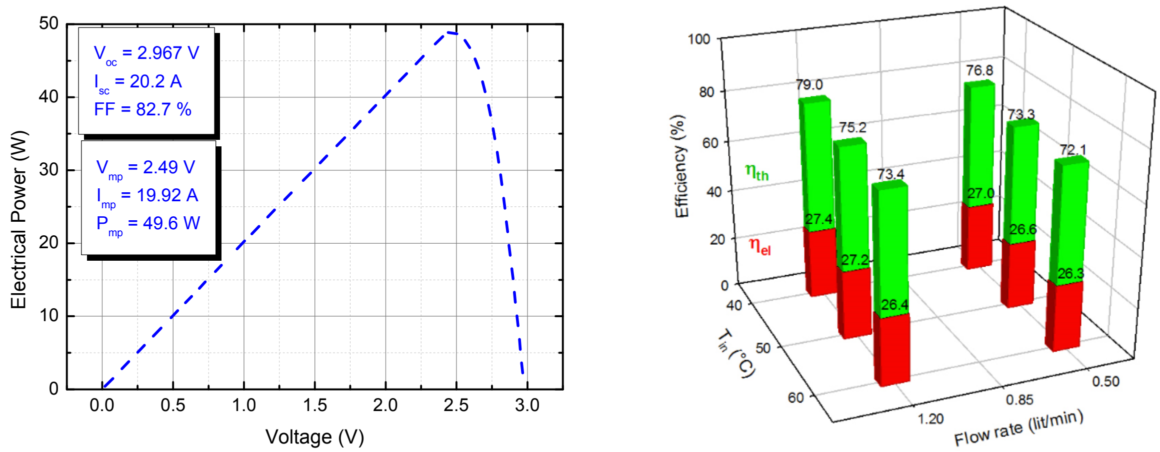
FIGURE 3. Temperature dependence of the CHP performance under a DNI of 650 W/m^2. (a) IV curves obtained with different inlet temperature (T_{in} = 35 °C and T_{in} = 50 °C) with flow rate of 0.5 liters/min. (b) Electrical, Thermal and Total CHP efficiencies as a function of T_{in}.

Figure 3(a) reports the comparison between the I-V curves recorded with $\dot{V}$ = 0.5 liters/min and heating the inlet fluid at 35 °C and 50 °C, respectively. The increase of T_{in} causes a reduction of P_{el}^{max} from 36.7±0.1 W to 35.4±0.1 W associated with an increase of T_{cell} from 72±1 °C to 87±1 °C. Accordingly with the procedure described above we have calculated the thermal power: $\dot{Q}$ decreases from 67±3 W (T_{in} = 35 °C) down to 64±3 W (T_{in} = 50°C). Figure 3(b) reports η_{el}, η_{th} and η_{tot} as a function of T_{in} in the range 35-60 °C. We observe that the CHP efficiency decreases in the investigated range: η_{tot} reduces from 80% down to 73%, this finding agrees with previous studies [9], and is due to the increase of convective heat transfer to the environment. This problem could be solved by improving the thermal insulation of the heat sink.

Outdoor Tests

The CHP efficiency has been measured on field under a DNI ≈ 900 W/m^2 corresponding to a P_{sun}^{inc} ≈ 181 W.

Figure 4(a) reports the P-V curve recorded with $\dot{V}$ = 1.2 liters/min and T_{in} =40 °C that gives a maximum electrical power P_{el}^{max} close to 50 W with efficiency η_{el} ≈ 27.4%, the cell operating at T_{cell} = 63±2 °C. The fluid temperature increment is ΔT = 1.14±0.04 °C, from which we measure the extracted thermal power $\dot{Q}$ = 93±4 W that corresponds to an efficiency η_{th} ≈ 51.6%. Then, under these fluid flow rate and temperature, the total efficiency of the CHP module is η_{tot} ≈ 79%. We have also estimated the effects of both T_i (ranging from 40 °C to 60 °C) and $\dot{V}$ (ranging from 0.5 liters/min to 1.2 liters/min) on the CHP performances; the results are displayed in the histogram of Fig. 4(b). In agreement with the tests performed indoor, the efficiencies decrease on increasing T_{in} and on decreasing $\dot{V}$, η_{tot} remaining larger than 72% in all the test conditions.



(a) (b)

FIGURE 4. (a) PV curve obtained under a DNI of 900 W/m^2 with a flow rate of 1.2 liters/min and inlet temperature of 40 °C. (b) Electrical (red), Thermal (green) and Total CHP efficiencies as a function of T_{in} and $\dot{V}$; for each bar we indicate the values of electrical and total efficiencies.

CONCLUSIONS

The tests performed indoor and outdoor have shown good performance of our CHP prototype working at 2000× solar concentration with reflective optics. The designed aluminum heat sink provides provides an efficient cooling of the InGaP/InGaAs/Ge triple-junction solar cells in the investigated range of fluid parameters: flow rate $\dot{V}$, from 0.2 liters/min to 1.2 liters/min, and inlet temperature T_i , from 35 °C to 60 °C. This allows to extract both electrical and thermal energy with efficiency of about 30% and 50 %, respectively. In particular, the field tests have evidenced that under a DNI of 900 W/m^2 (incident power of 181 W) the CHP output power obtained at T_i = 40 °C and $\dot{V}$ = 1.2 liters/min is 143 W (93 W thermal and 50 W electrical) with a total efficiency close to 80%. These results are promising to design efficient and cost-effective solar CHP systems working at an extremely high solar concentration.

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