Compact Spectral And Circumsolar Sensor For CPV Installation Performance Monitoring

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Abstract. A very compact direct sunlight sensor is presented which uses 3 component solar cells in a fully molded package. The 3 Channel Isotype Sensor (3CS) is less than 10 cm long and less than 2 cm thick. A fused silica light guide is used for the optical path such that air filled cavities can be avoided completely. The sensor features an exchangeable front aperture which allows the adaptation of the opening angle of one or more channels to the acceptance angle of a CPV System. The sensor is described in detail and outdoor results are presented.

Keywords: DNI, sensor, measurement, power prediction, spectral, spectrum, isotype, component, radiometer
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INTRODUCTION

Pyrheliometers, which are commonly used to measure the direct normal irradiation (DNI), do not resolve the power distribution in the solar spectrum. Multi junction solar cells, in contrast, are sensitive to a red or blue shift in the spectrum. The spectral shift results in the current limitation of the cell stack by one sub cell. Current matching of several sub cells is usually only achieved for a specific spectrum, AM1.5d, as defined in ASTM G173.

In most cases the output of a CPV system will appear low when compared to a pyrheliometer, which does not reflect the current limitation in a multi junction solar cell stack. Pyrheliometer data for the DNI is therefore not sufficient for a precise power prediction at a certain site.

Isotype sensors, in contrast, show precisely how much current a corresponding multi junction solar cell can generate under a certain spectrum [1]. They use stacked solar cells in which only one sub cell is electrically active. The other sub cells work as optical filters to maintain the spectral response of the active sub cell in the stack.

THE DESIGN OF DIRECT LIGHT SENSORS

A typical direct light sensor basically consists of a collimator tube, a front aperture and a sensor at the end of the tube with a rear aperture. The World Metrological Organization WMO gives recommendations for the design of direct light sensors (Fig. 1) [2].

As seen from the middle of the rear aperture, the sensor should have an opening half angle $\alpha/2$ of 2.5°, which is determined by the radius of the front aperture r1 and the optical length L. The finite radius of the rear aperture r2 results in a reduced sensitivity of the sensor for light coming in at angles higher than the slope angle which should be 1° according to the WMO recommendation.

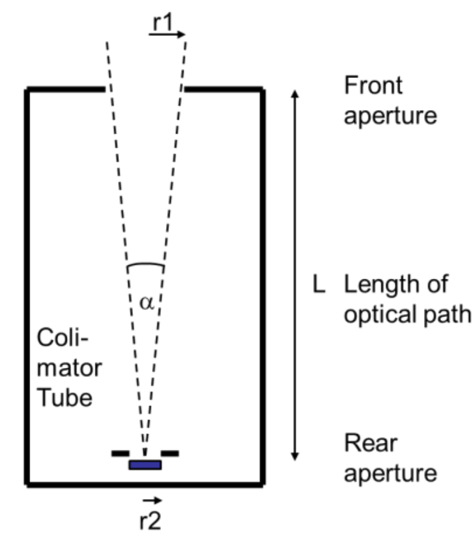

FIGURE 1. Basic design of a direct light sensor

In the case of pyrheliometers the sensor is basically a black disc, which heats under illumination. The temperature increase is measured.

Isotype cell (= component cell) sensors, in contrast, use several collimator tubes with a different isotype cell in each tube.

THE 3 CHANNEL ISOTYPE SENSOR 3CS

Common isotype sensors are relatively bulky and expensive. The objective of this work was the design of a very compact and cost competitive sensor, which could find wide application in CPV field installations.

This was achieved by a fully molded design, which uses a fused silica block as a light guide (see Fig. 3). A circuit board with three isotype cells is glued to one side of the block with transparent glue. The block is embedded in black molding material, which swallows any light that hits the walls and which protects the solar cells. The only side, which is not molded, is covered with an aperture sheet. Three holes in the sheet act as front apertures for the corresponding three sub cells.

Unwanted light paths are blocked by two holes in the fused silica, which are filled up by molding material. Thus light that passes through aperture 1 can't reach cell 2 or cell 3. Within the holes 3 mm threads are cast into the molding, which can be used for the easy attachment of the sensor to the side of a module or to an adjustable bracket.

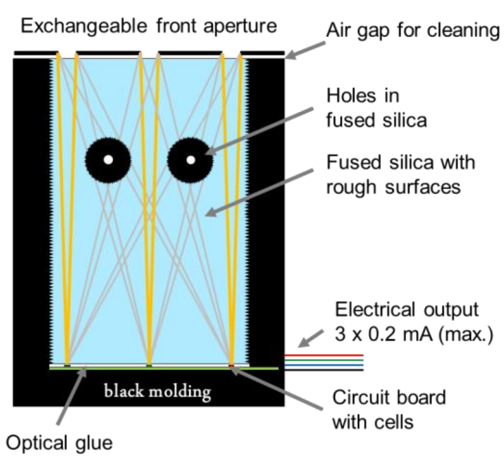

FIGURE 2. The 3CS direct irradiation sensor

The whole sensor is less than 10 cm long and less than 2 cm thick. It will therefore fit easily on the side of any CPV module on a tracker.

Under 1000 W/m^2 AM1.5d each isotype cell generates a signal current of ≈0.2 mA which changes linearly with the illumination in the respective spectral range. It can be converted in a 0-80 mV voltage signal with a 400 Ω (+/- 0.1%) resistor.

The prototype sensor described in this paper has a middle and a top cell each sitting behind a 2.5° half angle front aperture. The third channel is equipped with another top cell. It has a 1° half angle aperture which receives the full light from the central sun disc but only a small portion of the circumsolar light. By comparing the 1° and 2.5° apertures, the amount of circumsolar light can be quantified [3]. The angular sensitivity of the 2.5° and the 1° channels are compared to the WMO recommendation in Fig. 3.

The 3CS uses small isotype cells as sensors, which result in steep slope of the angular sensitivity around the opening half angle. This allows the usage of small apertures while still receiving all of the light from the sun disc. Thus the opening angle of the sensor can be adapted to the acceptance angle of various CPV systems.

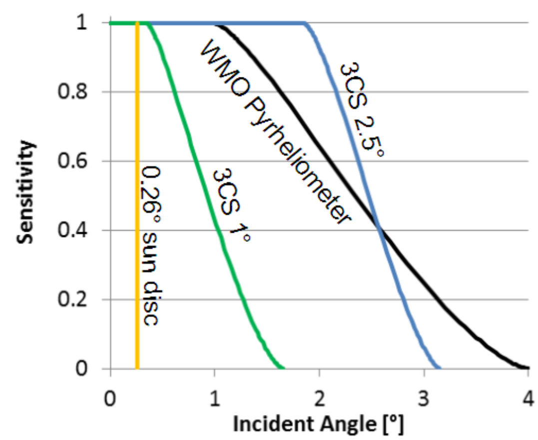

FIGURE 3. Angular sensitivity of the 3CS with different apertures in comparison to a WMO standard pyrheliometer

DETERMINATION OF THE AM1.5D REFERENCE CURRENTS

In order to do quantitative measurements, the reference currents under AM1.5d (ASTM G173) must be known. For this a reference sensor with known reference currents is required.

Such a sensor was built from so called working standard isotype cells. Working standards are taken from the same wafer as calibrated cells and referenced against the calibrated cells with very little error. These cells were placed in a black box with correctly sized front apertures and intermediate apertures to trap stray light.

This reference sensor and the 3CS were measured simultaneously on a clear day in Valldoreix, Spain, on a solar tracker. The reference currents of the 3CS were adapted such that both sensors show the same irradiance value.

The readings were compared to the signal from a Kipp & Zonen CHP1 pyrheliometer. The result is shown Fig. 4. The unit of the signal is the per mille value of the respective reference current under AM1.5d, 1000 W/m^2. This value is also commonly called the “effective irradiation” of this component cell. The effective irradiation has the same unit as the DNI [W/m^2] but different readings depending on the spectrum and the solar cell under examination. In the case of a stacked solar cell, the effective irradiation is determined by the current limiting sub cell.

In Fig. 4 a lower DNI can be attributed to a higher air mass. Consequently the spectrum is red shifted and the middle cell signal surpassed the top cell signal. In this example the top and middle cell signals match at about 950 W/m^2 where they are 2.4% lower than the DNI reading from the pyrheliometer.

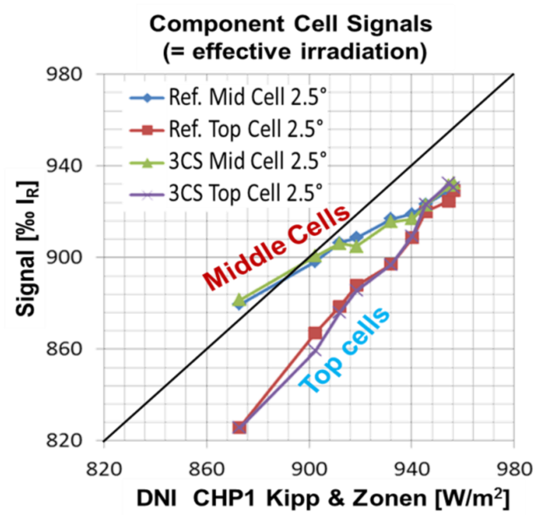

FIGURE 4. Component cell signals from two different sensors compared to the DNI measured by a CHP1 Kipp & Zonen pyrheliometer. All sensors have a 2.5° field of view half angle.

FIELD RESULTS ON A CPV SYSTEM

All sensors were mounted on the tracker of a CPV system. Figs. 5-8 show the system output in comparison to the sensor readings on a mostly clear day on March 27th in Valldoreix, Spain. The minimal air mass was 1.29. The system output is given in arbitrary units adjusted to the respective comparison.

The system output falls way below the pyrheliometer and 2.5° middle cell signals in the evening at higher air mass (Figs. 5 & 6). However the system output closely follows the 2.5° top cell signal from the 3CS in Fig. 7. The 1° top cell signal in Fig. 8 shows greater variations to the system output again.

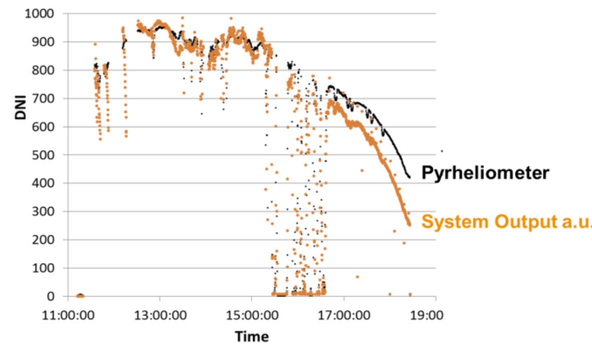

FIGURE 5. CPV system output compared to DNI.

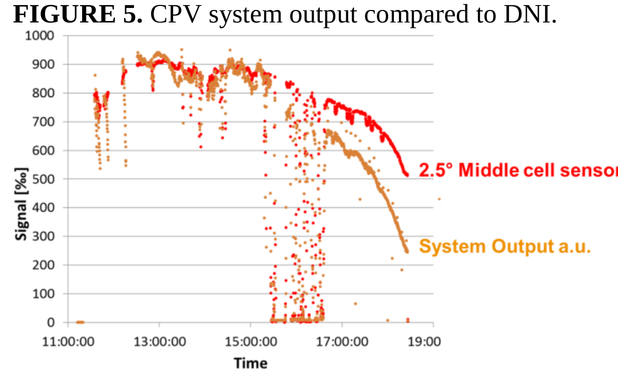

FIGURE 6. CPV system output compared to 3CS middle cell sensor with 2.5° opening half angle.

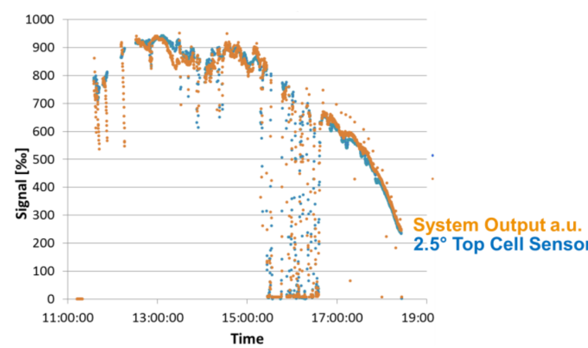

FIGURE 7. CPV system output compared to 3CS top cell sensor with 2.5° opening half angle

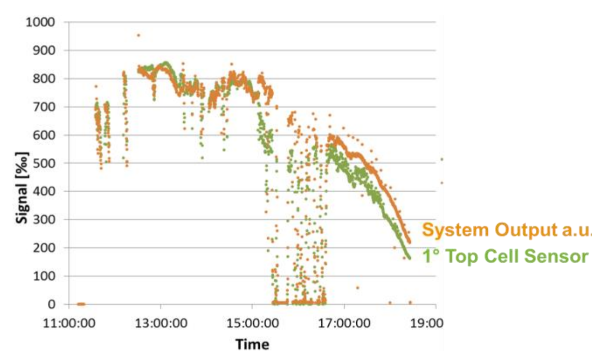

FIGURE 8. CPV system output compared to 3CS top cell sensor with 1° opening half angle

INTERPRETATION OF THE FIELD RESULTS

Current limitations by sub cells during the course of one day are unavoidable. For the best system yield the system should be balanced. A balanced system will be middle cell limited in the high DNI blue spectrum at noon (low air mass) and top cell limited under the red shifted morning and evening spectra. This is illustrated in the Fig. 9.

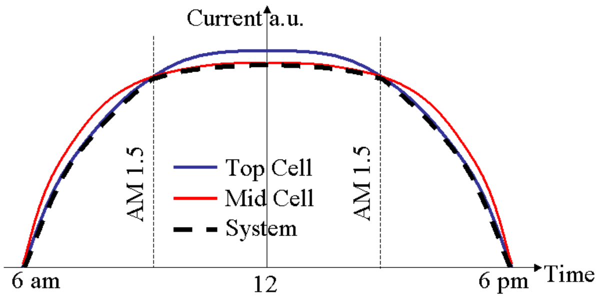

FIGURE 9. A balanced CPV system is top cell limited in the morning and evening and middle cell limited at noon.

The system output under investigation, however, is always proportional to the 2.5° top cell current of the 3CS [Fig. 7]. This indicates that the system is top cell limited even under a 900 W/m^2 DNI spectrum with AM1.3. This behavior corresponds to the exaggerated sketch in Fig. 10.

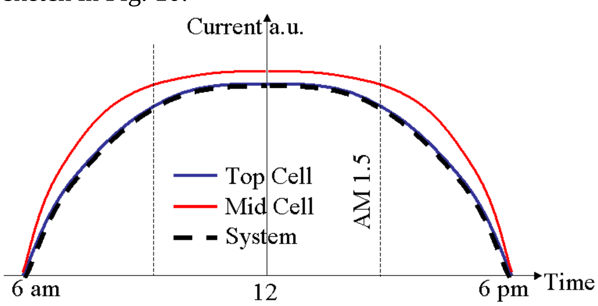

FIGURE 10. A CPV system with too little blue response is always top cell limited.

The information that the CPV system is top cell limited most of the time is valuable. It will consequently be tuned to have a higher response in the short wavelength regime. In this way the system yield will be improved.

The low readings from the 1° top cell sensor in the evening show that the aperture of 1° has been chosen too small compared to the acceptance angle of the CPV system. The CPV system gathered a higher fraction of the circumsolar evening light than the sensor. The 1° aperture should be increased to fit this acceptance angle.

CONCLUSION AND OUTLOOK

The 3CS was presented. It is a very compact 3 channel isotype cell sensor for the measurement of direct sunlight. Due to its fully molded design it has no cavities that could attract moisture.

The sensor proved to be highly valuable in a first application on a CPV system. It shows that the CPV system tends to be top cell limited and that an improved response to blue and UV light will lead to an improved system performance.

In addition to system optimization the sensor is ideally suited for CPV performance prediction and monitoring.

The 3CS is designed for cost effectiveness and can already be produced in reasonable quantities. The outdoor testing is presently continued and a lab referencing procedure is under development.

AZUR SPACE Solar Power GmbH hopes to achieve a wide distribution of this sensor in CPV field installations. Thus valuable field spectral and performance data can be obtained. They will show the performance of AZUR SPACE Solar Power cells under various spectra in different CPV systems.

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