OPTIMIZING CPV SYSTEMS FOR THERMAL AND SPECTRAL TOLERANCE

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ABSTRACT: Martifer Solar, in collaboration with the Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES) in Madrid, has developed a new CPV system. The IES provided the optical design and helped to select component suppliers. The scope of the project is to provide a state-of-the-art system with minimal technical risk: i.e. a well-executed rather than novel system that leveraged the capabilities of the current CPV supplier ecosystem. Early on, a choice was made to use all-glass optics: a silicone-on-glass primary lens combined with a molded glass secondary optical element (SOE) as the choice that would combine high performance and reliability. As recent work has shown, when designing concentrator systems with SOG lens their high sensitivity to temperature must be taken into account, and it is shown how an appropriate SOE can reduce this sensitivity. In this paper, we discuss best practices for implementing concentrator systems using SOG primaries and DTIRC SOEs, and show how a range of characterization techniques may be used to optimize them, including the study of their performance sensitivity to focal distance and temperature. We discuss early performance results for the system and show how the final system shows reduced thermal and spectral sensitivity compared to other systems.

Keywords: Concentrators, Optical Losses, Thermal Performance, Silicone-on-Glass, Secondary Optics

1 INTRODUCTION

Martifer Solar, in collaboration with the Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES) in Madrid, developed a new CPV system. The IES provided the optical design and helped to select component suppliers. The central concept of this CPV development program was combine the best available CPV optical components, but without incorporating any novel optical designs that would increase technical risk. Two elements that have recently been introduced into the CPV supplier ecosystem, the SOG lens and the molded glass secondary, were chosen as those that would extract the highest performance from a conventional point focus system, while prototype module size and concentration ratio was kept conservatively low, with plans to increase these values for later production designs.

As recent work has shown, when designing concentrator systems with SOG lenses, their high sensitivity to temperature must be taken into account, [3-5]. These lenses exhibit performance that varies with temperature due to a significant variation of the index of refraction with temperature, and to the fact that the coefficient of thermal expansion (CTE) of glass and silicone are mismatched. The change of index of refraction essentially modifies the focal distance of the lens, and the CTE mismatch causes a deformation in the facets, producing a slope angle error and therefore deviations in the refracted rays, as has been previously investigated. This will produce a decrease in the geometric concentration of the lens (the "spot" of light will increase in diameter), and the overall concentrator system design should account for this. In particular, the secondary optical element (SOE) should provide a large enough aperture to efficiently capture all of the light from the primary across the range of temperatures expected in operation.

For the Martifer Solar optical system, we have carried out an in-depth temperature sensitivity study, the results of which are discussed. It is shown that the addition of a DTIRC secondary significantly reduces the system efficiency sensitivity to lens temperature. Also, early results for prototypes modules based on the optics developed in this work are shown.

2 SECONDARY OPTICAL ELEMENT

The SOE was designed to be very tolerant to changes in the spectral and spatial irradiance distribution within the spot casted by the primary lens. Assembly and tracking errors, changes in the spectral distribution of light reaching the CPV system, and changes in SOG lens effective concentration and focal distance due to temperature cause significant variations at the entrance of the SOE. Hence, the design of this element results crucial to guarantee a uniform illumination of the solar cell and the tolerance of the whole system to all the above mentioned phenomena. The secondary type chosen is the dialectic total internal reflector (DTIRC) introduced by Ning. This concentrator design approaches ideality (as expressed by the relationship between concentration and acceptance angle as given by Equation 1) using both refraction and total internal reflection in a non-imaging design.

2.1 SOE Design

The SOE used for the Martifer concentrator was designed by imposing optical path conservation for the extreme-angle incident beam, at the maximum positive entrance angle ($+\theta_{entrance}$). The maximum concentration of the SOE, X_{DTIRC} is given by:

$$X_{DTIRC}\sin^2(\theta_{entrance}) \leq n_{DTIRC}^2 \qquad (1)$$

The minimum value for $\theta_{entrance}$ is the angle of the cone of light cast by the primary, and increasing $\theta_{entrance}$ results in decreasing concentration ratio and therefore SOE entrance area. This decreases system tolerances to errors in the shape of the primary optic, such as those caused by temperature. At the same time, as $\theta_{entrance}$ approaches the angle of the primary light cone, the internal reflections work closer to the critical angle, producing a secondary that is less tolerant to manufacturing (surface) defects. Therefore a trade-off exists between tolerance in TIR performance (higher SOE angular acceptance and lower SOE concentration and overall system performance (a larger SOE entrance area).

Two DTIRC secondary designs were prototyped and compared: one with the minimum required entrance angle and a larger entrance area, and a smaller secondary with safety-factor added to the angle of the extreme ray, as a trade-off between tolerance allocations. It was found the larger design provided not only better acceptance angle, but higher on-axis efficiency, indicating that TIR performance was not an issue for this SOE. This SOE is used in all later discussion.

3 FOCAL DISTANCE OPTIMATION

In any concentrator system design flow, a nominal focal distance is chosen and used optical in simulations. However, once actual optical components and cells are available, this distance should be optimized experimentally both system efficiency and acceptance angle, to take into account effects of spatial and spectral non-uniformity that are difficult to simulate. [3] In the case of SOG lenses, this optimization additionally should be carried out with the lenses at or near operational temperature, and it is often useful to perform experiments at many lens temperatures in order to choose a focal distance that will provide the best tolerance to temperature changes. In this work we have characterized various system parameters versus lens temperature and focal distance, for a unitary system. We compared the as-designed optic to an equivalent single-stage system represented by the same system with the SOE removed.

3.1 Experimental Set-up

In order to perform this optimization, we used the indoor setup of [3], shown in Figure 1 and 2. A thermal chamber was placed in the collimated beam produced by the IES-UPM Solar Simulator [4]. The mechanical means were provided to support an SOG lens, as well as various receivers on a movable stage. Three types of experiments were performed:

1) Imaging the profile of the flux at the cell entrance using the method of [6] and [8].
2) The cell photocurrent was measured and compared to calibrated isotype cells, so that the internal current matching between the top and middle subcell could be estimated using the method of [7].
3) Finally, an entire receiver was used to measure system electrical efficiency.

The two stage optics chosen for the Martifer project (A) were compared to a representative single-stage concentrator, represented by the same system with the SOE removed. (B) All studies were performed for multiple temperatures and focal distances, allowing us to find optimal receiver to lens distance based on expected lens operating temperature range.

The performance losses attributed to operating at non-optimal temperatures and focal distances are a combination of effects, including:

- Overall transmission: As lens concentration is decreased, some rays are lost completely.
- Overall current mismatch due to chromatic aberration.
- Irradiance non-uniformity: Additional series resistance losses. [8]
- Spectral non-uniformity: a non-homogenous spectrum across the cell causes additional losses[7].

The multi-parameter study carried out in this work as described is capable of breaking down performance losses in order to discriminate between performance loss sources. A full discussion is outside the scope of this article, so we will focus figure of merit of most interest to the system designer: system electrical efficiency.

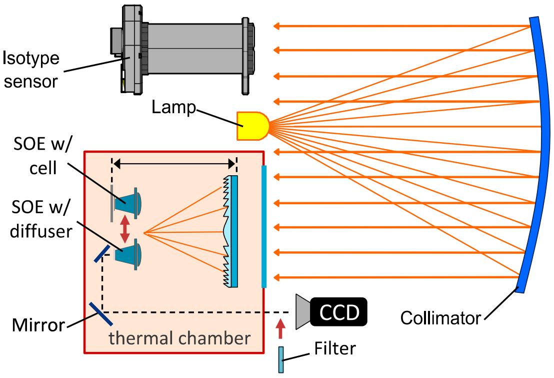

Figure 1: Schematic of xperimental set-up for optimizing SOG-based CPV systems over a range of temperatures.

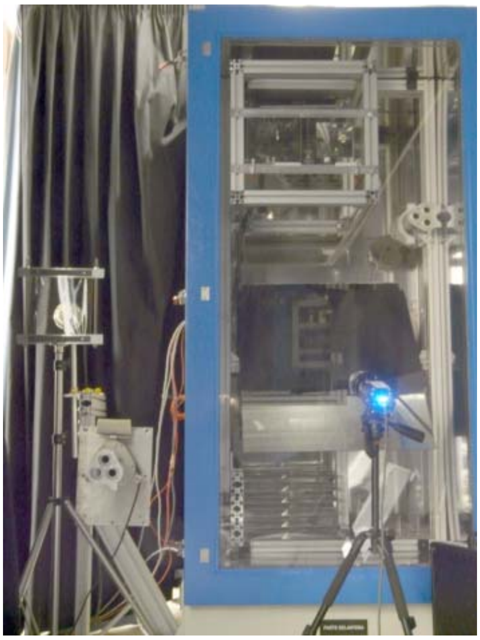

Figure 2: Experimental set-up for optimizing SOG-based CPV systems over a range of temperatures.

3.2 Results – Primary Lens

It is interesting to begin by examining the results of the behavior of the primary lens on its own. The images recorded at the focal plane can be processed using the methods of [5] to find the spot diameters containing 95% of the incident flux at the focal plane. In Figure 3 we show the variation of this parameter with temperature and focal distance.

The expected behavior is seen: as temperature increases the effective focal distance of the lens (the distance at which the minimum spot is formed) moves steadily farther out. Also, the best in-focus behavior is observed when the lens is near the temperature at which the lens was cured, in this case near 45°C. From a system design standpoint, the fact that there is not a single module design will have to be produced with a single focal distance, corresponding to a single intended lens operating temperature, but the module will have to operate over a range of lens temperatures, and therefore will often operate with the receiver at a non-optimal distance from the lens.

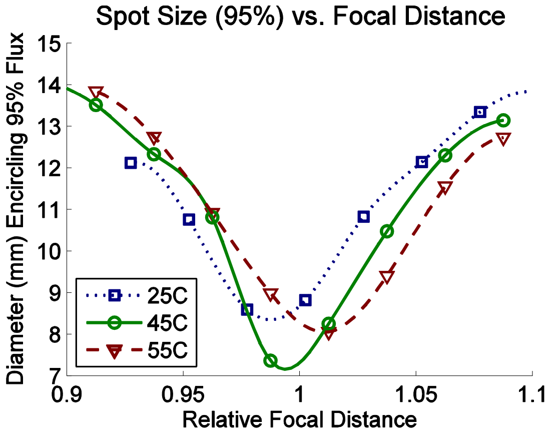

Figure 3: The size of the “spot” of light vs. focus for different lens temperatures.

3.3 Results – System Efficiency

For both the system with and without the SOE, the electrical efficiency of a unitary system was measured at Standard Test Conditions (STC). For measurements with the thermal chamber at higher than room temperature (in order to adjust lens operating temperature) the resulting IV curves were translated to STC using a diode model.

The resulting efficiency comparison is shown in Figure 4. In the single-stage case, the efficiency curve is approximately the inverse of the spot size curve, with maximum efficiency seen when the lens was focused, and quickly dropping off as the focus is adjusted. By adding the secondary, the focal tolerance at all temperature levels is greatly increased. The focal tolerance of the SOE system alone is shown in Figure 5 for detail. It can be seen that the these curves also show an increasing optimum focal distance, but that the since the curve is much flatter, it is possible for the system designer to choose a nominal focal distance that maintains near-optimal performance across a range of temperatures.

In these graphs, the focal distance is shown normalized to an optimum chosen in order to obtain the best performance across a range of expected lens operating temperatures. The temperature response of a CPV system with a focal distance fixed to these nominal can be found by interpolation, and is shown (as F= 1) in Figure 6. However, one can reasonably expect that for a variety of reasons (manufacturing error, flexure in the module, thermal expansion, etc.) the real focal distance experienced by the system in the field could vary by a small amount from this chosen nominal. Therefore, the temperature response curves are shown for a focal distance varied by ±1% as well. From this figure we can see that by adding a dielectric secondary we have reduced the effect of temperature on CPV electrical efficiency from about 5% absolute to around 0.5% absolute across a range of approximately 25°C.

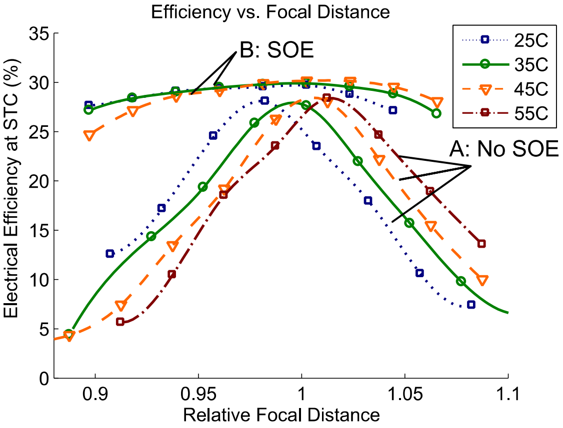

Figure 4: While changes in focal distance tend to quickly reduce efficiency in single-stage system the addition of the SOE greatly increases focal tolerance.

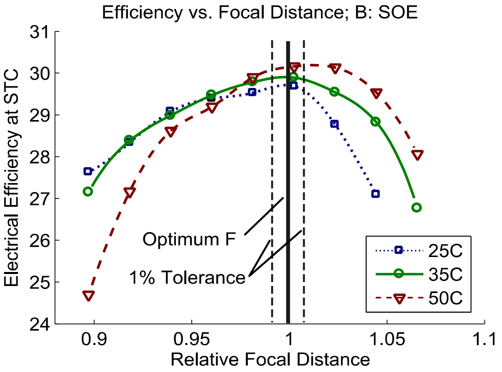

Figure 5: The two-stage offers a focal distance with near optimal performance at multiple temperatures.

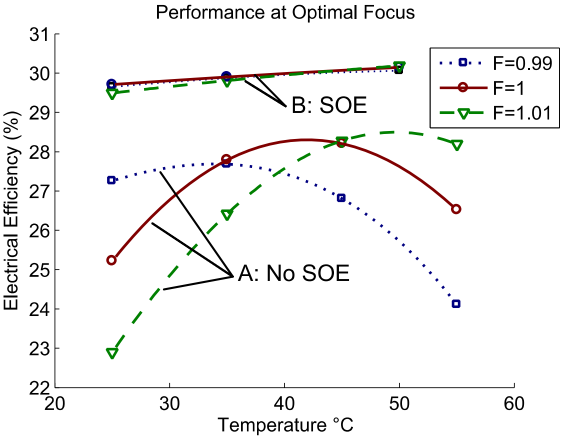

Figure 6: The resulting performance variation with temperature for a fixed focus.

4 INIITAL PROPTYPE RESULTS

Prototype modules employing this optical system with a DTIRC SOE have been built for purposes of demonstration and field test (Figure 7). In this section we will briefly discuss initial results of these prototypes.

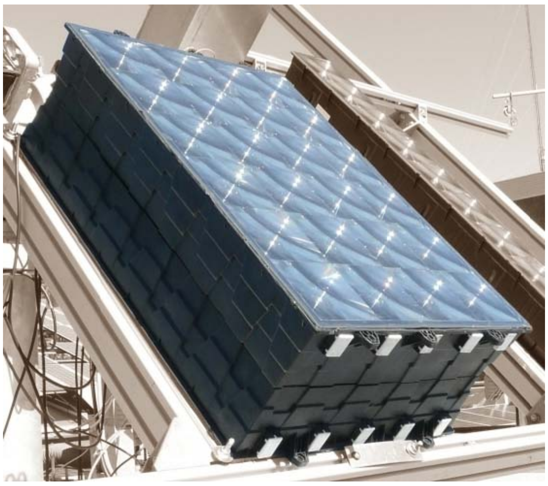

Figure 7: Module prototype in outdoor test.

In preparation for a calibrated measurement of these modules at STC in our solar simulator, as described in [10] we have calibrated representative modules outdoors, on a clear day, in winter. This involves comparing the DNI normalized module ISC to the SMR as it changes over the course of a day or days. Since we previously measured the photocurrents of these cells before installing them in the designated module, one can also use this data to extract an effective optical efficiency, according to.

$$\eta_{Op,Eff} = \frac{I_{SC,Outdoor} \cdot X_{CellTest}}{I_{SC,CellTest,Avg} \cdot X_{Geom} \cdot DNI_{Outdoor}} \qquad (2)$$

This effective optical efficiency includes the effects of spectral mismatch and so varies with spectrum. Data for a number of days is shown in Figure 8. The observed optical efficiencies, in the range of 85%, are very promising. We note that the optimum optical efficiencies are observed when the spectrum is red-shifted from AM1.5D. This is not necessarily a disadvantage; it is not yet clear for which spectrum the modules should be optimized such that energy is maximized, and it is possible that optimizing performance for red-shifted spectra is desirable.

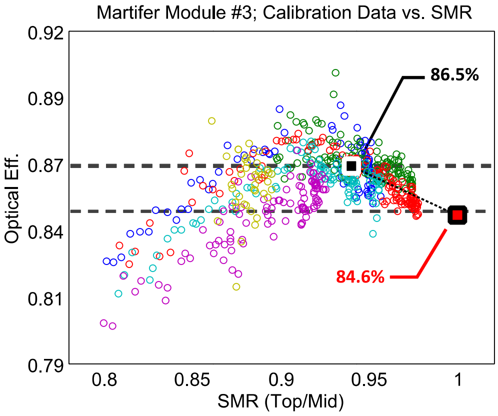

Figure 8: Effective optical efficiencies measured outdoors.

Finally, IV Curves and transmission curves of prototype modules have been recorded at Standard Test Conditions indoors, and summarized in Table I. An example I-V and transmission curve are shown in Figures 9 and 10. Not only is efficiency promising for these first hand-built units, but the DTIRC secondary´s high concentration ratio can be seen to provide a very tolerant acceptance angle of ±1.2º. It is especially notable that the flatness of the transmission curve, with only 2% losses in a range of almost ±0.7°, should ensure maximum power generation at all times.

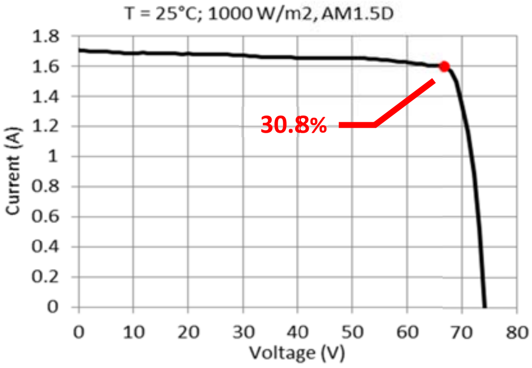

Figure 9: I-V Curve of protoype module at STC

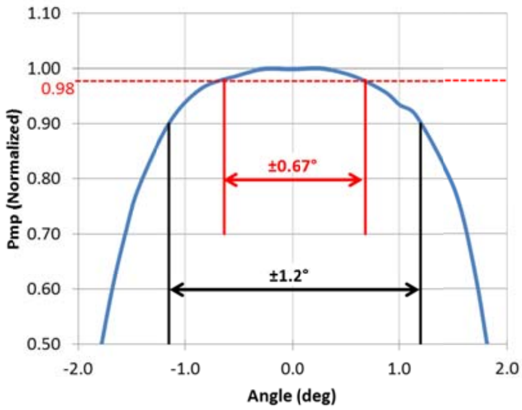

Figure 10: The representative module level transmission curve (rotated about module long axis) as measured in solar simulator, displaying a very flat curve.

Table I: Module level performance of Martifer system at STC (TC = 25°C, 1000 W/m2, AM 1.5D).

Parameter	Nominal Value
Efficiency (active area)	30.8%*
Acceptance Half-Angle (90%)	±1.2°
Acceptance Half-Angle (98%)	±0.67°

** For 38% efficient solar cells.*

5 CONCLUSIONS

The IES has collaborated with Martifer Solar to develop a new CPV system. The DTIRC Secondary Optical Element used has proved to be effective at eliminating the issue of temperature dependence in SOG based concentrator systems, by providing for tolerance to changes in POE behavior. A detailed temperature study has been proposed and carried out, and we suggest that such a study is best practice for empirically optimizing the focal distance used in such concentrators. Initial prototype results are promising, and long-term outdoor testing is ongoing to confirm the findings of the indoor study.

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