Optimization Of Tolerant Optical Systems For Silicone On Glass Concentrators

Stephen Askins[1], Marta Victoria[1], Rebeca Herrero[1], César Domínguez[1], Ignacio Antón[1], Gabriel Sala[1], André Coutinho[2], José Carlos Amador[2]

[1]Instituto de Energía Solar - Universidad Politécnica de Madrid, +34 914533553, steve.askins@ies-def.upm.es, Madrid, Spain. [2]Martifer Solar, Oliveira de Frades, Portugal

Abstract. Over the past year, Martifer Solar, in collaboration with the Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES) in Madrid, has been developing a new CPV system. A goal of the project was to choose "off-the-shelf" components that did not require new R&D, as well as to focus on a tolerant system to maximize value and performance. A SOG primary was coupled with a dielectric secondary, creating a very tolerant system. It is shown how this choice of SOE is very successful in eliminating the issue of temperature dependence that is well known in silicone primaries, as well as allowed the team to quickly begin building high performing modules.

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INTRODUCTION

Over the past year, Martifer Solar, in collaboration with the Instituto de Energía Solar of the Universidad Politécnica de Madrid (IES) in Madrid, has been developing a new CPV system. The IES provided the optical design and helped to select component suppliers. The goal was to design 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. Silicone-on-glass [1] was chosen for the primary lens due to its good mechanical properties (flatness, rigidity, toughness). This POE was coupled to a molded glass dialectic total internal reflector (DTIRC) [2] secondary optical element (SOE) specifically designed for it. The DTIRC can provide very high geometric concentration ratio, translating into large SOE entrance apertures, and recent advances in glass molding make them a strong choice for performance and reliability.

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, a significant variation of the index of refraction with temperature, and to the fact that the coefficient of thermal expansion (CTE) is very different for glass and silicone. 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.

OPTIMIZATION

In any concentrator system design flow, a design focal distance is chosen and used in optical simulations. However, once actual optical components and cells are available, this distance should be optimized experimentally for both system efficiency and acceptance angle, to take into account effects of spatial and spectral non-uniformity that are difficult to simulate [6]. In the case of SOG lenses, this optimization additionally should be carried out at a range of 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.

In order to perform this optimization, we used the indoor setup of [3], shown in Figure 1. 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.

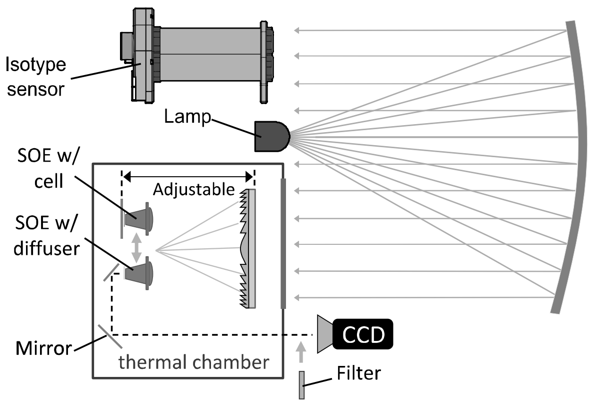

FIGURE 1. Experimental Setup.

Results

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 2 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 optimum focal distance is problematic, as the final 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.

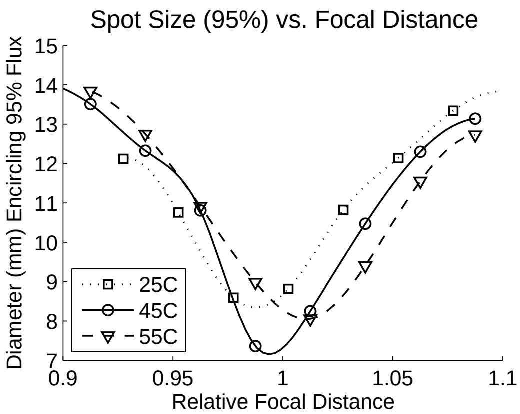

FIGURE 2. Behavior of POE at different temperatures.

The performance losses attributed to operating at non-optimal temperatures 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: when light spectrum is not homogenous across the cell, especially where limiting subcell is not the same across the entire area, this causes additional losses [7].

A multi-parameter study as described in the last section is capable of breaking down performance losses in order to discriminate between performance loss sources. However, a full discussion is outside the scope (and space limitations) of this article, and instead we will turn to the figure of merit of most interest to the system designer: system electrical efficiency

System Efficiency Comparison

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 3. 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 4 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 5. 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.

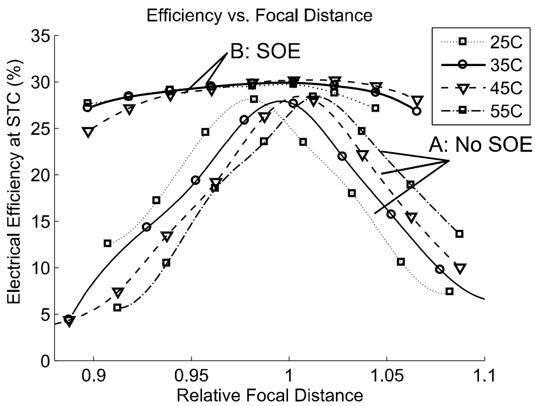

FIGURE 3. Comparison of focal distance vs. efficiency curves at different temperatures for the two systems.

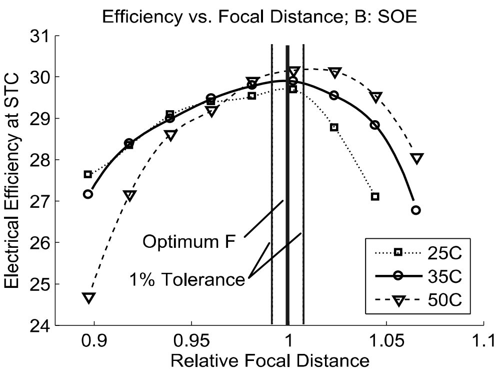

FIGURE 4. Efficiency curves for the Martifer optical system with optimal focal distance and 1% tolerance band.

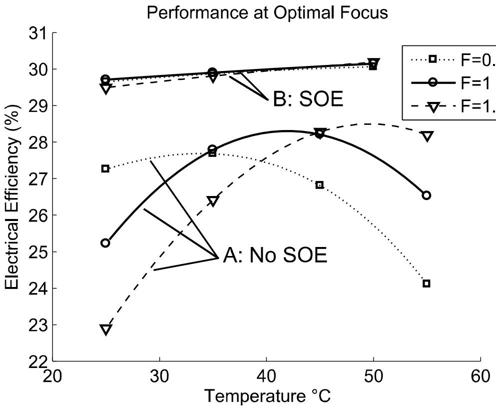

FIGURE 5. Temperature sensitive for systems operating at their nominal focal distance

An important observation is that for the system with no SOE, small differences in F completely changes the temperature sensitivity curve, including the systems optimum temperature of operation. Therefore, the effect may be worse than the value quoted above, because in a real module in operation, there would be a distribution of distances between lens and receiver. In modules employing serial-only connection, performance would be limited by the receiver with the worst performance for a given lens operating temperature.

INITIAL PROTOTYPE RESULTS

Prototype modules employing this optical system with a DTIRC SOE have been built for purposes of demonstration and field test (Figure 6). In this section we will briefly discuss initial results of these prototypes.

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 I_{SC} 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.

$$\eta_{Op,Eff} = \frac{I_{SC,Outdoor} \cdot X_{CellTest}}{I_{SC,CellTest,Avg} \cdot X_{Geom} \cdot DNI_{Outdoor}} \quad (1)$$

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 7. 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

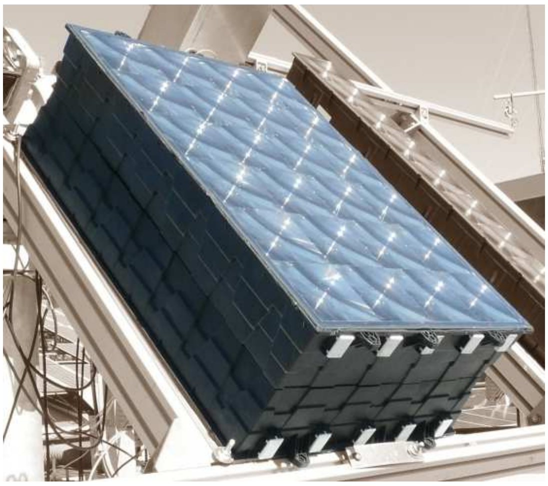

FIGURE 6. Module prototype in outdoor test.

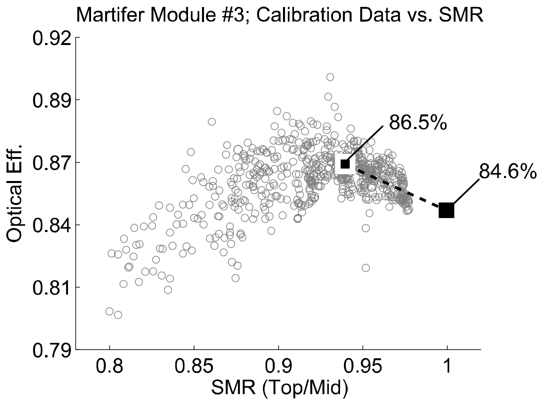

FIGURE 7. Effective optical efficiencies measured outdoors.

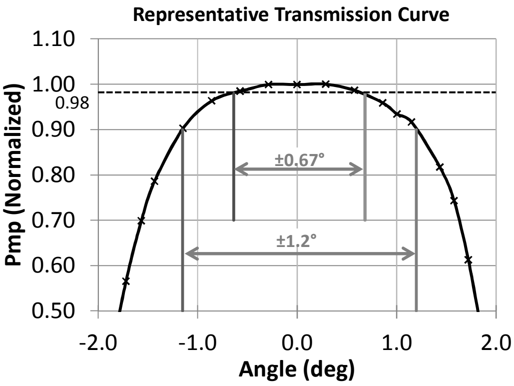

FIGURE 8. The representative module level transmission curve (rotated about module long axis) as measured in solar simulator, displaying a very flat curve.

TABLE 1. Module level performance of Martifer system at STC (T_C = 25°C, 1000 W/m^2, AM 1.5D).

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

* For 38% efficient solar cells.

maximized, and it is possible that optimizing performance for red-shifted spectra is desirable.

Finally, IV Curves and transmission curves of prototype modules have been recorded at Standard Test Conditions indoors, and summarized in Table 1. An example transmission curve is shown in Figure 8. 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 thatthe flatness of the transmission curve, with only 2% losses in a range of almost ±0.7°, should ensure maximum power generation at all times.

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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