Tolerance Analysis and Characterization of Hybrid Thermal-PV Solar Trough Prototype

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Abstract: Hybrid thermal-PV solar trough collectors combine concentrated photovoltaics and concentrated solar power technology. In this work, we analyze the optical and mechanical tolerances that affect the solar energy collection using non-sequential ray tracing techniques. The study is complemented with a half scale prototype characterization. We aim to establish a basis for tolerances required for fabrication and manufacturing of such systems.

OCIS codes: (350.6050) Solar Energy; (080.2208) Fabrication, tolerancing; (220.4298) Nonimaging optics.

1. Introduction

The benefits of combining thermal and PV techniques to collect and store solar energy have been recognized [1]. In particular, concentrated thermal processes and concentrated PV can be used to enhance optical efficiency, increase solar power concentration, and allow for dispatchability of solar power plants [2,3]. In this project, we are developing a hybrid concentrated thermal-PV solar energy collection system based on spectral beam splitting technology to increase the efficiency and exergy of solar plants for large-scale deployment.

The system combines two existing technologies to capture and store solar energy: concentrated solar power (CSP) and concentrated photovoltaics (CPV). CSP systems are low-cost and proficient at storing a broad portion of solar spectrum by collecting focused sun light as thermal energy, however, their annual solar to electric efficiency tends to be lower than traditional flat PV systems (around 16% for CSP and 22% for PV systems) [4, 5]. CPVs, on the other hand, use parabolic mirrors to concentrate light onto high efficiency photovoltaic cells [6]. CPVs are highly efficient over their finite absorption band (above 40% efficiency under controlled conditions have been reported [6]) but the generated electricity cannot be easily stored, rendering them ineffective at night or when shadowed. Our system combines the storage capacity of CSP and the efficiency of CPV technology at reasonable costs. Here we present a tolerance analysis for this hybrid thermal-PV solar trough system as well as preliminary results from a half scale prototype with a 1.6 meter long trough segment.

2. Hybrid Thermal-PV solar trough

The hybrid thermal-PV Solar trough system consists of a set of cylindrical mirrors arranged in a Cassegrian configuration (Fig.1). The primary mirror M1, collects the sunlight and concentrates it towards its focal line where a thermal tube is placed. A secondary mirror M2, which has an optimized dichroic filter, transmits the sunlight which is not usable by the designed multi-junctions PV cells (mostly UV and IR radiation). The details of the dichroic filter design can be found in our previous work [7]. The rest of the sunlight is reflected towards an additional optical module that concentrates the sunlight into efficient micro PV cells. For the following tolerance analysis, we will refer at the normalized amount of transmitted light through the dichroic mirror as the thermal efficiency, and the equivalent normalized reflected light as the optical efficiency. Both quantities were simulated separately and analyzed with an ideal cylindrical detector, representing the thermal tube, for the thermal efficiency and ideal micro detectors placed after the secondary optical module, for the optical case.

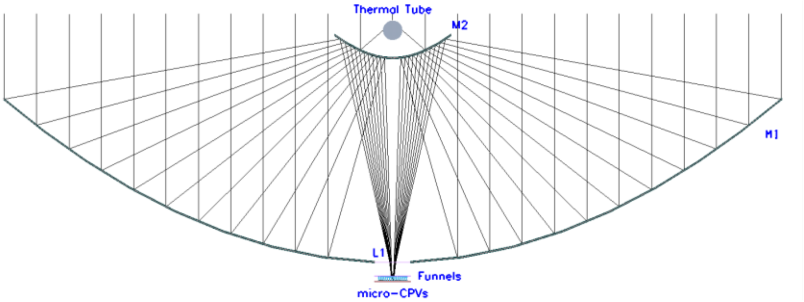


Fig. 1. Hybrid thermal-PV solar trough system. M1 has a collection area of 5 x 1.6 m^2. M2 only reflects the sunlight usable by the micro PV cells, which are placed under a secondary concentrating optics module.

3. Tolerance analysis and ray tracing

In order to quantify the effects of shifting and tilting the mirrors from their ideal position, different misalignment cases were analyzed in LightTools non-sequential ray tracing software. For this tolerance analysis, we focused on the normalized efficiency rather than actual energy collection.

For these simulations, the mirrors were assumed to be 100% reflective for all wavelengths and the Standard Air Mass 1.5 solar spectrum was included in the modeled solar source. Non-sequential optical effects were considered, including Fresnel losses, total internal reflection, absorption, and additional ray paths from secondary reflections. The mirrors were shifted along the z-axis and tilted by angles α and β about the y-axis and x-axis, respectively (Fig.2).

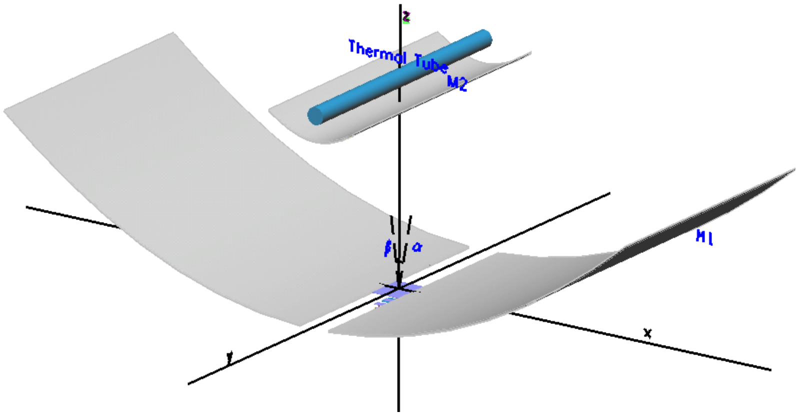


Fig. 2. Angle definitions: α angle represents tilting about x-axis while β about the y-axis. The mirrors were shifted along the z-axis.

Simulation results are shown in Fig. 3. The optical efficiency is more severely affected than the thermal efficiency by shifting effects due to the fact that light is only reflected once along the transmitted optical path. The thermal efficiency has a tolerance of ± 40 mm and above ± 100 mm for M2 and M1 positions respectively. In comparison, the optical efficiency has ± 10 mm for both cases. In Fig. 4, the optical efficiency is further analyzed by tilting the mirrors by α and β. Tilting tolerances about the x-axis are more relaxed than those about the y-axis due to the cylindrical nature of the system. This is shown by having a ± 0.25° α tolerance for M2, but up to ± 1° β tolerance for M2.

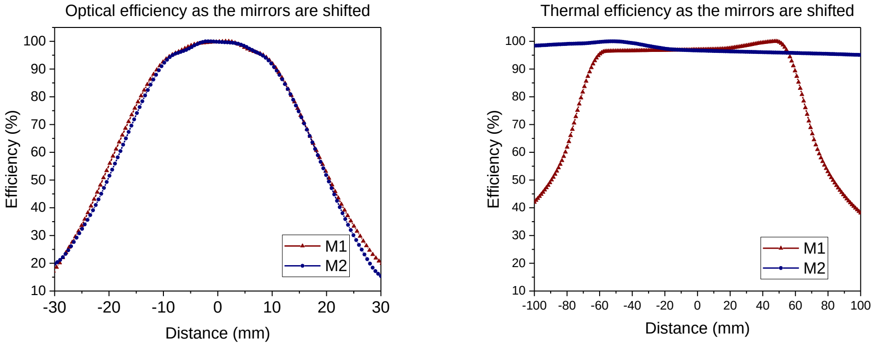


Fig. 3. Optical and thermal simulation results: optical efficiency (left) and thermal efficiency (right) as M1 and M2 are shifted along z-axis.

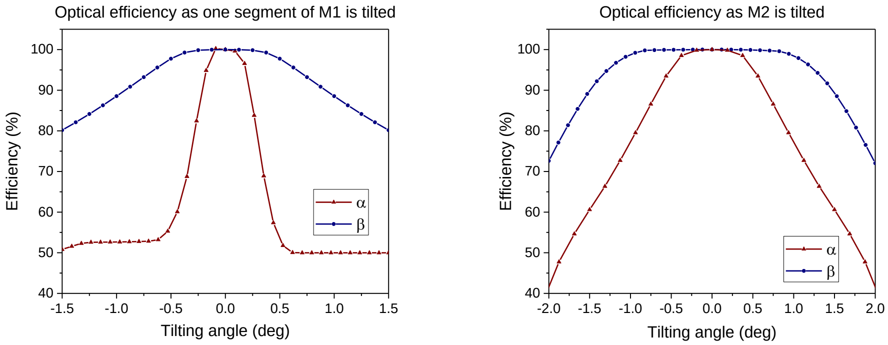
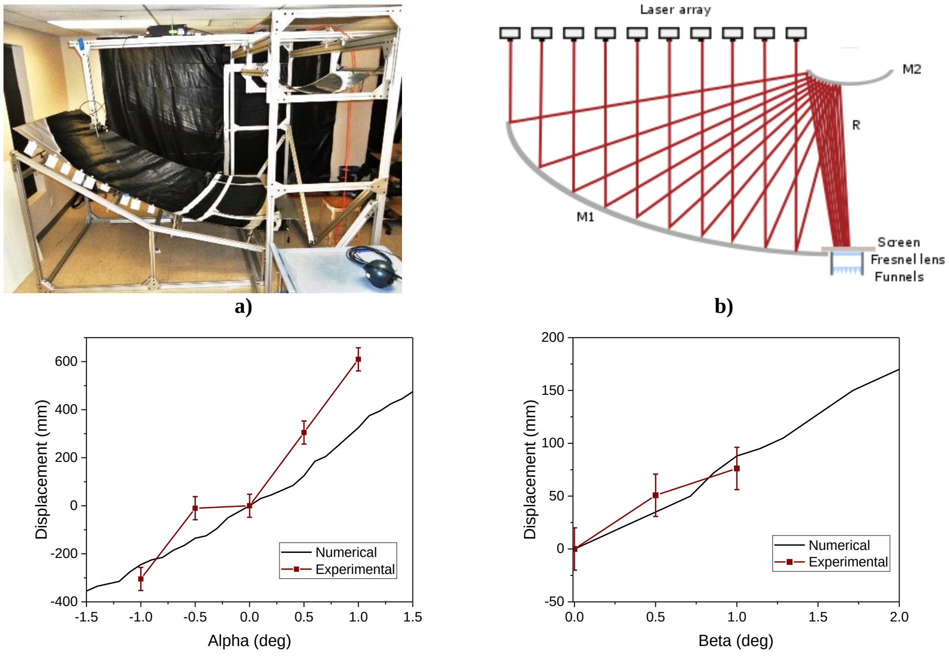


Fig. 4. Optical simulation results: optical efficiency as M1 (right) and M2 (left) are tilted by α and β.

4. Prototype characterization and simulations comparison

The prototype was assembled with a high reflective parabolic mirror for M1 and with a partially reflective dichroic mirror for M2 (Fig. 5). A laser array was used to generate beam spots and analyze the effects of tilting M1. As M1 was tilted along α and β, the focused beams moved in the x-axis and y-axis direction, respectively. For large positive α values, the measured beam shifting was higher than the simulated results. This beam path deviation was due to surface irregularities present on the primary mirror that were not taken into account in the model.



a) b)

d) d)

Fig. 5. Prototype and experimental setup: a) Image of prototype. b) Characterization setup with laser array. c) Beam spots shifting as the primary mirror is tilted by alpha and d) beta angles

5. Conclusions

The ray tracing simulations indicate that hybrid thermal-PV solar trough systems have smaller tracking tolerances along the x-axis (tracking angle) than along the y-axis (skew angle). The optical efficiency is more severely affected by tilting and shifting effects than its thermal counterpart. This demonstrates that hybrid systems have tighter mechanical tolerances than systems that only utilize a single concentrating mirror as the solar collection area is smaller at the micro PVs than at the solar thermal tube. This must be considered when designing these systems which have much higher theoretical optical throughput than traditional collector systems.

6. Funding and Acknowledgments

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7. References

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