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RAY TRACING ANALYSIS OF CPC-HEAT PIPE COLLECTORS FOR INDUSTRIAL LOW- AND MID-TEMPERATURE HEAT PRODUCTION USING REFLECTORS OF DIFFERENT MATERIALS AND GEOMETRIES

Summary

This work evaluates alternatives for the geometry and reflector material in CPCs (Compound Parabolic Concentrators) for generating hot fluid at approximately 150 °C. The study highlights the use of polished stainless steel as a reflector material -a less-explored option in the literature of solar thermal energy systems- and compares it with more commonly studied materials such as solar commercial aluminum-based reflectors, incorporating reflectivity measurements. The analysis also considers geometric variants, weighing the opposing effects of increasing the concentration ratio (which reduces heat loss area) and decreasing optical efficiency, as well as the possibility of varying the inclination angle of the surface throughout the year. The results aim to provide practical criteria for selecting materials and geometries for CPC-heat pipe systems in industrial processes.

Keywords: CPC heat pipe, reflector materials, stainless steel, optical efficiency, ray tracing, industrial heat

1. Introduction

The replacement of fossil fuels with renewable energy in industrial thermal processes is a central challenge for advancing the decarbonization of the productive sector. In this context, CPC solar concentration systems coupled with heat pipe vacuum tubes emerge as efficient and reliable alternatives for medium-temperature heat generation. These systems offer advantages such as the capture of both direct and diffuse solar radiation, low maintenance, and good thermal stability. Given their potential application in industry-a sector still highly dependent on fossil fuels-their study is fundamental for developing technologies that drive the energy transition toward clean and sustainable sources. However, the cost of reflective materials used in concentrators can significantly affect the economic viability of the system, especially for large-scale applications.

Various studies have addressed the optimization of CPC systems, particularly regarding the choice of reflective materials and concentrator geometry. For example, previous research has analyzed the impact of different metallic reflectors on the optical efficiency of concentrators (García-Ortiz et al., 2016). Other works have used ray-tracing simulations to evaluate solar radiation distribution in concentration systems and its impact on thermal efficiency (Santos-González et al., 2014). For heat pipe tubes, significant improvements in heat transfer and system stability have been reported when using optimized geometries and high-reflectivity materials (Zhang et al., 2025). This study builds upon these efforts, focusing on the optical and economic performance of various reflective materials in CPC systems, intending to provide practical criteria for industrial implementation.

The objective of this work is to analyze the optical efficiency of different CPC systems with heat pipe tubes, using optical simulations via ray tracing with Tonatiuh software. Three reflective materials-high-reflectance aluminum-based sheet (HRABS), commercial polished stainless steel sheet (CPSS), and commercial polished aluminum sheet (CPAS)-are evaluated, alongside several geometric configurations with different concentration ratios. The study quantifies how the choice of material and concentrator geometry affects the fraction of useful solar radiation reaching the absorber tube. Optical losses are estimated, which, together with thermal losses, allow for the evaluation of the overall performance of each configuration. Geometric variants are also analyzed, considering the trade-offs between increasing the concentration ratio (reducing the area of thermal losses) and decreasing optical efficiency, as well as the possibility of varying the inclination angle of the surface throughout the year.

2. Work and Methodology

First, the optical properties of the reflective materials are studied. Reflectivity of various aluminum and stainless steel samples are measured in the spectral range of 400 to 1000 nm using an Ocean Optics (S2000) spectrometer and an Ocean Optics (ISP-REF) integrating sphere, which incorporates a light trap to capture the specular component reflected by the sample, thus differentiating between diffuse and total reflectivity. Both total and diffuse reflectivity are determined by quantifying the intensity difference between each sample and the device reference, using a Spectralon Labsphere (WS-1-SL) as reference.

Subsequently, Tonatiuh software is used for optical ray tracing simulation of the solar system, adjusting different geometric parameters and material properties to observe how these changes influence the path of solar rays within the system and to determine the achieved optical efficiency. Both the diffuse and specular components of reflectivity are considered separately. A standard-dimension vacuum tube with a CPC reflective surface was modeled (see Figure 1).

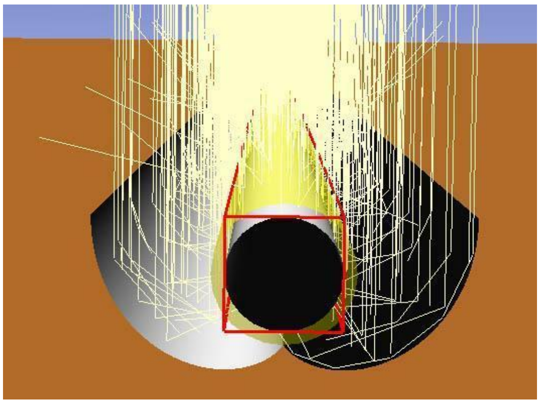

Fig. 1. RayTracing model

A variable collector inclination is also considered, adjustable throughout the year. Ray tracing is used to analyze the behavior for different inclinations, and, using a typical meteorological year (with separation of direct and diffuse radiation), the annual solar radiation received by the receiver is calculated.

Finally, the effect of the concentration ratio on overall efficiency is evaluated, considering the opposing effects of changes in optical efficiency and thermal losses (for working temperatures around 150 °C). The results of optical efficiency are combined with thermal loss parameters (from experimental tests) to assess the global performance of each collector configuration.

3. Preliminary Results

The reflectivity results are presented in Figure 2, showing reflectivity as a function of wavelength for four different reflector samples: three aluminum and one steel. The aluminum samples include a HRABS and two sections from a CPC-type heat pipe collector CPAS –one from the film-protected side and the other from the weather-exposed side– while the steel sample is mirror polished (commercial grade). The left graph of Figure 2 displays total reflectivity (ρ_t), while the right graph shows specular reflectivity (ρ_e) obtained as the difference between total and diffuse reflectivity.

The HRABS exhibits the highest reflectivity in both total and specular measurements, showing wavelength-dependent oscillations characteristic of a surface thin film that generates an interference pattern. Among the two CPC aluminum samples, the film-protected one demonstrates higher total reflectivity and a marked difference in the specular component. In contrast, the weather-exposed sample behaves similarly to a diffuse reflector, with minimal specular reflectivity. As for the mirror-polished stainless steel sample (CPSS), it shows the worst total reflectivity performance but nevertheless surpasses the aged CPAS in specular reflectivity.

Preliminary optical efficiency results for a CPC collector with a concentration ratio of 1 under normal incident radiation show 56 % efficiency for the CPSS (commercial polished stainless steel) reflector and 81 % for HRABS (high-reflectance aluminum sheet). This substantial difference highlights the need to incorporate thermal losses and cost variations for a comprehensive cost-benefit analysis of collector performance.

The final study will present detailed analyses of global performance variations resulting from changes in optical efficiency and thermal losses. This will include evaluations across different concentration ratios and inclination angles for collectors using polished stainless-steel reflectors.

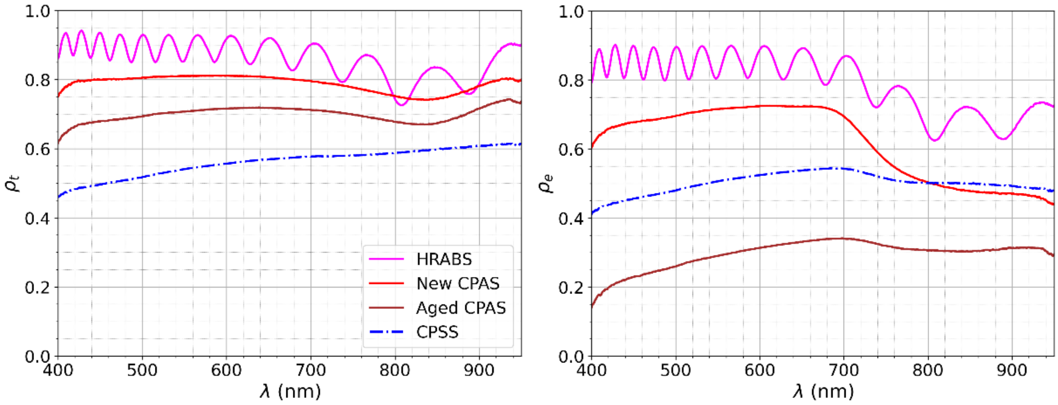

Fig. 2. (Left) Total reflectivity of the five samples of reflectors analyzed and (right) specular reflectivity of the same mirror samples.

4. References

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