ESTIMATION OF DUST ACCUMULATION IN PARABOLIC TROUGH CONCENTRATORS USING AERIAL LASER REFLECTION

Salvador Robles-Velázquez[1], Manuel I. Peña-Cruz[2,*], Marcelino Sánchez-González[3]

1 Centro de Investigaciones en Optica, A.C. Unidad Aguascalientes, Prol. Constitución 607, Fracc. Reserva Loma Bonita, 20200, Aguascalientes, Aguascalientes. México.

2 CONAHCYT - Centro de Investigaciones en Optica, A.C. Unidad Aguascalientes, Prol. Constitución 607, Fracc. Reserva Loma Bonita, 20200, Aguascalientes, Aguascalientes, México.

3 Centro Nacional de Energías Renovables, Ciudad de la Innovación 7, 31621 Sarriguren, Navarra, España.

Abstract

Solar thermal energy has a high capacity to supply a large part of the planet's energy demand. However, it is necessary to increase its efficiency and performance, as well as improve operation and maintenance (O&M) processes; since these systems are strongly affected by dust deposition, mainly parabolic trough plants. This work analyzes the deposition of dust on the transparent covers of the absorber tubes of parabolic trough collectors and the energy loss associated with it. An optical methodology is developed based on analyzing transmittance of the receiver in different dirt scenarios using a point laser and subsequently, the reflectance of a linear laser on the transparent cover of the absorbent tube captured by a camera mounted on an aerial vehicle; thus relating the luminous intensity to the amount of dust deposited and establishing an energy loss criterion.

Keywords: Dust deposition, Parabolic trough, concentrating solar energy, drones.

1. Introduction

Dust collection in concentrated solar power (CSP) plants presents significant challenges, primarily due to its impact on system efficiency and lifetime. Dust buildup on the mirrors and solar receivers, crucial components for concentrating sunlight, can significantly reduce the amount of solar energy captured, leading to a decrease in the plant’s originally estimated total energy output. This reduction in efficiency necessitates frequent, resource-intensive cleaning, especially in arid regions where water scarcity further complicates maintenance efforts. Furthermore, abrasive dust particles can cause surface degradation over time, increasing maintenance costs and potentially shortening the lifespan of optical components. Therefore, the need for effective dust mitigation strategies is crucial to maintaining the efficiency and cost-effectiveness of solar technology (Maghami et al., 2016).

Studies have increasingly focused on quantifying the impact of dust accumulation on optical efficiency, revealing that dirt accumulation can significantly degrade the performance of solar collectors (Hachicha et al., 2019). Niknia et al. (2012) highlighted that dust accumulation on parabolic trough concentrators adversely affects both reflectance and transmittance, which are critical for the efficiency of solar receivers. Zhao et al., (2020) examines the impact of dust accumulation on a linear Fresnel reflector, finding that dust density increases while relative reflectivity decreases over time, with a 9.4% drop in reflectivity for every 1 g/m^2 increase in dust.

Several factors contribute to the loss of efficiency in solar collectors due to dust accumulation, including the geographical location of the solar plant, the orientation and position of the collectors, nearby facilities like highways or factories that might contribute to dust levels, the frequency of rainfall in the area, and the prevailing wind conditions (Deffenbaught et al., 1986). Each of these factors plays a role in determining how quickly dust builds up on the collectors and how severely it impacts performance (Usamentiaga et al., 2020).

To overcome these challenges, various cleaning methods and equipment have been developed to maintain the cleanliness of CSP systems (Bergwon J.F. 1981). For example, Fernández et al., (2014) optimizes cleaning methods for solar reflectors in CSP plants under semi-desert conditions, finding that demineralized water with a brush is most effective, achieving up to 98.8% efficiency, while steam cleaning is less effective, and adding detergent offers no significant benefit. These findings underscore the importance of regular monitoring and cleaning to preserve the optimal performance of CSP plants.

10.18086/eurosun.2024.07.16 Available at http://proceedings.ises.org

In response to these challenges, this work uses laser technology mounted on a Remote Piloted Aircraft (RPA) system to detect dust deposition levels on parabolic trough (PT) solar receivers. First, by study how increasing levels of dust deposited on a PT receiver affect light transmittance over time. Second, by impinging a laser beam onto the solar concentrator in an experimental campaign that provides valuable information on the relationship between laser reflected light intensity and energy loss caused by dust deposition. These innovative approaches offer the potential to develop more accurate and effective dust mitigation strategies, ultimately improving the performance and longevity of CSP plants.

2. Materials and Methods

This project introduces an optical system which consists of a laser mounted on a Remotely Piloted Aircraft (RPA) to evaluate dust deposition and surface conditions of parabolic trough receivers in solar power plants. The innovative approach focuses on characterizing the collectors based on varying levels of dirt accumulation, with the goal of establishing a link between dust buildup and consequent energy losses. By quantifying the transmittance losses on the receiver tube at different levels of dirt accumulation, the project provides a detailed understanding of how dust impacts the efficiency of solar energy collection.

The system operates by directing a linear laser beam onto the receiver tube during night-time conditions, capitalizing on the hypothesis that dust particles scatter light. This scattering effect is expected to influence the reflectance measured by the system, allowing for precise assessments of dust-related degradation in optical performance. The night-time testing is particularly significant as it minimizes the interference of ambient light, thereby enhancing the accuracy of the laser-based measurements. The project's findings could lead to more efficient maintenance schedules and improved cleaning strategies, ultimately contributing to the optimized performance of solar power plants by reducing energy losses caused by dust accumulation.

2.1 Transmittance validation phase

The methodology begins with an experimental validation phase, in which a 550 nm laser (see Tab. 1 for technical characteristics) was directed towards the glass cover of the solar receiver of a PT collector. The transmittance of the laser light when passing through the glass cover with different levels of dirt was measured using a calibrated radiometer. Additionally, and as a reference, this same measurement was carried out outside the glass cover, as a way of determining the base value of radiative flux incident by the laser.

Table 1. Laser technical data

Laser characteristics	
Model	Z-LASER-ZM
Type	Clase 1M
Operating voltaje	5-30 V
Operating current	300-400 mA
Wavelength	532 ; 635-685 nm
Weight	85 g

Fig. 1 depicts the technical arrangement for the experimental setup of the validation phase measuring the transmittance of the glass cover of the PT receiver over time. Additionally, the optical system is able to move along the receiver tube, allowing the identification and analysis of average dirt levels. This approach provides a detailed assessment of how surface contamination affects solar energy collection efficiency.

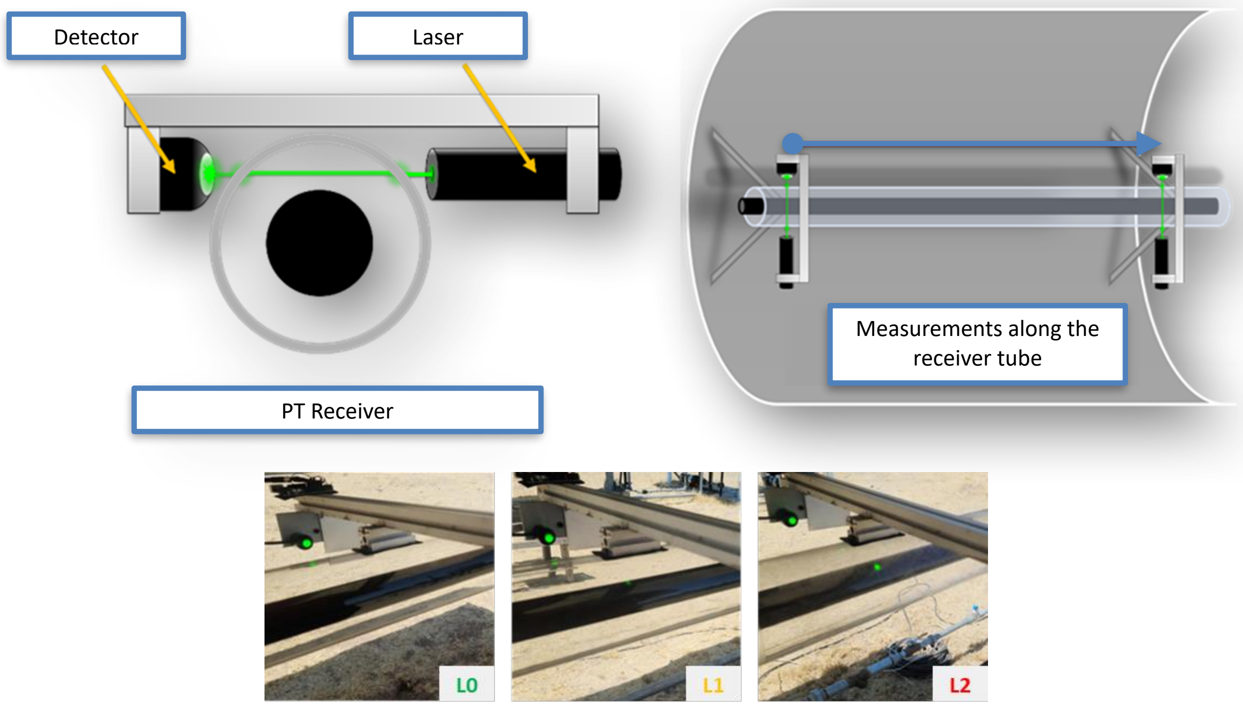

Fig. 1: Experimental setup for measuring transmittance of the parabolic trough receiver over time.

An experimental campaign was carried out over 60 consecutive days, in which dust was allowed to settle on the solar receiver in order to accurately assess the different levels of dirt that were accumulating over time. According to Deffenbaught et al., (1986), the transmittance decreases considerably after the first month of exposure to the outdoors. Therefore, it was decided to divide the accumulation of dirt into three levels. Level L0 represents a recently cleaned receiver. Level L1 represents a receiver that has been outdoors for 15 days. Finally, after two months, an extreme dirt level of L2 is considered (See Tab. 2).

Tab. 2: Levels of dust depositions according to the days without cleaning.

Dust deposition level	**L0**	**L1**	**L2**
Days without cleaning	0	15	60

Fig. 2 provides a visual representation of dust accumulation on the solar receiver over the course of the 60-day experimental campaign. The image clearly illustrates the progressive buildup of dust over time, highlighting the increasing opacity of the solar receiver surface as the days pass. Each segment of the receiver displays varying degrees of dust deposition, making differences in cleanliness readily apparent. These variations in dust levels are critical as they directly impact the receiver's ability to effectively concentrate and convert solar energy.

Fig. 2: Levels of dust accumulation along the experimental campaign.

2.2 RPA laser reflectance system

The Remotely Piloted Aircraft system, (RPA), consists of a pilot-controlled controller, a DJI Matrice 100 and a Zenmuse Z3 camera. Several support designs were created to adapt the laser to the RPA, addressing the critical issue of weight restrictions. To minimize any impact on battery performance, a design was developed that weighs just 48 grams, ensuring that the RPA´s efficiency remains unaffected. Fig.3 depicts the methodology used to sweep the receiver tube of the PT concentrator with the laser.

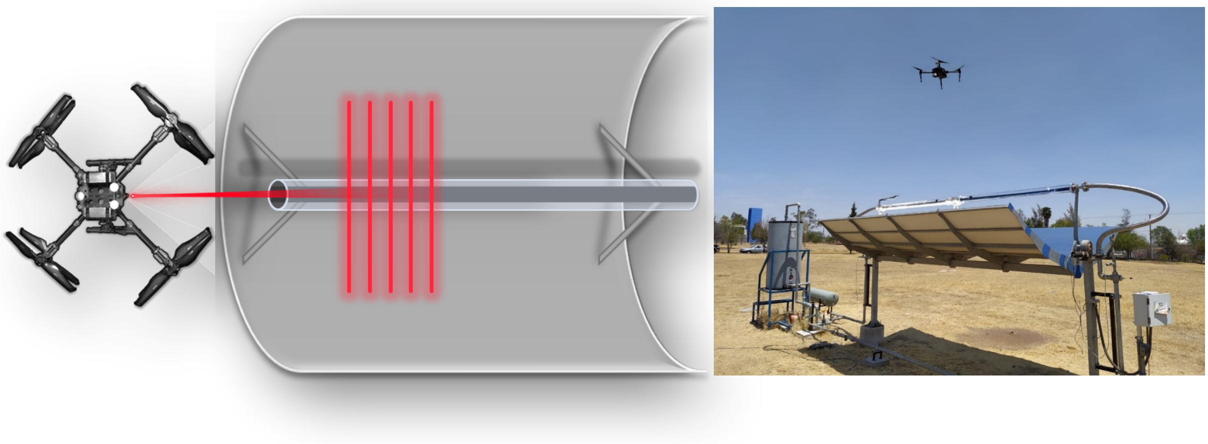

Fig. 3. Graphical representation of the RPA system and the laser system flying over the PT concentrator for the experimental campaign (left). Actual RPA system and PT concentrator.

Two types of flights were conducted to assess the system's performance. The first, a moderate flight, involved a test flight with various maneuvers within the designated flight test area of approximately 3,500 m², without any predetermined sequence. The second type was a static flight, in which the drone remained stationary at a height of 10 meters. This static flight allowed for a focused evaluation of the system’s stability and precision in capturing data without the influence of movement, providing a controlled environment to validate the accuracy of the optical measurements. These two flight scenarios were essential for determining how well the system could perform under both dynamic and static conditions, offering insights into the operational flexibility and reliability of the technology in real-world applications (See Tab. 3).

Tab. 3: RPA flight estimated times from 90% to 30% of battery.

Flight type	Moderate flight		Static flight	
	W/o Laser	W/ laser	W/o Laser	W/ laser
Duration (sec)	593	583	602	555

3. Results and discussion

This section presents the results obtained throughout the 60-day experimental campaign. Initially, the results of the average transmittance measured on the receiver tube are presented and then the analysis of the images obtained from the RPA campaign is performed.

3.1 Transmittance validation results

From the analysis campaign of the transmittance obtained from the incident laser on the glass cover of the receiver, operating intervals can be determined (see Tab. 4). For example, it is determined that the glass cover of the solar receiver presents levels above 93% when compared to the reference value of transmittance (when this is measured outside the glass cover). From 15 days to two months the transmittance decreases to 86 ±7% on average, and once it approaches two months of outdoor exposure, it decreases to an average of 79%.

Tab. 4: Estimates of mean transmittance by the level of dust deposition on the collector tube.

Dust deposition level	L0	L1	L2
Transmittance relative to reference (%)	> 93	86 ±7	< 79

It is worth noting that the experimental campaign was carried out in months with little rainfall. However, the strong wind currents and morning dew cause dust to settle on the receiver. Although these data are a particular case for the location, they serve as evidence that long periods of time produce substantial dust accumulations that affect the performance of solar technology.

3.2 RPA reflectance results

From the drone overflight over the parabolic trough collectors, the reflectance profile of the solar receivers was obtained. In Fig. 4, the incidence of the laser is shown for each level of dust deposition in the receiver tube. In it, a visual image is included, a broken blue line that represents the line where the luminous intensity is measured (called segmentation), and the result of the analysis with color representations corresponding to the levels of dust deposition. A plot representing the accumulation of dust on the receiver is also depicted in accordance with the previously determined levels of dirt.

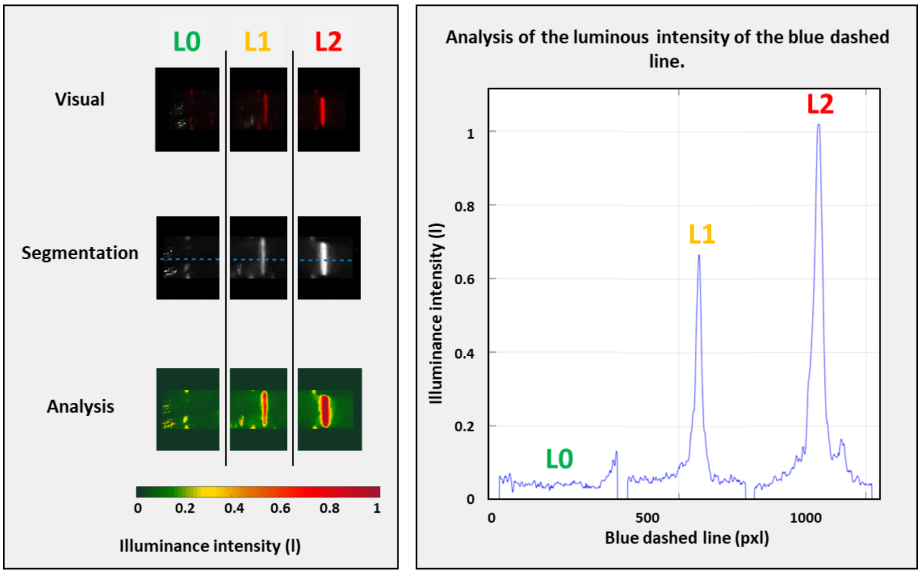

Fig. 4. Reflectance analysis of the aerial optical system on the solar receiver of the parabolic trough concentrator. Details of the methodology are shown in the left. An intensity plot is shown in the right.

Fig. 4 illustrates the luminous intensity (I) along the blue dashed line, correlating with different levels of dust accumulation (L0, L1, L2) on the receiver surface. The intensity profile shows a clear progression from L0 to L2, where L0 represents the cleanest state with the lowest intensity peaks, indicating minimal dust accumulation. As the dust levels increase (L1 and L2), the peaks in the intensity graph become more pronounced, with L2 showing the highest intensity peak, reflecting the greatest amount of dust accumulation. This suggests that as more dust accumulates, the reflectivity of the laser is increased by the scattering of the dust particles. Although the L2 level shows saturation, this case represents an extreme scenario where dust accumulation is already very significant. However, one of the strengths of this system is its adaptability; the operational conditions can be adjusted to meet the specific needs and circumstances of the user. This flexibility is a key advantage, as it allows the system to be fine-tuned for different environmental conditions and levels of dust accumulation. For example, in situations where dust levels are lower or where precision is more critical, the system's sensitivity can be increased to detect even minimal changes in dust deposition. Conversely, in harsher environments where dust accumulation is more pronounced, the system can be adjusted to prevent saturation and ensure accurate measurements. This adaptability also means that the system can be integrated into a variety of solar energy facilities, regardless of their geographical location or the specific environmental challenges. Whether in arid desert regions with frequent dust storms or in more temperate climates with occasional dust accumulation, the system can be calibrated to provide reliable and actionable data. This ensures that solar power plants can maintain optimal efficiency and reduce energy losses due to dust, ultimately leading to better performance and lower operational costs.

4. Conclusions

As shown by the results of the experimental campaign, it was found that there is a direct correlation between the dust accumulated in the parabolic trough receivers and the transmittance/reflectance generated by the incidence of a laser on it. It is possible to determine the operating conditions of the system by measuring the transmittance by shining a laser on the glass cover of the receiver and measuring it by a radiometer; subsequently, it is possible to quantify that the greater the accumulation of dust, the greater the reflectance of the incidence of a laser captured by a camera mounted on an aerial vehicle.

Significant advances have been made in the research and development of an RPA that allows for the rapid and effective estimation of dust accumulation in solar thermal plants. It was determined that adding the optical elements necessary to carry out this experiment does not represent a significant cost for the time and quality of flight of an RPA with the characteristics presented here. Finally, the main hypothesis regarding the visualization of dust on transparent materials using a laser has proven to be promising, particularly in low-light conditions, where very evident variations in the intensity of dust accumulation on the receivers were observed. In addition, this developed methodology has the advantage of being fast, economical, programmable and, when operated at night, it does not interfere with the operating conditions of the solar plant.

Among the results obtained are the following:

- A dust accumulation analysis methodology was successfully developed using an RPA.
- The necessary hardware was developed to implement the methodology in the RPA without compromising airworthiness.
- Three types of dirt were characterized, ranging from the most typical cases of dirt to extreme cases.
- The necessary software was developed to perform real-time signal processing, which is configurable according to the needs and specifications of potential users.

Future research will focus on quantifying the thermal energy losses directly attributable to varying levels of dust accumulation on solar collectors and establishing a clear correlation with the optical losses identified in this study. By integrating thermal performance metrics with the optical data, the goal is to create a comprehensive model that predicts how dust affects overall system efficiency in concentrated solar power (CSP) plants. This model will consider not only the immediate impact of reduced reflectance and transmittance but also the long-term effects of dust on thermal energy conversion efficiency. Additionally, future experiments may involve real-time monitoring of both optical and thermal losses under different environmental conditions, allowing for the development of predictive maintenance strategies and optimized cleaning schedules. This work will contribute to enhancing the reliability and cost-effectiveness of CSP technology by minimizing energy losses due to environmental factors.

5. References

Bergwon, J. F. K., 1981. Cleaning strategies for Parabolic-Trough Solar-Collector Fields; Guideline for decisions. Sandia National Laboratories.

Deffenbaught, D. M., Green, S. T., and Svedeman, S. J., 1986. The effect of dust accumulation on line-focus parabolic trough solar collector performance. Solar Energy, 36(2), pp. 139-146.

Fernández, A., Álvarez-Rodrigo, L., Martínez-Arcos, L., Aguiar, R., and Márquez-Payés, J. M., 2014. Study of different cleaning methods for solar reflectors used in CSP plants. Energy Procedia, 49, pp. 80-89. doi: 10.1016/j.egypro.2014.03.009.

Hachicha, A. A., Al-Sawafta, I., and Ben Hamadou, D., 2019. Numerical and experimental investigations of dust effect on CSP performance under United Arab Emirates weather conditions. Renewable Energy, 143, pp. 263-276. doi: 10.1016/j.renene.2019.04.144.

Maghami, M. R., Hizam, H., Gomes, C., Radzi, M. A., Rezadad, M. I., and Hajighorbani, S., 2016. Power loss due to soiling on solar panel: A review. Renewable and Sustainable Energy Reviews, 59, pp. 1307-1316. doi: 10.1016/j.rser.2016.01.044.

Niknia, I., Yaghoubi, M., and Hessami, R., 2012. A novel experimental method to find dust deposition effect on the performance of parabolic trough solar collectors. International Journal of Environmental Studies, 69(2), pp. 233-252. doi: 10.1080/00207233.2012.664810.

Usamentiaga, R., Fernández, A., and Carús, J. L., 2020. Evaluation of dust deposition on parabolic trough collectors in the visible and infrared spectrum. Sensors (Switzerland), 20(21), pp. 1-20. doi: 10.3390/s20216249.

Zhao, X., Chen, Z., Yan, S., Ming, T., Wu, Z., and Ma, R., 2020. Influence of Dust Accumulation on the Solar Reflectivity of a Linear Fresnel Reflector. Journal of Thermal Science. doi: 10.1007/s11630-020-1379-y.