Concentrated Solar Flux Measurement in a High Flux Solar Simulator Using an Optical Fiber Based Radiometer

Manuel Jerez[1*], Alejandro Carballar[1], Ricardo Conceição[2], José González-Aguilar[2]
[1]*Electronic Engineering Department, Universidad de Sevilla (E.T.S. de Ingeniería), C/ Camino de los Descubrimientos s/n, 41092, Sevilla, Spain*
[2]*High Temperature Processes Unit, IMDEA Energy, Av. Ramón de La Sagra, 3, 28935 Móstoles, Madrid, Spain*
Correspondence: mjerez@us.es

Abstract: A novel device for measuring concentrated solar fluxes using high-temperature optical fibers and photodiode-based radiometers is evaluated using a high-flux solar simulator based on Xenon arc lamps, showcasing promising results.

1. Introduction

Concentrating Solar Thermal Power (CST/CSP) is a dispatchable technology for large-scale clean electricity generation harnessing heat generated through solar energy concentration. However, this technique faces significant challenges, notably the difficulty in conducting proper plant operation monitoring [1]. In particular, conventional radiation measurement instruments are not suitable to determine continuously the value and distribution of the received radiation in solar tower technologies due to high temperatures (up to 1000 ºC) at the solar receiver [2].

To overcome these limitations, the use of high-temperature optical fibers installed in the tower receiver as a solar radiation collection element, coupled with photodiodes as radiation detection elements, emerges as a viable option to monitor incident concentrated sun light. An analogous setup was already successfully tested as a radiometer [3]. This configuration offers multiple advantages, such as spatial efficiency (reducing the needed sensor area in the receiver) and isolation of the measurement location from extreme temperatures. In this work, the proof of concept was tested at a high-flux solar simulator and results are presented.

2. Methodology

To test the feasibility of the proposed device, the KIRAN-42 high-flux solar simulator, located at IMDEA Energía, Madrid, Spain, was utilized. This facility features 7 Xe arc lamps arranged in an ellipsoidal configuration with elliptical reflectors, capable of achieving a flux up to 3.6 MW/m² at the focal point. Although, only two of the seven lamps were used in the experiments. A single lamp was able to provide a flux up to 300 kW/m^2, while when using the two lamps, outside the focal plant, a flux of 400 kW/m^2 was obtained. The optical fibers exposed to radiation were supplied by the company Engionic (https://www.engionic.de/) and were engineered to withstand temperatures up to 700 °C, protected with a special coating and placed within a steel capillary, with alumina filling the space between the fiber and the capillary itself, as shown in Fig. 1. The fibers retained for testing consisted of two specimens with 200 μm core diameter and 220 μm cladding diameter. One with gold coating (referred to as 200/220Au and shown in Fig. 1b) and the other with polyamide coating (referred to as 200/220PI and shown in Fig. 1c). Both had 0.22 numerical aperture (NA), resulting in a field of view (FoV) of 25º.

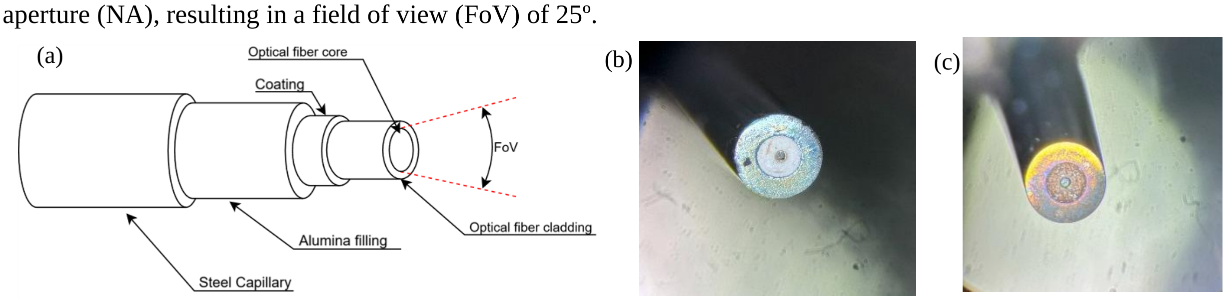

Fig. 1. (a) Schematic of the high-temperature optical fiber used for collecting concentrated flux;
(b) tip of 200/220Au fiber; and (c) tip of the 200/220PI fiber.

In the experimental setup, the optical fibers were exposed to radiation using an Inconel plate with two MK-125-A sealed connectors. The fiber passed through the plate and was covered with an alumina plate, ensuring that only a small section of the Inconel plate, containing the fiber terminals, was exposed. The fibers, at their non-exposed end, were connected to a THORLABS S140C silicon photodiode, which was in turn connected to an optical power meter for storage and subsequent processing of power traces, following the algorithm presented in [3]. Irradiance was also measured by a Gardon sensor, from Vatell Corporation. The sensor, coated with Pyromark 1200, can measure peak fluxes up to 1.6 MW/m² with a sensitivity of 0.062 mV/W/cm² and an accuracy of ±3%.

3. Results

The results obtained during the experiments demonstrated the viability of using this configuration for concentrated solar flux measurements, as showcased in Fig. 2. Although, the current setup still faces some challenges. Regarding static measurements, the 200/220Au fiber performed best, obtaining peak values of 194 kW/m² and 206 kW/m², against 173 kW/m² and 202 kW/m² for the 200/220PI fiber; with one and two lamps activated, respectively. However, recorded flux values were lower than the ones given by the Gardon radiometer, which were above 300 kW/m² for all cases.

The difference between the flux measured by the Gardon sensor and fibers is mainly attributed to the fiber NA, which despite being 0.22 and allowing coupling of all light from the central lamp, attenuates incident light at angles other than perpendicular [4]. The NA, however, allows practically no coupling of lateral light, which explains the minimal difference in fiber's measurements between operation with one or two lamps activated. Besides that, the extreme temperatures on the tip of the fiber and the connectors could also contribute to the loss of coupled optical power, as well as possible physical damage of the materials from subjecting the sensors to these conditions and their accelerated ageing due to exposure.

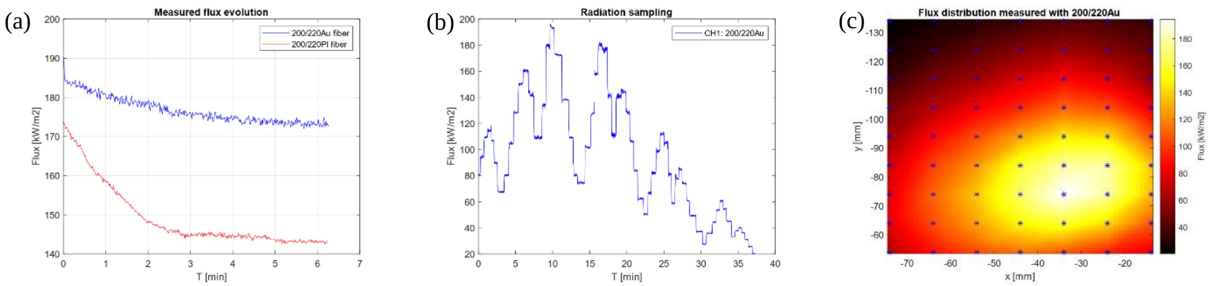

Fig. 2. Concentrated flux measurements: (a) evolution of the measured flux with both fibers for over 6 minutes; (b) sampling of the radiation received while moving fiber 200/220Au around focal area; and (c) flux distribution interpolated in the target from sampling and positions where the fiber was placed (blue dots).

Regarding the dynamic behavior of the measurements, both fibers exhibit a decline in the measurement from when the fiber's tip is placed at the light focus until stabilization, as shown in Fig. 2a, with less impact observed in the gold-coated fiber. The explanation provided for this phenomenon relates to the sample temperature: upon moving the fiber to the focus, a heating period of the Inconel plate and fiber connection begins, which coincides with the decrease in the measurement registered by the fiber, until stabilization occurs.

4. Conclusions

The results presented in this work demonstrate the feasibility of measuring concentrated flux using an optical fiber as a radiation collection element, measuring values surpassing 200 kW/m² in an environment of around 500 °C, although some challenges still need to be addressed. The measurements obtained fall short of those provided by the Gardon radiometer used as reference. This discrepancy may be due to multiple factors, notably the temperature dependence of the measurement and material degradation due to extreme operating conditions, as well as the limited numerical aperture of the fiber. Future work should focus on developing mechanisms to protect fiber tips from extreme environment and enhancing the field of view, with solutions that might include, but are not limited to, the use of diffusers and lenses, as well as reducing the measurements' temperature dependence.

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