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Optical design of a high radiative flux solar furnace for Mexico

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Abstract

In the present work, the optical design of a new high radiative flux solar furnace is described. Several optical configurations for the concentrator of the system have been considered. Ray tracing simulations were carried out in order to determine the concentrated radiative flux distributions in the focal zone of the system, for comparing the different proposals. The best configuration was chosen in terms of maximum peak concentration, but also in terms of economical and other practical considerations. It consists of an arrangement of 409 first surface spherical facets with hexagonal shape, mounted on a spherical frame. The individual orientation of the facets is corrected in order to compensate for aberrations. The design considers an intercepted power of 30 kW and a target peak concentration above 10,000 suns. The effect of optical errors was also considered in the simulations.

Keywords: Solar concentration; Segmented concentrator; Radiative flux; Solar furnace; Solar chemistry

1. Introduction

Modern solar furnace technology starts in the 1950s decade. The first research in these devices was directed towards studying the effects of high temperatures (around 3500 °C) on the properties of different materials exposed to highly concentrate solar fluxes (Glaser, 1958). Among their applications is the study of properties like thermal conductivity, expansion coefficients, emissivity, melting points (Hisada et al., 1957), and also the study of ultra refractory materials, determination of phase diagrams, crystal growth, and purification of materials. At the same time, methods for the measurement of high temperatures in receivers (Brenden et al., 1958), and the flux density of concentrated radiation (Loh et al., 1957) have been developed. The later have evolved and image digitalization techniques are used (Jonhnston, 1995), together with calorimetric techniques (Pérez-Rábago et al., 2006; Estrada et al., 2007).

Among the first furnaces built, were the furnace of Arizona State College in the USA, in 1956 (Kevane, 1957), and the furnace of the Government Institute for Industrial Research, in Japan (Hisada et al., 1957). Solar furnace technology has evolved, and larger furnaces have been built, like the one of the CNRS in Odeillo, France, with 1000 kW (Trombe and Le Phat Vinh, 1973); the furnace of the Academy of Sciences of Usbekistan, with 1000 kW (Abdurakhamanov et al., 1998); the furnace of Paul Scherrer Institute (PSI), of 25–40 kW (Schubnell et al., 1991); the furnace of CIEMAT, in Plataforma Solar de Almería, Spain, with 45 kW; and the furnace of DLR, in Cologne, Germany, of 20 kW (Neumann and Groer, 1996). More

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recently, a designs based on nonimaging optics has been developed (Chen et al., 2002; Lim and Li, 2009)

Mexico has an ideal position for the implementation of solar technologies, due to its favorable geographical location in the sunbelt of the planet. The estimated yearly average insolation is higher than 5.5 kW h/m^2 per day over the country. In particular, in the northwestern states this insolation can reach nearly 6 kW h/m^2 and has a very important component of beam solar radiation. This high quality solar resource makes that area ideal for the implementation of concentrating solar technologies (CST), either for electrical power generation or for the production of solar fuels as Hydrogen. With the aim of promoting the development of CST in México, the construction of a high radiative flux solar furnace (HRFSF) was proposed, as a tool for research and development in the field. This development is part of a larger project known as "National Laboratory for Solar Concentration Systems and Solar Chemistry", which involves also the development of a Heliostat Test Field and a Solar Photocatalytic Water Treatment Plant. Federal funding for the development of this infrastructure was approved by Consejo Nacional de Ciencia y Tecnología (CONACYT), and the project is now in progress, with additional funding from Universidad Nacional Autónoma de México (UNAM) and Universidad de Sonora (UNISON). The HRFSF is being developed in a 3 year period, starting from September 2007, by UNAM, in collaboration with Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE), and other institutions. The main applications of this infrastructure are expected to be in the areas of solar chemistry and solar materials processing (Fletcher, 2001).

Based on the information available in the literature and with the aim of building a highly concentrating system, the design targets for the HRFSF were set as follows: thermal power of 30 kW and peak concentration above 10,000 suns, producing a solar image of 10 cm diameter or smaller. In order to achieve the above targets, several possible configurations were analyzed and the optical characteristics of the system were optimized by means of ray tracing simulations.

There is little information in the literature regarding the detailed optical analysis of the existing furnaces and discussing the considerations and methods that led to their final optical design. In order to contribute to the understanding of the effect of different parameters and their interaction on the performance of high concentration solar devices, the procedures followed in the design of the HRFSF are discussed here. In the following, the results obtained for the different studied optical configurations are presented, and the effect of the different parameters is discussed.

2. Preliminary design

The project started with an initial proposal of a furnace with around 30 kW power. The sizes of the main components were determined from this restriction, resulting in a 36 m^2 concentrator and a 81 m^2, flat heliostat, located at 14 m distance from the vertex of the concentrator. Note that, because of the low latitude of the site chosen for the furnace (the city of Temixco, in the Morelos state; at 18° 50′ 20.81″ North), as compared with other existing facilities, a large heliostat is required to fully illuminate the concentrator during a sufficient number of hours: 3 h at least in the summer solstice, and 8 h in the winter solstice. Actually, winter is the best season for experimenting with highly concentrated radiation at the site.

Some solar furnaces like those at DLR or NREL have an off-axis configuration. In the present case it was decided to use a horizontal on axis configuration instead; i.e., one with the focus in the same axis joining the center of the concentrator and the vertex of the heliostat. This kind of configuration suffers from shadowing by all the structures located in the focal region, including the positioning table, but on the other hand, reduces off axis aberration effects. The effective focal distance of the concentrator was set to 3.68 m, in order to attain a near optimal numerical aperture for the system. In general, for a faceted concentrator this optimal value differs from that for an equivalent ideal paraboloid, as has been pointed out elsewhere (Riveros-Rosas et al., 2008, submitted for publication). Actually, it has been found the optimal numerical aperture depends strongly on both the size of the facets and their optical error.

It was decided that the concentrator would be fabricated as a faceted mirror, formed by polished, first surface, glass mirrors. This kind of mirrors was chosen because they easily provide the high optical quality required for the furnace and, at the same time, they can be manufactured with very good specifications in México. Because of fabrication cost considerations, spherical curvature is chosen for the mirrors. This implies that facets are not segments of a single larger parabola, but small independent mirrors instead. The shape of the facets was chosen to be hexagonal, because this geometry fills quite well the concentrator area, still being relatively easy to polish. From the point of view of filling the space, square facets would be an interesting option also, but they are much more difficult to polish adequately.

From the results reported by Riveros-Rosas et al. (2008, submitted for publication) about the influence of the number of facets in the concentration factor, it was sought that the concentrator had the largest practical number of facets. Therefore the size of the facets was chosen to be 40 cm apothem, on the basis of local fabrication capabilities and mounting considerations.

3. Methodology

With all the above conditions established, there are still several parameters which can be optimized for the system: the spatial distribution of the facets (geometry of the sup-