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Optical performance evaluation of a solar furnace by measuring the highly concentrated solar flux

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ABSTRACT

We evaluated optical performance of a solar furnace in the KIER (Korea Institute of Energy Research) by measuring the highly concentrated solar flux with the flux mapping method. We presented and analyzed optical performance in terms of concentrated solar flux distribution and power distribution. We investigated concentration ratio, stagnation temperature, total power, and concentration accuracy with help of a modeling code based on the ray tracing method and thereby compared with other solar furnaces. We also discussed flux changes by shutter opening angles and by position adjustment of reflector facets. In the course of flux analysis, we provided a better understanding of reference flux measurement for calibration, reflectivity measurement with a portable reflectometer, shadowing area consideration for effective irradiation, as well as accuracy and repeatability of flux measurements. The results in the present study will help proper utilization of a solar furnace by facilitating comparison between flux measurements at different conditions and flux estimation during operation.

1. Introduction

The solar furnace concentrates solar radiation usually up to thousands of suns and even above ten thousand [1]. It can serve as a heat source for solar thermal plants to produce electricity with conventional thermodynamic cycles or hydrogen through thermochemical processes. Currently, many worldwide research institutes take advantage of the solar furnace as a facility to develop key technologies required for high-temperature solar thermal applications [2–7]. Because the solar furnace allows temperature above 3000 K at an atmospheric environment, its application extends to emerging technologies such as space vehicle materials and nano-scale materials.

Generally, a combination of fixed parabolic reflectors and tracking flat reflectors enables high concentration in the solar furnace. Characterization and analysis of concentrated solar flux is crucial to performance evaluation of a solar furnace and its utilization. The so-called flux mapping method is a well-known approach to measurement of concentrated solar flux distribution [5,8–10]. In the flux mapping method, a CCD camera captures a bright image of the solar radiation scattered from a diffuse target surface, and the image is numerically converted to the solar flux distribution after calibration with a heat flux gage output or the total power to be delivered. Ulmer et al. [9] reported a good reference to details about the flux mapping method and measurement accuracy.

Concentrated solar flux distribution provides basic measures to represent optical performance of various concentrating systems; maximum and average values of concentration ratio that is defined as a ratio of concentrated solar flux to DNI (direct normal insolation), total power when concentrated solar flux distribution is integrated over a whole target surface, and stagnation temperature that is the highest attainable temperature for a blackbody absorber. Another important measure is concentration accuracy in terms of the standard deviation of surface slope errors [6,8]. However, its assessment is difficult because various error sources are involved and concentrated solar flux distribution does not determine it by itself. An indirect estimation approach is comparison between measurement and modeling [8,11]. If a representative parameter that accounts for slope errors of reflector surface is considered in a modeling algorithm, its fitting allows an estimation of concentration accuracy.

In the present study, we analyzed the solar flux concentrated by a solar furnace in the KIER (Korea Institute of Energy Research). We obtained main results with the flux mapping method and for comparison used a solar flux modeling code that is based on the ray tracing method. First, in regard to the flux mapping method, we investigated difference between the flux-gage-based calibration

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Nomenclature

AM	air mass
DNI	direct normal insolation
KIER	Korea Institute of Energy Research

and the total-power-based calibration. Then, we conducted measurements before and after adjustment of parabolic reflector facet positions and presented optical performance of the KIER solar furnace in terms of concentrated solar flux distribution, power distribution, and basic measures. Because shutters in front of the parabolic reflector play an important role in adjusting solar flux, we investigated solar flux estimations at different shutter opening angles by reducing the full opening results. We utilized a flux presentation in normalization for easy flux estimation during operation, and especially we paid attention to assessment of accuracy and repeatability of flux measurements. Such assessment will allow us to appreciate flux variability between measurements or between estimations.

2. Solar flux measurement system

Since we developed the KIER solar furnace (refer to Fig. 1a) in 2009, we have made modifications and improvements for better performance and operation. A flat reflector is comprised of aluminum-back-coated mirror facets, and its total area is 9.305×9.387 ($\sim$87) m^2. It tracks the sun in elevation and azimuth angle directions with two servo motors so that the reflected sunlight illuminates an indoor parabolic reflector parallel to the optic axis. Inner and outer radii of the parabolic reflector are respectively 0.75 m and 4.5 m so that its aperture area roughly becomes 62 m^2. Focal length is 4.98 m, and the corresponding rim angle becomes 48°. The parabolic reflector is also comprised of back-coated mirror facets, but coating material is silver. It is 35 m apart from the flat reflector to the south, and an array of rotating strip shutters is installed in between to adjust the amount of solar radiation. Sunlight blockage occurs due to reflector facet frames, shutter thicknesses, stage supporting structures, and so on. As a result, the effective aperture area in the parabolic reflector is reduced to approximately 85% of the designed area. A movable stage to accommodate solar receivers or chemical reactors lies around the focal point. As shown in Fig. 1b, a target surface for flux measurement can be installed at the stage as well.

Fig. 2 illustrates a schematic diagram of the flux mapping system installed in the KIER solar furnace. Essential components are a heat flux gage, a diffuse target surface, a CCD camera, and a computer for monitoring and data acquisition [7]. A CCD camera captures an image of concentrated solar flux after scattering from the diffuse target surface. Conversion from a pixel gray level to a numerical value makes a distribution of image brightness become a two-dimensional numerical matrix. This numerical matrix is proportional to solar flux distribution because of diffuse scattering and linearity between flux and brightness. The distribution is calibrated according to a reference measurement with the heat flux gage. Additionally the measurement system includes a portable reflectometer and a pyrheliometer so that solar flux results can be normalized to that of the designed condition and solar fluxes in other applications can be easily estimated from the normalized data.

We made use of the Gardon-type circular foil radiometer [12] as a heat flux gage thanks to its fast response and handiness. The Gardon radiometer consists of a thin circular foil and a heat sink surrounding foil circumference. The foil is coated with black Zynolyte for high absorption and exposed to heat flux. A measured voltage difference between foil center and heat sink yields a temperature gradient, and thereby a heat flux is calculated by solving a heat transfer equation under the assumption of uniform irradiation over the foil surface. Therefore, it is desirable that the radiometer is placed as much at the central peak of solar flux as possible even if flux distribution arriving on radiometer surface is not uniform. We selected a Thermogage-1000 model radiometer from Vatell Co., whose diameter of exposure is 25.4 mm. Because circulating water from a chiller cools the radiometer, this model is capable of measuring up to 5 MW/m^2. Previous studies evaluated radiometer

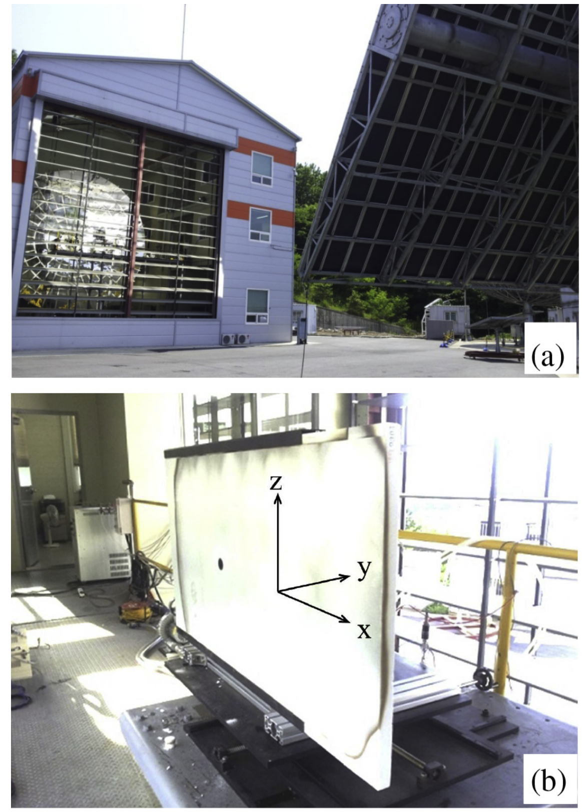

Fig. 1. Pictures of (a) the KIER solar furnace and (b) the target surface with a radiometer in the flux mapping system.

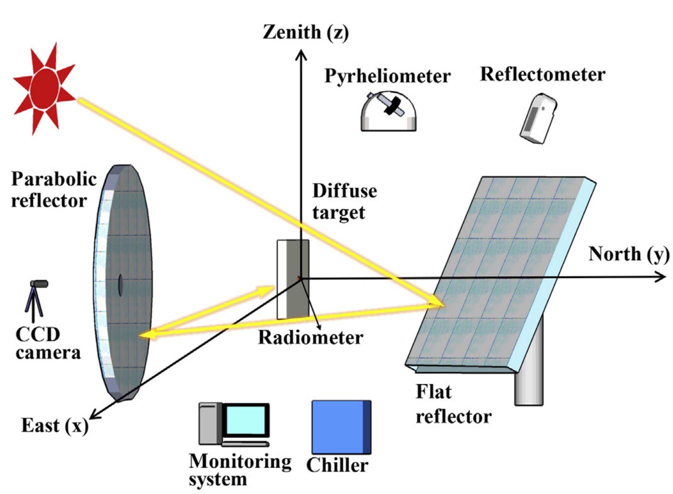

Fig. 2. Schematic diagram of the furnace and the flux mapping system.

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