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# Flux distribution of solar furnace using non-imaging focusing heliostat

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**Abstract**

This paper discusses on the flux distribution of a quasi-single stage solar furnace which consists of a non-imaging focusing heliostat as the primary stage and a much smaller spherical concentrator as a secondary. As the optics of the primary stage heliostat is of non-imaging nature, the analytical method for studying the flux distribution of the hot spot of this type of solar furnace would be complicated. Therefore, a digital simulation approach has been employed. Flux distributions of the hot spot for several different incident angles, which have covered all the extreme cases of operating conditions have been simulated. Simulation result shows that a solar furnace using an $8 \times 8$ m non-imaging focusing heliostat with 289 mirrors coupled with a spherical concentrator with 0.7 m aperture and 27 cm focal length is theoretically capable of achieving flux concentration of 25,000 suns. Concentration contours of flux distribution for several interesting cases are presented, the different working areas of high flux footage from 5000 to 15,000 suns have been compiled.


*Keywords:* Solar furnace; Flux distribution; Spinning-elevation; Heliostat

## 1. Overview

Solar furnace has two types of configurations: a moving target type and a fixed target type. For the convenience of application, e.g., melting of silicon for purification, a fixed target type is preferred. A fixed target type of solar furnace usually consists of two parts, a heliostat as the primary stage and a concentrator as the secondary stage (e.g., a parabolic dish) with aperture size close to the reflection area of the heliostat. This type of solar furnace is expensive and is usually owned and managed by renown research institute such as the solar furnace at PSI, DLR, Sandia Laboratory etc. One of the reasons why solar furnace is expensive is that the aperture size of the concentrator must match the size of heliostat because the reflection of heliostat is of parallel or near parallel nature. The construction of a large aperture concentrator is expensive in the present days because of the need for large area of imaging optics and the requirement of high rigidity steel structure. Such object would be difficult for mass production in the near future.

However, it would be interesting to ask why we must use a large aperture second stage if we can make the heliostat a focusing device. With a focusing heliostat, the second stage can be made much smaller, e.g., 50 times smaller, than the collection area of heliostat. A small size concentrator would be very much easier to fabricate, thus much cheaper. The major challenge of incorporating a focusing heliostat into a solar furnace would be the control of the off-axis aberration of heliostat following the change of incident angle during sun tracking. The reduction of

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off-axis aberration could be achieved by using a target-aligned heliostat with a reflection surface constitutes of two radii of curvature as first proposed in Markus and Harald (1990), Zaibel et al. (1995) and in Steinfeld and Schubnell (1993). Meanwhile, the principle and practice of non-imaging focusing heliostat (similar to the target-aligned heliostat) was independently developed by Chen et al. A non-imaging focusing heliostat could be a good approach to "scale down" the size of secondary stage without sacrificing the collection power. Using a non-imaging focusing heliostat as the primary stage and a small parabolic concentrator as the secondary stage, a 2 × 2 m prototype of high temperature solar furnace has been constructed as reported in Chen et al. (2002).

The principles of non-imaging focusing heliostat which employs a spinning-elevation tracking mode were first disclosed in Chen et al. (2001). The reports of the thorough implementation the new tracking formulae into a working prototype and its applications have been narrated in Chen et al. (2002) while a detailed discussion of the off-axis aberration and its first order corrections for non-imaging focusing heliostat have been presented in Chen et al. (2003). Finally, Chen et al. (2006b) presents the generalization of the new tracking formulae and the discussion of the special cases of the general formulae.

Throughout the series of report from year 2001 to 2006 on the development of non-imaging focusing heliostat, the analysis of the optical performance in terms of flux concentration, particularly for the application of solar furnace has not been published. It is the aim of this paper to do the job, which result could be of great interest for engineers and scientists in the related field.

## 2. Principle of the new solar furnace

### 2.1. An overview of spinning-elevation tracking mode

The new solar furnace consists of a non-imaging focusing heliostat and a spherical concentrator. A non-imaging focusing heliostat is a heliostat which reflector comprises $N$ rows and $M$ columns of facet mirrors and its tracking methodology employs a spinning-elevation tracking mode. Fig. 1 describes in brief the optical configuration of a non-imaging focusing heliostat and the tracking formulae. The derivations and discussion of the tracking formulae can be found in Chen et al. (2001) and Chen et al. (2006b).

The spinning-elevation tracking formulae are

$$\beta_H = \arcsin\left(\frac{\begin{array}{c}1-\sin\lambda(\cos\Phi\cos\delta\cos\omega+\sin\Phi\sin\delta)-\cos\lambda\sin\phi\cos\delta\sin\omega\\ +\cos\lambda\cos\phi(-\sin\Phi\cos\delta\cos\omega+\cos\Phi\sin\delta)\end{array}}{2\cos\theta_i}\right), \tag{1}$$

$$\theta_i = 0.5\arccos\left[\begin{array}{c}-\sin\lambda(\cos\Phi\cos\delta\cos\omega+\sin\Phi\sin\delta)-\cos\lambda\sin\phi\cos\delta\sin\omega\\ +\cos\lambda\cos\phi(-\sin\Phi\cos\delta\cos\omega+\cos\Phi\sin\delta)\end{array}\right], \tag{2}$$

$$\theta_H = \frac{\pi}{2} - \arcsin\left(\frac{\begin{array}{c}1-\sin\lambda(\cos\Phi\cos\delta\cos\omega+\sin\Phi\sin\delta)-\cos\lambda\sin\phi\cos\delta\sin\omega\\ +\cos\lambda\cos\phi(-\sin\Phi\cos\delta\cos\omega+\cos\Phi\sin\delta)\end{array}}{2\cos\theta_i}\right), \tag{3}$$

$$\rho_H = \arcsin\left(\frac{-\cos\phi\cos\delta\sin\omega+\sin\phi(\sin\Phi\cos\delta\cos\omega-\cos\Phi\sin\delta)}{2\cos\theta_i\cos\beta_H}\right) \tag{4}$$

where $\phi$ is facing angle, $\lambda$ is target angle, $\omega$ is hour angle, $\Phi$ is the local latitude at which the heliostat is installed, $\delta$ is Sun's declination angle, $\theta_i$ is the incident angle of sunray on the reflector of heliostat, $\rho_H$ is the spinning angle for one of the tracking shaft and $\theta_H$ is the elevation angle for another tracking shaft.

### 2.2. The optical configuration of new solar furnace

The implementation of spinning-elevation tracking mode in the application of a solar furnace can be of the following model as shown in Fig. 2.

The reflector of the new heliostat consists of $N$ rows and $M$ columns of mirrors arranged in a matrix. Each mirror can be a flat mirror, a spherical mirror or even a hyper-geometry mirror as disclosed in Chen et al. (2006a). For the case of the new solar furnace, all mirrors are spherical with the same radius of curvature and all are aimed at the center of the target. In this case, the spherical surface is chosen because it is easier to fabricate though the parabolic surface can also be used with similar performance. The orientations of these mirrors are actively controlled in rows and columns tilting movement manners according to the first order aberration correction formulae (Chen et al., 2001) as the following:

$$\gamma_m = \frac{1}{2}\arctan\left(\frac{H_m}{L\cos\theta}\right), \tag{5}$$