Solar Energy 135 (2016) 253–264

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Latitude-orientated mode of non-imaging focusing heliostat using spinning-elevation tracking method

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ARTICLE INFO

Article history:
Received 24 December 2015
Received in revised form 8 May 2016
Accepted 23 May 2016

Keywords:
Non-imaging focusing heliostat
Latitude-orientated
Canting
Solar thermal energy

ABSTRACT

A comprehensive study of the latitude-orientated configuration of non-imaging focusing heliostat (LO-NIFH) is reported. In this configuration, we have made the sun tracking formulas of a non-imaging focusing heliostat (NIFH) to be independent of the latitude where it is installed; hence we name it a latitude oriented non-imaging focusing heliostat or LO-NIFH. With the new configuration, the LO-NIFH introduces certain potential advantages in field applications; such as offering a standard in mechanical/optical designs, simplifying the mechatronic control schemes, offering high modularity and high scalability in both production and project implementation. One of the most important merits of latitude oriented configuration is that it makes a heliostat operating at a very narrow range of incident angles in a day; for instance, incident angles ranging from 0° to 52° for 14 h of tracking time per day. When a NIFH tracks the sun at a moderately small incident angle, it always makes a reasonably small focused spot (at the target) with a high optical efficiency above 88% at a *f/D* ratio of greater than 1. For an off-axis solar concentrator, such level of optical efficiency is considered very impressive as it is just 10% less than that of on-axis parabolic dish. We found that the astigmatic spread of a working LO-NIFH has little variation with time as compared to that of a spherical reflector operating in off-axis manner. Computer simulation of the focused spot images was conducted and compared with the spot images photographed at the site of a prototype LO-NIFH with an array of 5 × 5 mirror facets tracking at an incident angle of 23°.

1. Introduction

Non-imaging optics, a concept in geometrical optics that does not emphasize on perfect image formation, has been widely adopted in the designs of solar concentrators that have special requirements for the focused spot geometry, size and level of concentration but not the sharpness of the image of the sun. In literature, non-imaging solar concentrators, particularly those having large reflective areas, are usually categorized by two types of designs based on how the optical alignment is kept during sun tracking operations; i.e. the on-axis tracking design (Chong et al., 2010, 2009; Siaw et al., 2014; Tan et al., 2014; Wong et al., 2015; Yew et al., 2015), and the off-axis tracking design (Chen et al., 2001, 2002, 2003, 2005, 2004, 2006a, 2006b; Roos et al., 2007; Guo et al., 2007; Chong et al., 2010, 2011; Chong and Tan, 2011, 2012; Chong, 2010a, 2010b). Each type of design stands on its own merits. We will concentrate on the latter in this article. There are numerous merits of using non-imaging optics with segmented mirror facets in concentrating solar power system. Firstly, as the application does not require formation of perfect image, it enables greater flexibility in the selection of mirror facets in the concentrator design, such as the type and the size of mirror; hence it can allow further optimization to simplify the installation, handling, transportation, and production. Secondly, the non-imaging design of a solar concentrator that is consisted of many mirror facets provides the flexibility of on-site adjusting the focal point as well as the pattern of the focused spot by simply canting all the mirror facets to the appropriate tilted angles. Hence, the solar flux distribution profile can be tailored towards a specific need via the said mirror canting process.

For on-axis tracking design, the astigmatic aberration of non-imaging solar concentrator does not vary with time throughout the entire tracking range. On the other hand, for off-axis tracking design, there is a significant change of image size and pattern caused by astigmatic aberration from time to time because the incident angle between the incident sun ray and the normal of the mirror facet changes continuously during sun-tracking (Igel and Hughes, 1979).

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http://dx.doi.org/10.1016/j.solener.2016.05.038

As an extension to the second point, the NIFH allows canting or pre-tilting of the initial positions of mirror facets to focus at any chosen incident angle, which we call it the operational incident angle, and remain reasonably good focusing even when Sun incident angle moderately deviates from the canting angle; thereby to obtain an optimal annually average spot size which is significantly smaller than those attainable by other off-axis concentrator with axially symmetry geometry, such as a spherical concentrator or a paraboloid concentrator.

To actively correct astigmatic aberration, it will require $2 \times M \times N$ actuators for a heliostat with an array of $M \times N$ mirror facets. For a heliostat field involving hundreds to thousands of azimuth-elevation tracking heliostats (Vant-Hull and Hildebrandt, 1976; Schramek and Maass, 2010), it is obviously not realistic to implement an active astigmatic correction mechanism because it will be too expensive in terms of capital cost, maintenance cost and long-term reliability. The NIFH proposed by Chen et al. (2001) is a spinning-elevation tracking heliostat in which all the mirror facets in the same tangential or sagittal group can be adjusted to certain angles in such a way that the astigmatic solar images at the target can be actively corrected during sun-tracking. The spinning-elevation tracking method, also named as the target-aligned tracking method by Ries group (Ries and Schubnell, 1990; Zaibel et al., 1995; Roos et al., 2007; Buck and Teufel, 2009; Pfahl, 2014), allows a welcoming reduction in the amount of actuators from "$2 \times M \times N$" to only "$M + N - 2$" because it keeps the tangential and sagittal directions fixed with respect to the heliostat frame during the sun-tracking. Although the sharing of actuators cannot perfectly correct the astigmatic aberration, it does not sacrifice quality of the concentrated sunlight by much, especially the solar concentration ratio of a system. To achieve high solar concentration ratio, Chen et al. (2002, 2005, 2009, 2010) had demonstrated that a secondary concentrator of a relatively small size coupled with a primary NIFH was sufficient for a solar furnace system to achieve temperature as high as 3450 °C.

The idea of a fixed geometry NIFH by omitting active astigmatic correction was first proposed by Chen et al. (2004) for the application in the heliostat field of a central tower system. In the study, cost saving can be achieved via canting the mirror facets of each heliostat in a fixed geometry that is optimized based on annual variation of incident angles and the spillage losses of the receiver at the central tower. Buck and Teufel (2009) conducted extended study of canting method for four types of heliostats in different kind of heliostat fields. Landman and Gauché (2014) further investigated on canting method using analytical method. All the aforementioned studies have concluded that the ideal facet canting can effectively improve the optical efficiency of target-aligned heliostat by reducing the annual variation of astigmatic aberration.

Despite a great reduction in astigmatic aberration being achieved in central tower system, it is not a modular design and the optical alignment of heliostats is labor intensive during installation because each heliostat has unique orientation and canting angles (i.e., unique target distance, facing angle and target angle). For mass production, modular design of solar concentrator is always preferred for the good reasons of simplicity in production line and project implementation. Chen et al. (2006a) outlined two special orientations of NIFH designs that have good potential to be used in modular way for solar energy application: latitude-orientated NIFH and polar-orientated NIFH. In this paper, the authors would like to report the comprehensive characteristic study of a latitude-orientated configuration of NIFH in the theoretical aspect.

2. Sun-tracking formulas

The direction of incident sunrays relative to the reflector, or simply cosine of incident angle of the sun rays is the major factor that impacts the optical efficiency of a heliostat, η_{opt}. The sun incident angle can be expressed in a function of hour angle (ω), declination angle (δ), latitude angle (Φ), and orientation angles of the heliostat (facing angle, ϕ, and target angle, λ). The average annual optical efficiency is the yearly integration of the optical efficiency function, η_{opt}, for every tracking moment divided by the total tracking time. According to Chen et al. (2003), the size of the primary focused spot of a NIFH is dependent on the incident angle while the advantage of having a smaller focused spot is that it allows the use of smaller receiver or even miniaturizing the secondary optics for the high concentration applications. Consequently, it is essential for the NIFH to operate in the narrowest range of incident angles annually in order to have the smallest range of motion and hence to obtain the highest optical efficiency.

Fig. 1 illustrates the orientation of a target (receiver) relative to the tracking shafts of a NIFH that can yield the maximum annual optical efficiency by attaining a narrowest range of incident angles throughout a year. This condition is clearly achieved if the target is located in such a way that it stays aligned in between the center of a NIFH and the sun during solar noon of equinoxes. We are calling a NIFH configured in such orientation a latitude-orientated non-imaging focusing heliostat or LO-NIFH. Unlike the general NIFH or the traditional heliostat, the LO-NIFH is always paired with an individual and spatially fixed target to form a new configuration of one-NIFH-one-receiver design as opposed to conventional design of many heliostats surrounded a central receiver.

The latitude-orientated configuration is a special configuration of NIFH heliostat with the target angle and the facing angle fulfilling the following criteria (Chen et al., 2006a):

$$\lambda = 90^\circ - \Phi \tag{1}$$

$$\phi = 180^\circ \tag{2}$$

where λ is the target angle of the heliostat ($\lambda = 0^\circ$ if the height of the heliostat is same level as the target; it is a positive value if the target is higher than the heliostat central and vice versa), and ϕ is the facing angle of the heliostat ($\phi = 0^\circ$ when the heliostat is due south of the target; it is positive if the spinning-axis is rotated about zenith-axis in clockwise direction and vice versa).

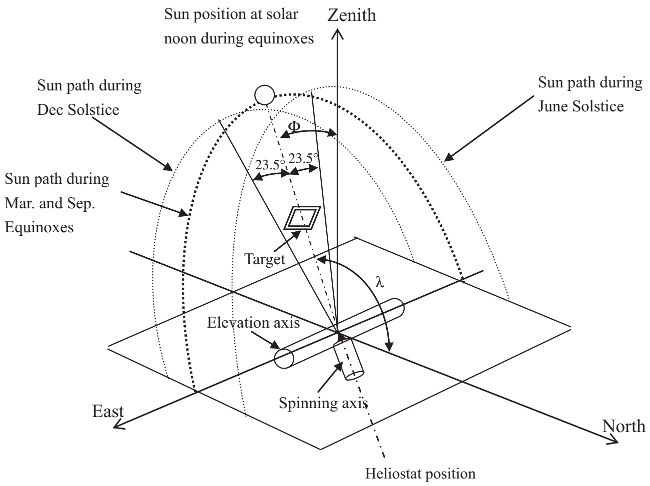

Fig. 1. The schematic diagram shows how to determine the best orientation of the heliostat that yields maximum annual optical efficiency. Latitude orientated non-imaging focusing heliostat (LO-NIFH) has been found to be the only configuration having the least variation of incident angle throughout the year and hence the most efficient off-axis design. In this configuration, target is located in such a way that it stays aligned in between the center of a NIFH and the sun during solar noon of equinoxes.