Calculation of optical efficiency for the first central-receiver solar concentrator system in Korea


Abstract

In 2011, the first Korean central-receiver solar thermal plant of 200 kWc was developed as a government research project. Its solar field consists of 450 heliostats in the northern half to a 49 m tall tower, and each heliostat is made of 4 flat mirror facets with a 1 m² reflecting area. In this paper, we present its optical efficiency calculated with a Monte Carlo ray-tracing code. The code enables to break down the optical efficiency into its six components, that is, cosine, air transmission, shadowing, reflectivity, blocking, and spillage, while taking into account the solar limb darkening without circumsolar radiation as well as reflector surface slope error. We carried out calculations at specific times on summer and winter solstices and autumn equinox. Negligible block efficiency demonstrates that the no-blocking heliostat field layout is well realized. The shadowing efficiency, which is due mainly to the tower rather than neighboring heliostats, is also insignificant except winter solstice. Net optical efficiency is best on autumn equinox but worst on summer solstice mainly because of the cosine efficiency.

Keywords: central-receiver system; heliostat; Monte Carlo ray tracing; optical efficiency; solar concentrator

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1. Introduction

The concentrated solar power (CSP) technology collects solar radiation energy, heats up a working fluid to drive an engine or turbine, and then produces electricity. Because solar radiation flux is too low to heat up a working fluid, concentration of solar flux is essential. There are generally four types of solar concentrators: parabolic dish, parabolic trough, central-receiver, and linear Fresnel. Out of them the central-receiver system (CRS) is technically most difficult to evaluate and design, but it is believed to have high potentials of improvement in the future [1]. The era of hundreds-megawatt-scale central-receiver solar thermal plants has recently begun [2], and thereby significant cost reduction of CSP plants is anticipated.

In 2011, for the first time, a project to develop a central-receiver solar thermal plant in Daegu, Korea (refer to Fig. 1) was completed [3]. This research-oriented project targeted 200 kW electricity generation with an open-air solar receiver using porous ceramic material and a steam turbine after heat exchange. Most components were designed, developed, and manufactured by domestic participants so that they could upgrade their competence in solar thermal area. Since the project, we have developed a Monte Carlo ray-tracing code to model optical performance of CRS solar thermal plants. This paper presents optical efficiency calculations for the first Korean central-receiver solar thermal plant.

Fig. 1. View of the first central-receiver solar thermal plant in Korea.

2. Korean central-receiver solar concentrator system

The central-receiver CSP project was supported by the R&D government program of renewable energy in Korea, and it lasted from December 2008 to September 2011 for 34 months [3]. The project pursued a solar thermal plant of 200 kW electricity generation. An open-air solar receiver using porous ceramic material was developed, and superheated steam was produced via heat exchange. In this paper, only the concentrating system is of interest, so a brief description about it is presented below. The concentrator field consists of 450 heliostats in the northern half to a 49 m tall tower, as shown in Fig. 2. In design of the heliostat field layout, an important strategy was to maximize optical efficiency, and thus no-blocking field was adopted [4, 5]. Due to land area restrictions, the field is not strictly rectangular. Heliostat radial distances to the tower range from 43 m to 120 m, and the angular span was set to 45°.

Each heliostat (refer to Fig. 3) is made of 4 flat mirror facets with a 1 m² reflecting area. The mirror facets are tilted to reduce the concentrating area of heliostat such that the four corner vertices of a heliostat can approximate parabolic dish with a focal length to the receiver center. Note that the tilt angle for a specific heliostat changes according to its position in the field. Nevertheless, slight tilt angles for all the heliostats are very small and result in the substantial heliostat aperture area of 2x2 m², which sums up to 1,800 m² reflecting area for the field. The reflecting surface is made of silver back-coated low-iron glass, whose solar-weighted reflectivity is 0.93. Individually controlled heliostats
focus sunlight on the 2x2 m$^2$ receiver surface installed at 43 m height. The receiver was mounted at a tilt angle of 25° downward.

![Fig. 2. Heliostat layout in the solar field [3].](image)

![Fig. 3. Picture of heliostats.](image)

### 3. Calculation of optical efficiency

A well-known tool to model solar flux distributions is the Monte Carlo ray-tracing method, in which a large number of rays are generated and traced while undergoing optical events such as reflection and absorption until they leave the system of interest [6, 7]. Finally, statistical averaging of total ray-tracing results yields solar flux distribution and optical efficiency. We developed a Monte Carlo ray-tracing code to model optical performance of central-receiver concentrator system [8]. Careful attention was paid on enabling detailed analysis of various optical efficiencies in order to facilitate potential improvements of the solar field. Therefore, various effects such as the solar limb darkening without circumsolar radiation [9], the cosine effect, air transmission [10], shadowing by tower and neighboring heliostats, blocking by neighboring heliostats, reflector surface slope error, and spillage on receiver are considered. Especially, laborious efforts were made to account for shadowing and blocking rigorously and efficiently using the hierarchical grouping technique [11]. Direct normal insolation (DNI) model is not applied yet, and instead its value is set to a constant of 1000 W/m$^2$. The direction of sun rays and the considered effects are independent of the solar insolation value in the current code, and the following calculations are purely geometry-dependent. Because we measured neither surface slope error nor concentrated flux, an accurate value of surface slope error is not possible.
However, we paid special attention on development and control of the concentration system, and we experienced temperatures high enough to melt ceramic receiver materials. Therefore, we assumed the standard deviation of surface slope error with a reasonably small value of 2 mrad in this paper.

Figure 4 shows optical efficiency variations on several notable days. Overall the optical efficiency of the Daegu plant is quite good because the gap between heliostats is large according to the no-blocking field layout design. Modeling results confirm that blocking losses do not occur. In the same context, shadowing effects are not significant while occurring on winter solstice solely by the tower rather than neighboring heliostats. Generally, net optical efficiency is best on autumn equinox whereas worst on summer solstice. The most dominant factor to affect net efficiency is the cosine effect. On summer solstice, zenith angles of sun are usually high, and thus the cosine loss becomes larger. Note that reflectivity loss is constant and transmission loss is also constant because it depends only on the heliostat distance from the receiver.

![Fig. 4. Optical efficiency variations.](image)

![Fig. 5. Optical efficiency distribution at 12 AM on summer solstice.](image)
A feature of the developed code is to display optical efficiency distribution in the solar field. Figure 5 and 6 show optical efficiency distributions at 12 AM on summer solstice and at 2 PM on winter solstice. From Fig. 5, it is obvious that the tower does not shadow any heliostat. Heliostats near to the tower have better efficiency than distant ones because air transmission and spillage efficiencies get worse in proportion with distance. As shown in Fig. 4, in terms of the optical efficiency of the field, i.e. mean efficiency of all the heliostats, the two cases in Fig. 5 and 6 have similar efficiencies (0.704 vs. 0.691). However, the two distributions heliostat by heliostat are totally different. At 2 PM on winter solstice, relatively cosine efficiency is better as in Fig. 6, but tower shadowing offsets the efficiency gain.

As mentioned before, the current code uses a constant solar insolation value. The calculated solar flux value is therefore far from reality, but the flux value can be interpreted as concentration ratio. Figure 7 shows peak and mean values of concentration ratio. Concentration ratio values do not change significantly. Maximum peak value is 756 sun
at 12 AM autumn equinox whereas minimum is 703 sun at 2 PM winter solstice. On the other hand, mean value ranges from 311 sun to 333 sun.

4. Summary

We numerically investigated optical efficiencies of the first Korean central-receiver solar power plant with a Monte Carlo ray-tracing code. The code enables to break down the optical efficiency into its six components, that is, cosine, air transmission, shadowing, reflectivity, blocking, and spillage, while take into account the solar limb darkening without circumsolar radiation as well as reflector surface slope error. Calculation results on summer and winter solstices and autumn equinox demonstrate that the no-blocking heliostat field layout is well realized and the shadowing efficiency is also insignificant except winter solstice. Optical efficiency is best on autumn equinox but worst on summer solstice mainly because of the cosine efficiency. Meanwhile, concentration ratio does not change significantly. Peak value ranges from 703 sun to 756 sun when the standard deviation of surface slope error is 2 mrad.

Acknowledgements

This work was conducted under the framework of Research and Development Program of the Korea Institute of Energy Research (KIER) (B4-2481-08, B4-2425).

References