Optik 125 (2014) 1106–1112

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Comparison of different types of secondary mirrors for solar application

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ARTICLE INFO

Article history:
Received 22 March 2013
Accepted 28 July 2013

Keywords:
Solar
Two-stage concentrator
Secondary mirror
Optical analysis

ABSTRACT

Two-stage solar concentrators make solar beams downwards providing flexible choices for energy utilization. Five types of secondary mirrors (a flat mirror, an ellipsoidal mirror, a hyperboloidal mirror with upper/lower sheet and a paraboloidal mirror) are compared. Effects of geometry parameters and concentrator precisions on the optical performance are analyzed using Advanced System Analysis Program. The results indicate that concentrators with a flat mirror or hyperboloidal mirror with lower sheet are more sensitive to rim angle or relative location. The secondary mirror is better a convex surface especially when rim angle is more than 90°. A flat mirror or hyperboloidal mirror with lower sheet performs better with higher redirect focal points. A hyperboloidal mirror with upper sheet is the best however numerical aperture changing. The intercept factors decreased with the increase of random errors or optical errors. Both the fabrication and assemblage requirements for a concentrator with a hyperboloidal mirror with lower sheet are the strictest. Experiments are carried out based on a hyperboloidal mirror with upper sheet. The experiments results are in accordance with the ray-tracing results. Therefore, further studies on optimization of the two-stage concentrators using the ray-tracing model can be conducted.

1. Introduction

Concentrating is an efficient way to improve the solar energy density [1–3]. Two-stage concentrators are introduced into the concentrated solar power (CSP) systems for more flexible structures, e.g. with an upward-facing receiver [4] or convenient heat storage arrangement [5], for higher concentration ratios, e.g. compound parabolic concentrator (CPC) [6,7], or for efficient power delivery [8] and so on.

Two-stage concentrators in CSP have attracted an increasing attention since 1976. Rabl [9] proposed a flat Fresnel "tower reflector" in a power tower system to avoid excessive thermal losses and conducted the optical analysis mathematically. Mauk et al. [5] simulated the performance of a Cassegrain type solar collector for chemical energy storage using an off-axis optics method and found that the focal length of the hyperboloid was not an important factor. Feuermann et al. [10] characterized a purely imaging two-stage solar concentrator using a complementary Cassegrain concentrator and evaluated the potential improvements with secondary concentrators. A solar fiber-optic mini-dish concentrator using a flat mirror to redirect rays was also designed and demonstrated experimentally by Feuermann et al. [4,8]. The min-dish concentrators were also designed and estimated in concentrating photovoltaic systems [11]. Karabulut et al. [12] conceptually described a system consisting of a parabolic dish and a Stirling engine mounted at the bottom using a double reflection mechanism. Chen et al. [13,14] simulated a dish system with a hyperboloid or ellipsoid mirror using a ray tracing method and found an ellipsoidal mirror is slightly better than that with a hyperboloidal mirror. Jiang et al. [15] analyzed a nondimensional optical model for a two-stage parabolic trough concentrating photovoltaic/thermal system using a parabolic beam splitting filter to evaluate the local radiation flux density distribution on the elements' surfaces. Kribus et al. [16], Segal et al. [17] and Suzuki [18] have offered related simulation work on solar tower reflector adopting hyperboloid or ellipsoid, respectively.

A secondary mirror plays an important role in a two-stage system. Representative secondary mirrors include flat mirrors [4,8,11], ellipsoidal mirrors (the Gregorian system) [13,17], hyperboloidal mirrors with upper sheet (the Cassegrain system) [5,13,14,16,17], hyperboloidal mirrors with lower sheet (the Complementary Cassegrain system) [10] or paraboloidal mirrors [15,19]. They have been researched individually but less comparison has been done. This work tries to compare five representative types of secondary mirrors based on a dish using Advanced System Analysis Program (ASAP) software provided by Breault Research Organization. ASAP has been widely used in the simulation of optical systems. Effects

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0030-4026/$ – see front matter © 2013 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2013.07.113

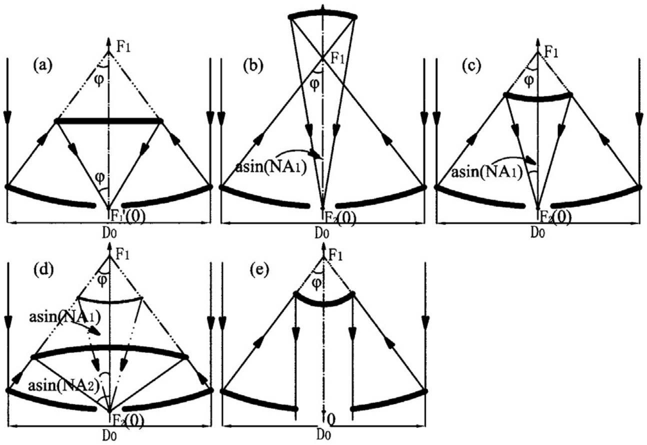

Fig. 1. Five types of two-stage concentrators (a) plane (b) ellipsoid (c) hyperboloid with upper sheet (d) hyperboloid with lower sheet and (e) paraboloid.

of geometry parameters and concentrator precisions on the optical performance are discussed and compared. Experiments are carried out using a hyperboloidal mirror with upper sheet as the secondary mirror.

2. Optic description

2.1. System description

Schematica of two-stage systems with different types of reflectors are shown in Fig. 1. Rays parallel to the optical axis are first reflected by a primary dish (PD) to a secondary mirror and then are redirected by the secondary mirror. If the focal point of secondary mirror is coincident with that of PD (F_1), rays reflected from secondary mirror would be redirected and focus onto its second focal point (F_2/F_1') in Fig. 1(a)–(d) or still parallel to the optical axis in Fig. 1(e).

For a flat mirror system (FS), redirected focal point (F_1') is just image of the focal point (F_1) of PD, as shown in Fig. 1(a). A bigger secondary mirror is needed when a lower F_1' is wanted. For an ellipsoidal mirror system (GS), a hyperboloidal mirror with upper sheet system (CS) or a hyperboloidal mirror with lower sheet system (CCS), the redirected focal point is, respectively, the second focal point (F_2) of the conic, as shown in Fig. 1(b)–(d). Here we define CS and CCS have common upper and lower focal points, so secondary mirror of CCS would be bigger than that of CS. For a paraboloidal mirror system (PS) in Fig. 1(e), rays redirected by a paraboloidal mirror whose focal point is just falling on F_1 are still parallel to the optical axis of PD.

2.2. Mathematic analysis

A two-stage concentrator includes a PD and a secondary mirror. Rim angle of the PD (φ) and numerical aperture of the secondary mirror (NA_1/NA_2) are defined as follows:

$$\varphi = a\tan\left(\frac{8}{16(f_p/D_0)-(D_0/f_p)}\right) \tag{1}$$

$$NA_n = \sin\ \theta_n \quad (n = 1, 2) \tag{2}$$

where f_p, D_0 and φ denote the focal length, aperture diameter and rim angle of PD, respectively. θ_1/θ_2 is the half-angle of the maximum cone of light that can enter or exit the secondary mirror, as shown in Fig. 1. For FS, $\theta_1 = \varphi$.

The relative location of the redirected focal point F_2 (F_1') is defined as follows:

$$m = \frac{OF_2}{f_p} \tag{3}$$

When F_2 (F_1') is between the focal point (F_1) and vertex (O) of the PD, i.e. $0 < m < 1$; when F_2 (F_1') is just at the vertex (O) of the PD, i.e. $m = 0$; when F_2 (F_1') is below the vertex (O) of the PD, i.e. $m < 0$. For PS, the redirected focal point is at infinity, so m is defined as relative location of a paraboloidal mirror here.

For a two-stage concentrator based on a dish with given diameter D_0 and rim angle φ, shape parameters of secondary mirror could be calculated out when m and NA_1 are restricted. Parameters of secondary mirrors are list in Table 1. Geometry structure of the concentrator could be generated by Excel and MATLAB codes.

3. Comparison and discussion

Five types of secondary mirrors are discussed and compared at different cases based on a given PD here. The simulation assumptions are made as follows [13,14]:

(a) The incident radiation is 1000 W/m^2. All the incident rays are assumed to be carry equal energy with a solar half-angle (δ_s) of 4.65 mrad.
(b) Diameter of PD (D_0) is 1000 mm. Reflectivity is 0.95 and absorptivity is 1.

Diameter of the concentrated spot is equal to the diameter of a circle which contains 90% of total flux on the receiver. Flux concentration ratio and shading percentage of secondary mirror can be calculated by:

$$C_f = \frac{I_{\text{spot}}}{I_0} = \frac{Q_{\text{spot}}}{A_{\text{spot}} I_0} \tag{4}$$

$$p = \frac{A_{\text{sec}}}{A_{\text{PD}}} \tag{5}$$

where A_{PD}, A_{sec} and A_{spot} denote aperture areas of PD, the secondary mirror and the concentrated spot, respectively. I_{spot} and I_0 denote radiation intensities on concentrator spot and PD, respectively. Q_{spot} is 90% of the total flux within a spot. The intercept factor γ is defined as the ratio of sunrays which hit the receiver to all incoming rays reflected by the PD. The amount of incoming radiation blocked by the secondary mirror is corrected with its theoretical value assuming a perfect concentrator. The intercept factor is a characteristic performance for the interface between concentrator and receiver. Intercept factors close to 1 are the objective for high-performance solar collector fields.

The effects of the geometric variations, such as the rim angle, the relative position (m) and NA_1 of the secondary mirror could be studied using this model. The effects of concentrator accuracy could be evaluated using sensitivity studies.

3.1. Effects of the rim angle

Fig. 2 showed effects of the rim angle on flux concentration ratios and shading percentage of these five systems. The rim angles vary from 30° to 120° at $m = 0.9$ and $NA_1 = 0.2$.

As shown in Fig. 2(a), flux concentration ratio of FS increases to maximum and then decreases with rim angle increasing from 30° to 90°. When rim angle is greater than 90°, a flat mirror cannot be used as a secondary mirror any more. The flux concentration ratios of GS and CS are close at first and decrease when rim angle increases. The flux concentration ratio of GS is higher than that of CS in 30–80° range but lower in 80–120° range. The difference