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Optimal design of symmetrical two-stage flat reflected concentrator

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Abstract

The optimal design of a symmetrical two-stage flat reflected concentrator (STFC) was investigated. It is composed of two symmetrical off-axis concentrators and inclined flat reflectors. The variable range and its influence on the energy transmission of STFC were detailedly analyzed. The best values were derived by considering a space solar power station (SSPS) without any convection cooling device. When the optical system is moved following the sun, we adopt the approach of rotating the secondary reflectors to cope with change. Afterwards we simulated the concentrating characteristics of STFC by Monte-Carlo ray tracing method (MCRTM). When the two sides' focal spots just coincide, the concentrated flux distribution presents uniform in the extreme. Finally the construction of primary concentrators and effect are discussed for reference.

Keywords: SSPS; STFC; Uniformity; MCRTM

1. Introduction

SSPS which is also known as space-based solar power station, converts solar energy into electrical energy and transmits it to ground through wireless. Exploiting SSPS is necessary and it did has become a favorite topic in recent years for its sustainability and economic value.

Internationally, concentrator photovoltaic (CPV) system was widely used in SSPS (Feingold, 2002). When the power satellite orbits the earth (usually on GEO), the primary concentrators have to keep track of the sun. Meanwhile the solar panel must also stand face to the ground to steadily emit microwave energy. To control the light path and obtain appropriate concentrated solar power on solar cells, engineers adopt the second-stage reflectors, called 'Cassegrain-type concentrators'. They have been widely used for SSPS in recent years. For instance, 2003 Reference System proposed by JAXA (Mori et al., 2006) and 2007 SBSP illustrated in the official website of NSS (National Space Society (US) and Rouge, 2007) are both advanced and practical projects.

Since its good compactness and high flux densities, Cassegrain-type concentrator was widely adopted in solar energy applications, especially electricity generation which has been commercialized (Gordon and Feuermann, 2005; McDonald and Barnes, 2008). Cassegrain concentrator with optical fiber transmitting has been utilized as solar surgery (Feuermann and Gordon, 1998; Feuermann et al., 2002), solar thermal propulsion (Henshall and Palmer, 2006), CPV systems for multi-junction solar cells (Sun et al., 2005; Anton et al., 2007) and natural illumination for indoor lighting (Whang et al., 2009). With the application of beam splitting technology, some concentrating hybrid solar system were proposed, including laser pumping/PV conversion (Yogev et al., 1996), thermal/PV conversion (Jiang et al., 2010), etc.

Irradiance uniformity is a crucial factor for solar panels. Traditional concentrators were lacking in the homogenization performance, which led to the low efficiency and short lifetime. This fact has encouraged people to propose novel approaches to problems. Kaleidoscope flux homogenizer is

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a classical method. Depending on the light-pipe's length and shape, the distribution on solar batteries can be homogenized in different degrees. A 'kaleidoscope' can be arranged with a reflective paraboloidal (Ries et al., 1997), refractive fresnel lens (Leutz et al., 2010), tailored (Jenkins, 2001) primary mirror or Cassegrain-type reflector (Fraas et al., 2005), which achieved good performance sometimes. However the most recognized disadvantage is that light-pipe must be long enough for better irradiance uniformity, causing the increasing number of reflections and decreasing efficiency. Another popular method is the Köhler illuminator or integrator (Zhang and Winston, 2010). Advanced Köhler integrator arrays with two optical surfaces have been designed to obtain high irradiance uniformity. They placed secondary reflectors at the focal plane array of the primary (Benitez et al., 2006). Nevertheless the uniformity decreased in three dimensions.

Concentrating technology affects the concentrated flux distribution on receiving surface, which makes it an important role in energy conversion of CPV. Uniform flux density distribution, proper concentration ratio and stable performance in orbit ensure the high efficiency and reliability of SSPS. So it is significant for the optimization of optical system. In recent years, although a large amount of literature about SSPS is emerging, the key technologies are seldom discussed. On the one hand, the study of energy transfer in a bilateral symmetrical concentrator is inadequate. On the other hand, the optimized structure parameters are needed to provide a reference for building SSPS.

This paper will discuss the concentrating characteristics and optimal design of STFC by Monte-Carlo ray tracing method (MCRTM). In order to obtain the optimal values for SSPS design, the range of parameters and its influence on the energy transmission of STFC are analyzed detailedly due to the requirement of a high degree of flux distribution uniformity. We taking giant space application without convection cooling device as the target, the flux distribution of solar array in a certain concentration ratio and the best parameter values are simulated. In addition, when the optical system is moved following the sun, we adopt the approach of rotating the secondary reflectors to cope with change. This method performed excellently. Finally the parabolic concentrator is constructed as the joining of several individual mirror facets. And corresponding results are discussed considering certain inaccuracy in slope design.

2. Design of STFC

2.1. Structural model

The off-axis paraboloid is widespread and convenient to be modularized. They are truncated by two inclined planes through a dish concentrator and proposed on both sides of STFC. The biggest advantage lies in the unobstructed transmission of sunlight, which can make full use of the surface area. Two second-stage circular reflectors are placed aside the focal point at a certain dip angle. There are three reasons for choosing flat mirror as the secondary reflectors:

(1) Solar array for SSPS have an area of several square kilometers (Mankins et al., 2012). Space environment and giant receiving surface make it not suitable for installing convection cooling system. Therefore the energy concentration ratio (ECR) should not be very high. Using flat mirrors could efficiently diffuse the concentrated solar rays as well as help to achieve a low ECR.
(2) When placed a secondary curved surface which shares the same focus with the primary concentrator, such as the hyperboloidal or ellipsoidal mirror, it can only obtain a single solar image whose flux distribution presents Gaussian distribution. In contrast, putting two symmetrical flat mirrors aside the focus brings two symmetrical solar images. According to the superposition principle, it is good for receiving a high degree of distribution uniformity.
(3) If placed two symmetrical curved reflectors aside the focus, theoretically we could also gain an uniform flux distribution. However, the geometric light-path would be complex. When a space station circles the earth, the solar radiation come from different directions. It is very complicated for the realization of uniformity and ray path's adjustment.

Solar transmission and y–z projection of the three-dimensional STFC is presented in Fig. 1. Two secondary mirrors are made into plane circular. As described in Fig. 1, the incident solar rays are gathered by the primary off-axis concentrators and diffused by the secondary planes.

2.2. Geometric parameters and formulations

\As can be seen from Fig. 1, θ_s is the solar semiconic angle. Parameters p_r and p_y represent the effective concentration radius and linear eccentricity of off-axis concentrator,

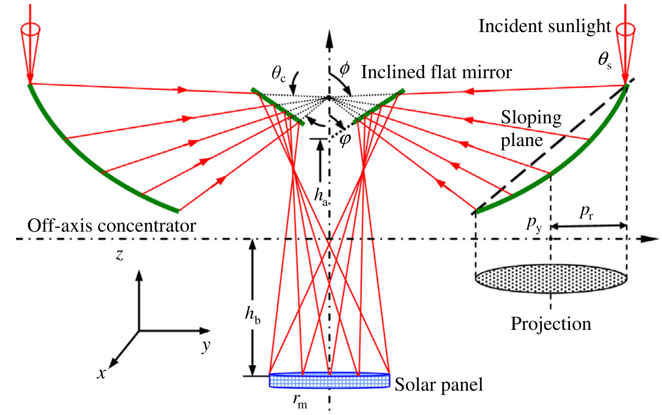

Fig. 1. Schematic of the principle of STFC.