Modeling for Two-stage Dish Concentrating Spectral Beam Splitting Photovoltaic/thermal System

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***Abstract*—Detailed optical and electric models are presented to evaluate the performance of the two-stage dish concentrating spectral beam splitting photovoltaic/thermal (TDCS) system. It mainly consists of parabolic concentrator, spectral beam filter, heat receiver and the cell component. The beam filter coated with 38 layers is designed and manufactured. Three-dimensional optical model, considering the effect of solar intercept angle and tracking error, is developed using ray trace method. The spectral and spatial distribution of radiant intensity is investigated. The optical and splitting efficiency of the system at AM1.5 is 66.1% and 78%, alternatively. The total power generating efficiency of the system in theory is 18% with silicon solar cell with geometric concentration ratio 80. Beam splitting can reduce the solar cell temperature and increase concentration ratio together with photoelectric conversion efficiency.**

***Index Terms*—PV system, dish concentrating solar system, spectral beam splitting technology, optical model**

I. Introduction

One of the suggested effective methods to reduce the amount of the expensive photovoltaic cell is concentrating sunlight using cheaper optical components [1]. The higher the concentration level is, the fewer cells are required. But high concentration system is not always cost-effective for the more expensive concentrator solar cell employed [2]. So the low-concentration-ratio solar system with conventional silicon cells is surveyed in this paper. Photoelectric conversion efficiency degrades as the cell temperature rises up because waste heat cannot be dissipated in time [3], [4], [5]. An option is to use spectral beam splitting technology to reduce the heat load on the solar cell and to increase the concentration ratio as well as the system efficiency [6], [7]. The beam splitting system is generally a PV/T hybrid system to increase solar energy utilization efficiency by recovery heat energy below the band-gap of the cell with receiver. An example of the linear focus system is the two-stage parabolic trough concentrating spectral beam splitting PV/T system (TTCS) [8], [9]. The geometric concentration ratio of TTCS is limited to 10X due to two-stage concentration, so considering additional tracking device it lacks competitive advantage in price with conventional panel PV system. For moderate concentration the point focus TDCS system, whose concept is presented in Fig. 1, is actually required and discussed in this paper.

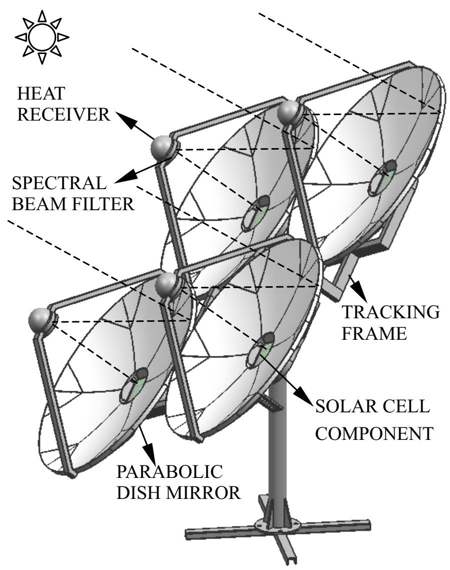

Fig. 1. Schematic view of the TDCS system.

II. Physical Model

The TDCS system mainly consists of parabolic concentrators, the beam filters, the cavity receiver for heat recovery and the component of cell with heat sink. Four dishes make up a unit set on the tracking frame driven by a decelerator with nominal power 10 W.

A. Optical Test

The material of the parabolic dish mirror is aluminum with protective coating and that of the dichroic mirror surface is deposed a wide spectrally selective coating. It is a complex multilayered film stack with a high transmittance for the

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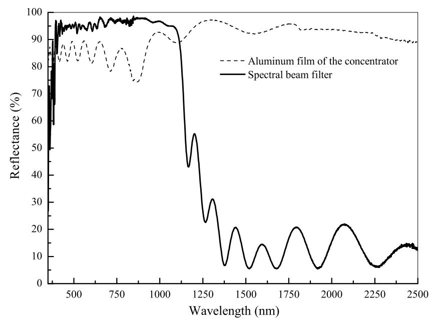

Fig. 2. Spectral reflectivity of the elements.

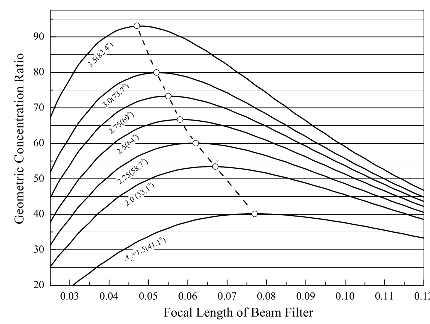

Fig. 4. Geometric concentrating ratio of TDCS.

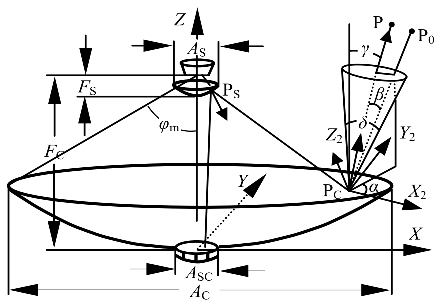

Fig. 3. Schematic diagram of the ray trace evaluation model.

photons below band-gap while the other photons are reflected onto the cell. The film stack is as follows

$$\mathrm{Air}\,|\mathrm{Nb_2O_5}\ \mathrm{SiO_2}|^{19}\,\mathrm{Glass} \quad (1)$$

Coating is carried out on the RAS-1100C magnetron sputtering plant made by Shincron Co. Ltd. Fig. 2 shows their optical properties tested with the U-4100 spectrophotometer of HITACHI Company.

B. Nondimensional Model

It is necessary to set up a nondimensional model to study different size of concentrators and beam filters. Hence the focus length of the parabolic concentrator is set equal to unity. Fig. 3 specifies the coordinate system used for describing the parabolic dish system. The optical axis is along Z, and the mirrors are defined as follows:

$$Z = (X^2 + Y^2)/4, \quad X^2 + Y^2 \le A_C^2/4 \quad (2)$$

$$Z = (X^2 + Y^2)/(4F_S), \quad X^2 + Y^2 \le A_S^2/4 \quad (3)$$

where A_C and A_S is the aperture of concentrator and beam filter, and F_S is the focal length of the filter.

III. Ray Trace Evaluation

The solar is not a point light source, so the apparent solar intercept angle δ changes from 4.742 mrad in January to 4.584 mrad in July, caused by the Earth elliptical orbit. The incident rays at one point of the concentrator constitute a sun beam cone [10], [11]. The unit vector of a ray in the cone local coordinate system is

$$\mathbf{n}_{\mathrm{Local}} = (\sin\beta\cos\alpha, \sin\beta\sin\alpha, \cos\beta)^{\mathrm{T}} \quad (4)$$

where α and β is the projection angle. The vector in the global coordinate system is defined as follows

$$\mathbf{n}_{\mathrm{Global}} = \begin{bmatrix} \cos\gamma\cos\theta & -\sin\theta & \sin\gamma\cos\theta \\ \cos\gamma\sin\theta & \cos\theta & \sin\gamma\sin\theta \\ -\sin\gamma & 0 & \cos\gamma \end{bmatrix} \cdot \mathbf{n}_{\mathrm{Local}} \quad (5)$$

where θ and γ is the radial and tangential tracking error angle. The incident ray at point $\mathrm{P_C}$ on the concentrator is as follows

$$\begin{cases} X = X_{\mathrm{P_C}} + \mathbf{n}_{\mathrm{Global,X}}t \\ Y = Y_{\mathrm{P_C}} + \mathbf{n}_{\mathrm{Global,Y}}t \\ Z = Z_{\mathrm{P_C}} + \mathbf{n}_{\mathrm{Global,Z}}t \end{cases} \quad (6)$$

The unit normal vector of normal line at $\mathrm{P_C}$ is

$$\mathbf{n}_{\mathrm{P_C}} = \frac{1}{2\sqrt{Z_{\mathrm{P_C}} + 1}}(-X_{\mathrm{P_C}}, -Y_{\mathrm{P_C}}, 2)^{\mathrm{T}} \quad (7)$$

The reflection ray is yielded according to Fresnel reflection law with (6) and (7). It is the same to the second reflection at the point $\mathrm{P_S}$ of the filter surface. Finally the incident point at the cell is obtained, and makes up the solar image on the solar cell. The size of the solar image on the solar cell plane is determined by the border sunlight of the incident ray cone at every incident point on the concentrator. The geometric concentration ratio, defined as the ratio of effective aperture area over the solar image on the cell plane, is

$$CR = (A_C^2 - A_S^2)/D_{\mathrm{Solar}}^2 \quad (8)$$

where D_{Solar} is the diameter of the solar image. The evaluation result of CR at different A_C and different F_S is shown in Fig. 4. There is a maximum CR to each A_C, so the optimum design should be along the dashed line in Fig. 4.

IV. Flux Density Distribution

A. Spectral Distribution of Flux Density

It is necessary to study spectral distribution of irradiance because the optical elements are spectrally selective and the cell has different quantum efficiency for different wavelength

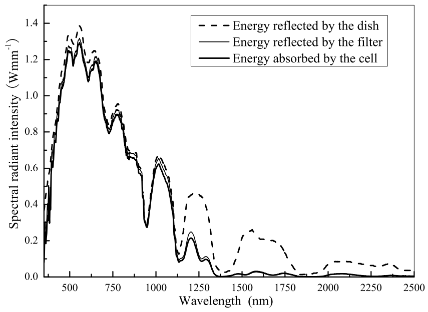

Fig. 5. Spectral distribution of the flux density.

irradiation. The incident solar direct radiation of the system is given by the equation

$$E_0 = \int_0^{\infty} E_{0,\lambda} \mathrm{d}\lambda \tag{9}$$

The energy of the light beam after reflection by the dish mirror and by the filter is as follows

$$E_\mathrm{C} = \int_0^{\infty} E_{\mathrm{C},\lambda} \mathrm{d}\lambda = \int_0^{\infty} \rho_{\mathrm{C},\lambda} E_{0,\lambda} \mathrm{d}\lambda \tag{10}$$

$$E_\mathrm{S} = \int_0^{\infty} E_{\mathrm{S},\lambda} \mathrm{d}\lambda = \int_0^{\infty} \rho_{\mathrm{S},\lambda} E_{\mathrm{C},\lambda} \mathrm{d}\lambda \tag{11}$$

where $\rho_{\mathrm{C},\lambda}$ and $\rho_{\mathrm{S},\lambda}$ are the spectral reflectivity of the mirrors. Finally, the radiation intensity absorbed by the cell is

$$E_\mathrm{SC} = \int_0^{\infty} E_{\mathrm{SC},\lambda} \mathrm{d}\lambda = \int_0^{\infty} (1-\rho_{\mathrm{SC},\lambda}) E_{\mathrm{S},\lambda} \mathrm{d}\lambda \tag{12}$$

where $\rho_{\mathrm{SC},\lambda}$ is the spectral reflectivity of the solar cell. To describe the utilization efficiency of the solar energy, the concentration optical efficiency of the system is defined as

$$\eta_0 = E_\mathrm{SC}/E_0 = \int_0^{\infty} (1-\rho_{\mathrm{SC},\lambda}) \rho_{\mathrm{S},\lambda} \rho_{\mathrm{C},\lambda} E_{0,\lambda} \mathrm{d}\lambda / E_0 \tag{13}$$

The single-junction cell cannot make use of the full solar spectrum, so the splitting optical efficiency is introduced in the concentrating beam splitting system as follows

$$\eta_0' = \int_0^{\lambda_g} (1-\rho_{\mathrm{SC},\lambda}) \rho_{\mathrm{S},\lambda} \rho_{\mathrm{C},\lambda} E_{0,\lambda} \mathrm{d}\lambda \Big/ \int_0^{\lambda_g} E_{0,\lambda} \mathrm{d}\lambda \tag{14}$$

where λ_g is the wavelength corresponding to the bad gap of the solar cell. The spectral distribution of the flux density in the TDCS, whose optical properties are shown in Fig. 2, is evaluated with (10)-(12) in Fig. 5 at AM1.5. The concentration optical efficiency is 66.1%, while splitting optical efficiency is 78.0%.

B. Spacial Distribution of Flux Density

The local flux density distribution is very important to the cell because non-uniform illumination produces significant local heating and reduces the efficiency of the cell [4], [12]. The distribution of the sampling points in the solar dish

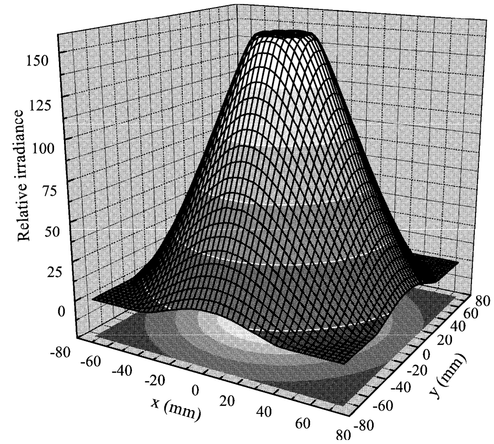

Fig. 6. Spacial distribution of the flux density.

TABLE I
EVALUATION PARAMETERS OF TDCS SYSTEM.

Parameters	*Value*
CR	80
A_C	3.0
A_S	0.085
F_S	0.05
f_c	500mm

is uniform for clear sky [13]. The parameters used by the evaluation are given in Table I and the result is presented in Fig. 6.

V. Photoelectric Conversion Efficiency

The photoelectric conversion efficiency, defined as the ratio of power generated over incident radiation of the cell, is

$$\eta = F_F U_\mathrm{OC} I_\mathrm{SC} / E'_\mathrm{SC} \tag{15}$$

where F_F is the fill factor of the cell, U_OC and I_SC are the open-circuit voltage and the short-circuit current of the cell. As to single cell in normal working conditions U_OC usually varies little, while I_SC is approximately equal to the photogenerated current I_ph

$$I_\mathrm{SC} \approx I_\mathrm{ph} = \int_0^{\lambda_g} q\eta_\lambda N_\lambda \mathrm{d}\lambda = \int_0^{\lambda_g} q\eta_\lambda \frac{E_{\mathrm{SC},\lambda}\lambda}{hc} \mathrm{d}\lambda \tag{16}$$

where q is the elementary charge, and N_λ is the photon number density. Then photoelectric conversion efficiency is derived

$$\eta = \frac{qF_F U_\mathrm{OC} \int_0^{\lambda_g} (1-\rho_{\mathrm{SC},\lambda}) \rho_{\mathrm{S},\lambda} \rho_{\mathrm{C},\lambda} E_{0,\lambda} \lambda \mathrm{d}\lambda}{hc \int_0^{\lambda_g} (1-\rho_{\mathrm{SC},\lambda}) \rho_{\mathrm{S},\lambda} \rho_{\mathrm{C},\lambda} E_{0,\lambda} \mathrm{d}\lambda} \tag{17}$$

The solar cells are made by Suntech Power Co. Ltd. in Wuxi city of China. The test result of the quantum efficiency is represented in Fig. 7. Thus, the photoelectric conversion efficiency is 27.2% in theory with (17). Considering the optical efficiency, the power generating efficiency of the system is $\eta\eta_0$=27.2%×66.1%=18%. Though it is lower than the efficiency 17.5% at STD, the TDCS becomes more competitive in price for much less cell employed.

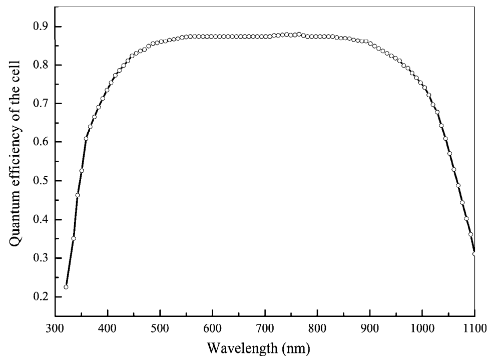

Fig. 7. Quantum efficiency of the cell.

VI. Conclusion

A two-stage reflective concentrating solar system is presented with beam splitting technology. The spectral beam filter is the key element in the concentrating beam splitting system.

The detailed three-dimensional optical model is helpful to evaluate the optical properties of the TDCS system. The evaluation results show that the filter we designed is effective. It is very significant to improve the optical efficiency of the concentrators and the cell. The electric model is also presented to study the photoelectric conversion efficiency of the concentrating beam splitting system. The power generating efficiency of TDCS is 18% in theory and it is very competitive in price. Further work is to be done to improve the optical efficiency using cheaper beam filter and the heat sink of the cell is also challenge under concentrating illumination.

Acknowledgment

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