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# Characteristics of Thermal Radiation in Parabolic Dish CSP System Based on Monte–carlo Ray Tracing

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In order to study the effect of collector shape and surface slope error on the efficiency of photothermal conversion in the parabolic dish concentrated solar power (CSP) system, the Monte Carlo ray tracing method was used to conduct related numerical simulation with four types of collectors and four surface slope errors. The results show that when the size of the focal plane is constant, the flux concentrating ratio is basically the same, and the heat flux on the focal plane presents the annular temperature distribution. The influence of condenser surface slope error on system heat radiation was also studied. Corresponding research results have provided theoretical reference for the design and actual performance prediction of parabolic dish CSP system.

## 1. Introduction

Recent years have witnessed the vigorous promotion of new energy technologies (Liu et al., 2016), which fuels the rapid development of solar power technology. Featuring broad application scopes and multiple ways of utilization, solar energy technology is a major solution to the problem of energy shortage. Solar power can be categorized into photovoltaic power generation and thermal power generation, the latter one playing the dominant role. Thermal power generation (Demir and Dincer, 2017; Sánchez et al., 2016; Sütterlin and Siegrist, 2017; Purohit and Purohit, 2017) is to convert solar radiation energy to heat energy through collectors, which is finally converted to mechanical energy through heat engines such as steam turbine, gas turbine, Freon steam turbine, and Stirling engine to provide power for the generators to generate electricity. According to different heat collecting equipment and thermoelectric conversion ways, the solar thermal power system can be parabolic dish solar thermal power system, parabolic trough solar thermal power system and solar thermal tower system.

As early as the 1970s, Sweden and the United States conducted considerable research on the parabolic disc solar power system, while China started late in such studies. Until now, several prototype testers have been developed in the country, but the demand for the construction of different prototypes to test different research objects causes high experimental cost and long test period. Moreover, it is difficult to produce ideal dish surfaces in actual practice; instead, the incidental scattering error (Ni et al., 2017) will redirect the reflected focal points and reduce the photothermal conversion efficiency by changing the heat flux on the cavity wall surface of the collectors. To address these problems, the Monte Carlo ray tracing method (Tomboulian and Hyers, 2017) is used to conduct related numerical simulation and compare the heat flux of collectors in different shapes and scattering errors. The research results provide theoretical reference for the design of collectors in the parabolic dish solar power system.

## 2. Numerical model

### 2.1 Monte carlo ray tracing method

The solar energy is considered as a large number of independent energy beams, each of them with the same energy to ensure the even distribution of solar energy. The absorption, reflection and scattering of energy

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beams on the collector surface are determined by a random number that follows a specific distribution function (Shuai et al., 2008).

The Monte Carlo ray traces every energy beam and records the surface it reaches. If the beam reaches the false surface, it will no longer be traced and an extra beam will be emitted; if the beam reaches the receiving surface, the ray will record its position in the surface; if the beam reaches the mirror, the ray will judge whether it is absorbed or reflected and continue tracing the reflected one or stop tracing the absorbed one (Shuai et al., 2006). Finally, the number of beams in each area of the receiving surface will be calculated to determine the corresponding heat flux.

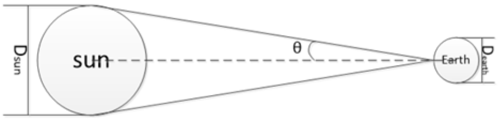

*Figure 1: The geometric relationship between the sun and the earth*

When the solar rays that reach the collector mirror scatter, the scattering direction is expressed by the zenith angle θ and the circle angle φ in the local coordinates O * X * Y * Z. According to Lambert's law, the probability model of θ and φ can be obtained as follows:

$$\theta = \arcsin\sqrt{R_{\theta'}} \;, \quad \varphi = 2\pi R_{\varphi} \tag{1}$$

Where $R_\varphi$ is the random number of the circumference angle $\varphi$, and $R_\theta$ is the random number of the zenith angle $\theta$.

The essence of Monte Carlo ray tracing is the probability theory (Wei and Sze, 2016). The hemisphere integral equation is approximately simplified in a way that the integer can be simulated by a few number of important samples. The factors of scattering and surface attributes are considered in the calculation process to produce the computation result closer to the real result. In the simulation calculation, the collector is made by vacuum aluminum, and the near ground solar radiation heat flux is 800 W / m2.

In the Cartesian coordinate system, the emission point model of the circular surface with radius r0 is:

$$x_0 = r_0 \cos\varphi \;, \quad y_0 = r_0 \sin\theta \;, \quad z_0 = z_0 \tag{2}$$

The sun is not a point source for the earth, but a light spot. There is a small angle between the sun lights. The diameter of the sun is d1, and the diameter of the earth is d2 = d1 / 109. The distance between the sun and the earth is L0 = 1.496 × 1,011m. The calculation model that considers the non-parallelism of sunlight is:

$$\tan\alpha = \frac{d_1 - d_2}{2L_0} = 0.46097 \times 10^{-2} \tag{3}$$

after calculation, $\alpha$=15'50''; if the non-parallelism of sunlight is ignored, $\alpha$=16'.

According to Lambert's law, the probability model for the direction of the solar rays is:

$$\theta = \arcsin\sqrt{R_\theta \sin^2 \alpha_{\max}} \;, \quad \varphi = 2\pi R_\varphi \tag{4}$$

In the numerical simulation process, it is necessary to judge whether the light is reflected or absorbed and whether the reflected light is diffuse reflection or mirror reflection, as they require different calculation procedures. The solar rays whose reflection time is over 30 can be ignored, i.e. the solar energy is zero. In other cases, the solar rays should be tranced constantly. When the sun's rays are absorbed by the surface, it is only necessary to count the number of rays without having to keep track of the light.

### 2.2 Concentration ratio and collector temperature

Concentration ratio is an important indicator of the performance of the collector system. Typically, the higher the concentration ratio of the condenser is, the higher the collector temperature is.

The concentration ratio can be divided into geometric concentration ratio C, which is the ratio of the condenser opening area Aa to the collector opening area Ar; and radiant flux concentration ratio Ce, which is the ratio of radiation energy density per unit area Ir to the incident energy density Ii. As the research focus in this paper is the heat transfer properties of the system, we use the radiation flux ratio as the analytical indicator.

$$C = \frac{A_a}{Ar}, C_E = \frac{I_r}{I_i}, C_E = \gamma\rho C \tag{5}$$

In the above formula, γ represents the percentage of reflected light absorbed by the collector; ρ represents the light reflectivity. Since the C value is only related to the structural parameters and is not affected by the ambient light factor, the CE value is usually below the C value.

The sun is considered as 5800K black body radiation, and it generates the radiant energy of

$$Q_S = 4\pi r_s^2 \sigma T_S^4 \tag{6}$$

Ignoring the collector convection and heat loss, the solar radiant heat received by and the radiant heat loss of parabolic dish solar collectors are

$$Q_r = \tau\mu A_a \frac{r_s^2}{L_{se}^2} \sigma T_S^4, Q_L = \varepsilon A_r \sigma T_r^4 \tag{7}$$

Where $r_s$ is the solar radius, $T_S$ is the solar surface temperature, $T_r$ is the collector surface temperature, $\sigma$ is the solar radiation coefficient, τ is the projection rate, $\mu$ is the absorptivity of solar radiation on the collector surface, $L_{se}$ is the distance from the sun to the earth, $\varepsilon$ is the radiation on the collector surface.

## 3. Geometric model

Rotary parabolic equation:

$$x^2 + y^2 = 4fz \tag{8}$$

Parabolic height h, focal length f, edge angle φ, and we have

$$h = \frac{d^2}{16f}, \tan\phi = \frac{1}{(d/8h) - (2h/d)} \tag{9}$$

$\tan\theta \approx \sin(\theta) \approx \theta \approx 0.00463 mrad$, θ=16'. and we have:

$$W = 2\rho \cdot \tan\theta, \rho = \frac{2f}{(1+\cos\phi)}, r = \frac{W}{2\cos\phi} \tag{10}$$

Thus,

$$r = \frac{2f \cdot \tan\theta}{\cos\varphi \cdot (1+\cos\varphi)} \tag{11}$$

Where $r$ is the radius of the focal spot. As can be seen from the above formula, the focal spot radius is determined by f and φ; the concentration ratio is the maximum when $\varphi$ is equal to 45 °; when $\varphi$ is greater than 45°, the concentration ratio declines, the reflected solar ray on the receiving surface is unevenly distributed, and the light spot scatters to some degree. This may damage the receiving window and apparatus, and thus φ value should be as small as possible.

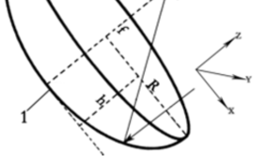

*Figure 2: parabolic dish solar structure (1-Parabolic condenser, 2-receiver)*

By substituting *d*=2.6, *f*=3 into the formula, the simulative paraboloid can be calculated as

$$X^2 + Y^2 = 12Z \tag{12}$$

A large number of studies have shown that the shape of the collector has a certain influence on the receivable amount of solar energy. As can be seen in Fig 3, the following four structures are selected for analysis, in which the radius of the collector face is 0.1m.

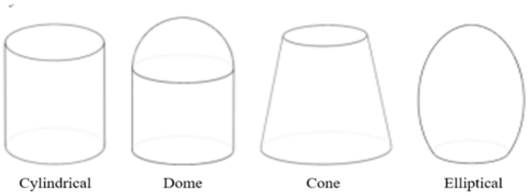

*Figure 3: four collector structures*

## 4. Result analysis

### 4.1 Concentration ratio

The concentration ratio (Rehman and Siddiqui, 2016; Salgado-Tránsito et al., 2015) is an important parameter to characterize the performance of the parabolic dish solar system, representing the increment of energy flux after the sunlight is collected by the collector. Since heat transfer on the collector is our research focus, we use radiant flux concentration ratio to evaluate the system performance about energy concentration. Radiant flux concentration ratio is the ratio of the average energy flux on the absorber to the direct solar radiation intensity. According to this definition, since the four collectors have the round focal plane with the same radius and the same condenser parameters, the corresponding parabolic dish CSP systems have equal radiant flux concentration ratios, as shown in Figure 4.

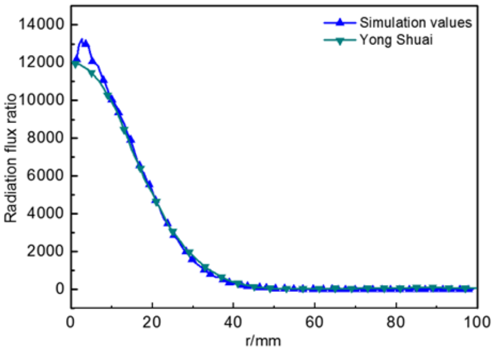

*Figure 4: Radiant flux concentration ratio of various collectors*

Yong uses the Monte Carlo calculation model to compare the computation result of our model with Johnston (1995) measured data, which proves the model accuracy. He also calculates the radiant flux concentration ratio of cylindrical collector with the same parameter. The results show that the calculated results are in good agreement with the results of the references, showing the global features of normal distribution.

### 4.2 Influence of collector structure on heat flux

Figure 5 shows the heat flux on the focal surface of the four types of collectors. The results show that the area and the value of the high heat region on the different types of collectors are basically the same, indicating that the heat flux on the focal plane is not affected by collector structure, but mainly by the incident light flux (the number of solar rays and the dish area). The more solar rays received by the dish, the higher solar energy that is collected, and the larger heat flux there is on the collector.

Due to the influence of processing conditions, the energy points collected on the dish are actually a spherical space with a certain range, which contains the collector. Therefore, the even distribution of heat flux on the collector cavity wall surface is of equal importance to the heat absorption efficiency. Figure 6 is the distribution of the heat flux on the collector cavity wall surface.

The results show that the heat flux on the cavity wall surface of various collectors is different. As the heat transmission is ignored, the boundary heat flux that is far away from the light spot approaches zero. Meanwhile, the heat flux on the focal plane of the collector decreases with the farther distance from the central point, dropping to zero on the outer boundary, as shown in Figure 5. According to Figure 6, the heat flux on the collector cavity wall surface increases along the collector axis, reaches the peak value and then begins to decrease. This phenomenon indicates that the radiant energy on the collector cavity wall surface follows graded distribution. From the perspective of actual engineering work, the evener the cavity wall surface temperature is distributed, the smaller impact of thermal stress on the collector structure. Therefore, the temperature distribution on the round-end collector cavity wall surface is relatively even, while the heat flux peak value of the conical collector is much higher than the others'. Although it will easily cause local overheating of the structure, it is possible to achieve the uniform temperature distribution of the cavity wall surface by adjusting the wall parameters.

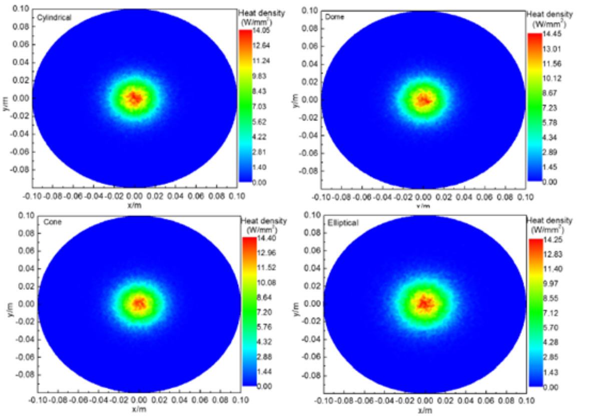

*Figure 5: Distribution of heat flux on the focal plane of various collectors*

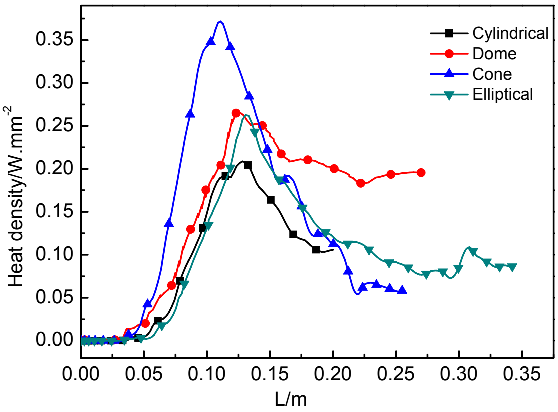

*Figure 6: heat flux on the cavity wall surface of different collectors*

### 4.3 Influence of surface slope error on heat flux

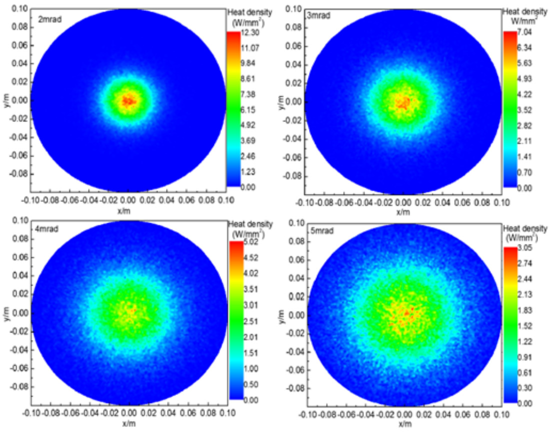

*Figure 7: Heat flux distribution of the focal plane at different surface slope errors*

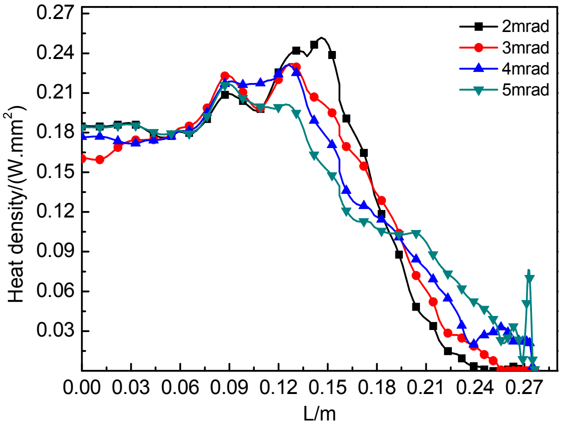

*Figure 8: Heat flux on the cavity wall surface at different slope errors*

In the previous analysis, it is found that the heat flux on the round-end collector cavity wall surface is relatively uniform. At the same time, Figure 5 shows that the heat flux on the focal surface of the collector is little affected by the collector shape. Therefore, in this section, the round-end collector is used as the research object to analyze the system thermal radiation characteristics when the surface slope error of the condenser is 2mrad, 3mrad, 4mrad and 5mrad, respectively.

Figure 7 is the heat flux distribution of the focal plane at different surface slope errors. The results show that the surface slope error of the condenser will greatly change the radius of the focal spot. The larger error means larger radius of the focal spot and smaller temperature change in the focal spot area. However, the larger focal spot has smaller heat flux in the center, less evenly distributed heat flux on the focal plane of the collector, and smaller heat radiation. Therefore, the larger the surface slope error is on the collector surface, the lower heat efficiency the system has.

Figure 8 shows the heat flux distribution on the cavity wall surface at different slope errors. The results show that all the characteristics are the same, except when the surface slope error of the condenser is smaller, the heat flux on the cavity wall is larger. This means that the surface slope error of the condenser has little effect on the heat flux distribution in the collector cavity. The reason for this phenomenon is that most of the reflected solar rays generate heat when passing through the focal plane within the current error range, and the light magnitude on the outer cavity wall is basically the same.

## 5. Conclusion

In this paper, the Monte Carlo ray tracing method is used to analyze the effect of different collector structures on the radiation characteristics of the parabolic dish CSP system. The conclusions drawn are as follows:

(1) The heat flux distribution on the collector surface is little affected by the shape change of the collector. When the structure and environmental parameters of the condenser are constant, the heat flux on the focal surface shows a circular distribution, highest in the central area.

(2) The heat flux distribution on the collector cavity wall surface is greatly affected by the collector shape. Along the axial direction of the collector, the heat flux is the highest in the middle section. The heat flux peak value of the conical collector is much higher than the others'; while the temperature distribution on the round-end collector cavity wall surface is relatively even.

(3) The influence of the surface slope error of the condenser is significant on the heat flux distribution on the focal plane, but insignificant on the heat flux distribution on the cavity wall surface. Greater surface slope error means larger focal spot radius, smaller heat flux on the focal plane, and lower thermal efficiency of the system.

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