A calculation method of precise direct normal irradiance based on measured CSR

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Abstract. Radiation from the circumsolar region called circumsolar radiation is part of direct solar radiation, but not all circumsolar radiation can be received by concentrating solar power (CSP). Circumsolar ratio (CSR) reflects the proportion of circumsolar normal irradiance in direct normal irradiance (DNI). CSR is related to the radial distribution of solar brightness (sunshape) and it is influenced by atmospheric turbidity and air mass (AM). Performance of CSP is affected by CSR, which should be considered in the CSP simulation and analysis. This work introduces a method of measuring CSR with a CCD camera and filters. Also a calculation method of DNI for different field of view based on the measured CSR is proposed.

1. Introduction

Solar radiation that reaches the earth mainly includes direct solar radiation and diffuse radiation. The concentrator of Concentrating Solar power (CSP) concentrates the direct solar radiation to generate power, so direct Normal irradiance (DNI) is important to the performance of CSP plants. Different concentrators have different acceptance angle, which leads to different DNIs accepted by different CSPs in the same condition. CSPs with small acceptance angles only can receive partly DNI[1]. Since the acceptance angle of the pyrheliometer is 5°, DNI is considered to be the energy of direct solar radiation within a field of view (FOV) of 5° (DNI5°). In CSP simulation, DNI5° used as input of CSPs may cause overestimation[2], so DNI needs to be more finely divided to improve the accuracy of the simulation of CSP.

![Figure 1. (a) Schematic diagram of direct solar radiation; (b) Buie sunshape model (CSR from top to bottom is 0.7-0.1)](image_url)

Direct solar radiation includes radiation from the solar disk within a FOV 0.53° (half angle of...
0.265°), and radiation from circumsolar region (half angle between 0.265° and 2.5°) called circumsolar radiation (Figure 1a). Circumsolar ratio (CSR) is the ratio of circumsolar radiation to DNI and is influenced by air mass (AM) and the composition of particles in the air. In previous studies [3, 4], it was found that the change of CSR would affect the energy distribution of light spot on the receiver of the concentrating solar power generation system, thus affecting the optical efficiency of the system.

In order to get the detailed distribution of radiation in the DNI, Buie proposed the sunshape model describing the brightness distribution of the sun (Figure 1b). The sunshape model is independent of geographic location. CSR is an important parameter of sunshape[5]. Schubnell et al. quantified the effect of changes in sunshape on the efficiency of the concentrator and the work shows that the change in CSR can cause a gap of up to 20% in optical performance[6, 7]. As a result, CSR measurement is an important part of the DNI measurement. Wilbert et al. developed the sun and aureole measurement instrument (SAM) to measure CSR. It consists of two cameras, one is only used to take the image of the sun disk, and the other is used to take the image of the circumsolar area[2]. The BPI-CSR460 sensor is introduced in[8]. It consists of two pyrheliometers (FOV 0.6° and FOV 5°), which can directly get CSR. These devices can measure CSR accurately, but the structure of these devices is complex[8], and the requirement for sun tracking accuracy is relatively high.

This work introduces a simple CSR measurement method, and on the basis of the measured CSR, a calculation method of DNI for different FOV is proposed.

2. Measurement device

Figure 2 shows the prototype of sunshape measurement. It consists of a pyrheliometer, a pyranometer (non-use), a charge-coupled device (CCD) camera and an illuminometer. All of them are mounted on a double-axis solar tracker. Inside the solar tracker, there are two high-precision stepper motors with reduction gearboxes. The pyrheliometer can measure DNI 5°. The CCD camera is used in conjunction with the neutral filters to take pictures of the sun. The illuminometer can directly measure the brightness of sun and circumsolar area.

3. CCD camera and filters

3.1 camera response function

CCD camera’s mapping from the brightness of the scene to the gray value of the image is affected by several complex factors, including vignetting, lens fall-off, shot noise, and dark current. Therefore, there is not necessarily a linear mapping between the brightness received by camera and the image intensity. The mapping relationship called response function.Debevec et al[9] developed a method to recover response function, which required photos of the same scene taken with different exposure times. Assuming that the response function is F as below

\[ Z = F(E) \] (1)

Z is the gray value of pixels in the picture; E is the brightness received by camera. Pictures taken with different exposure times of the same scene should be taken in a very short time, ensuring that the scene brightness (I) doesn’t change, and the brightness received by camera is proportional to the exposure time t. The relationship can be expressed as Ei=Itj, in which i is the index of the pixel, j is the index of picture taken with exposure time tj. Then the gray value of each pixel can be expressed as
\[ Z_i' = F(I_j) \]  

Since the assumption that \( F \) is monotonic, it is invertible. We define function \( g = \ln F - 1 \), and take the natural logarithm of both sides. The formula 2 can be rewrited as  

\[ g(Z_i') = \ln I_i + \ln t, \]  

\[ \text{(3)} \]

\( Z \) and \( t \) are known, and \( I \) is unknown, but \( E \) is proportional to \( t \). For the \( i \)th pixel, assuming \( I_i = 1 \), then \( E_i = t_j \), and the response curve can be recovered. Since \( E \) is relative brightness, the curve fitted by different pixels has the wrong value but the shape of curve is correct. Finally \( g(Z) \) is recovered by putting the fitted curves together, and what to do in the process is sliding the curves segments up and down.

Figure 3. (a)-(f) Pictures taken with different exposure times; (g) Fitting curve \( g(Z) \)

Figure 3a-f are pictures taken with different exposure times (1/8 s, 1/4 s, 1/2 s, 1 s, 2 s, 4 s). Figure 3g is the \( g(Z) \) piecewise fitted by a third-order polynomial[10]. \( g(Z) \) can only be used to convert pixel gray values to relative brightness.

3.2 Filters

Figure 4. (a) CCD camera and filters; (b) Solar spectrum filtered by the adopted filters

The CCD camera used in the experiment delivers an 8-bit digital signal (256 gray levels), but the sun disk brightness is more than 3-4 orders of magnitude higher than that of circumsolar region. It means that the sunshape cannot be completely obtained because the range of brightness distribution of the sun is larger than the gray levels of the CCD camera which causes pixel saturation. In order to solve this problem, the camera is equipped with 4 neutral filters (figure 4a). Three of the filters have fix light transmittances of 1% (25 mm in diameter), 2% (25 mm in diameter), 0.1% (50 mm in diameter), and another one has adjustable light transmittance from 0.25% to 50% (50 mm in diameter). The filters with diameter of 50 mm limit the luminous flux to protect CCD camera. The filters with diameter of 25 mm are used to reduce the light intensity of the sun disk. After that, sunshape can be obtained indirectly by CCD camera. Figure 4b shows the solar spectrum filtered by the adopted filters. It can be
seen that the filters adopted have very close transmission performance in the visible light range, so the intensity of sunlight filtered by these filters is comparable.

4. Illuminometer
The special advantage of the illuminometer is that the measurement range is large, covering 6 orders of magnitude, from 0.1-200,000 lux, so the illuminometer can measure the difference in light intensity between sun disk and circumsolar region. An illuminometer is used to measure light intensity as verification data in this experiment (Figure 2). A light passage of 1 m in length and 4 mm in diameter is used to limit the FOV of illuminometer and the inner wall of the light passage is blackened to eliminate the reflected light.

5. Experimental data and analysis

Figure 5. Flow chart of the measurement process of CSR
Figure 5 is a flowchart for measuring the CSR. CCD camera takes grayscale pictures of the sun. The exposure time of CCD camera is set to 0.25 ms to avoid overexposure. A matlab program is used to process and analyze the pictures. The program has the following functions: (1) Converting the gray value into the relative scene brightness according to the camera response function recovered in section 2.1; (2) Making the value of brightness within the small filter be multiplied by the filter's transmittance to recover the relative brightness of sun; (3) Extracting the center and radius in pixels of the sun, and calculating how many degrees a pixel represents in it according to the angular distance of the sun disk (0.53°); (4) Extract a series of relative brightness along the radial direction from the center of the sun, sunshape; (5) The brightness information at the edge of the small filter should be removed due to the brightening of the refraction and reflection. After normalization, a broken sunshape curve is obtained and CSR is also obtained by compared with Buie sunshape model. As a means of verification, the illuminometer is used to measure the brightness at 0°, 0.5°, 1°, 2° from the center of the sun. The light Passage of the illuminometer has a field of view of 0.229°, which means that the received light does not come from a point, but from an area. The relationship between the brightness in the sampling area and sunshape is processed in the calculation. After normalization, the processed brightness data is used to verify the sunshape extracted from the picture. In the experiment, a total of 126 sets of data were collected in November, December and January 2020 at N38°52′ E115°29′, and 24 m above sea level.
Figure 6. (a) Three sunshape model curves; (b)-(d) Three sets of sunshape data measured by CCD camera and illuminometer (CSR=0.3, 0.4, 0.5)

Figure 6a shows the measured sunshapes under different CSRs. Figure 6b-d shows three sets of measured data in which the blue dot is the sunshapes extracted from the pictures of the sun. The red “+” symbol is the processed brightness data measured by the illuminometer. The solid black line is the Buie sunshape model that matches the measurement data. There are also pictures of the sun during the experiment, DNI and AMs. As can be seen from the Figure 6, with the atmosphere becomes turbid, which increases the scattering of sunlight and blurs the boundaries of the sun disk, the CSR increases. Data measured by illuminometer at different atmospheric turbidity (CSR) conditions verify the accuracy of the CCD camera measurement data well and match the Buie sunshape model well. It means that the sunshapes and CSRs measured by CCD camera with light-reducing devices are reliable.

6. The calculation method of DNI with different FOV

Figure 7. (a) Schematic diagram of trough concentrator; (b) The relationship between $\eta$ and CSR

In the simulation of power generation or power forecast of CSP systems, DNI$^5$ is usually used as the input, but not all direct solar radiation can be intercepted due to the difference in the acceptance angle of concentrators, leading to overestimation of the simulation results. A simulation of the parabolic trough concentrator by ray tracing is taken, and the parabolic trough concentrator has a focal length of 1.71 m, a width of 5.76 m and its receiver has a diameter of 0.07 m (Figure 7a). The interception ($\eta$) is defined as the proportion of the energy intercepted by the receiver to the total energy of the incident light cone. The relationship between $\eta$ and CSR (the incident light cone-apex angle is 5°) is shown in Figure 7b. It can be seen that not all the energy is intercepted by the receiver, which means that the acceptance angle of the parabolic trough concentrator is smaller than 5°. It is calculated that when the incident light cone-apex angle is within 1.36°, all energy can be intercepted by the receiver, so when simulating the power generation or power forecast of this CSP model, DNI1.36° is more accurate as an input. Other CSP simulations should also require more accurate DNI calculation.

The calculation of DNI for different FOVs proposed in this paper is based on Buie sunshape model and the measured DNI$^5$. Sunshape model’s mathematical expression is as below

$$\phi(\theta) = \begin{cases} \cos(0.326\theta) & (\theta \leq 4.65\text{mrad}) \\ \cos(0.308\theta) & (\theta > 4.65\text{mrad}) \\ e^{\gamma\theta^\phi} & (\theta > 4.65\text{mrad}) \end{cases}$$

$$\gamma = 2.2\ln(0.52\chi)^{0.43} - 0.1$$
\[ \kappa = 0.9 \ln(13.5 \chi) \chi^{-0.3} \]  

\( \chi \) is CSR, \( \phi \) is sunshape.

There is a reasonable assumption that the radial solar spatial energy distribution has radial symmetry[6]. So the relative DNI for different FOV can be calculated by formula 8.

\[ \Psi = 2\pi \int \phi(\theta) \sin \theta d\theta \]  

(8)

\( \Psi \) is the relative DNI. Because the integral formula is a transcendental equation, it is hard to give analytical solution. In this study, the numerical integration is adopted. 

\[ I = \sum 2\pi RH \phi(\theta \cos \theta) \]  

(9)

\[ H = R(\sin(\theta + \Delta \theta) - \sin \theta) \]  

(10)

Figure 8. Scheme of numerical integration of irradiation

The sun and the surrounding sky are regarded as a spherical crown (figure 8). The spherical crown is cut into rings according to the angle \( \theta \), and the relative radiance of each ring is calculated. Finally, the relative DNI is equal to the sum of rings’ relative radiance as below

I is the calculated relative DNI. \( H \) is the height of the ring area. \( R \) is the radius of spherical crown. \( \phi \) is sunshape. The \( \cos \theta \) is due to the cosine effect. By using formula 9, the relative DNI (different FOV) and the ratio of DNI (different FOV) to relative DNI \( 5^\circ \) can be obtained. Then the absolute value of DNI (different FOV) can be calculated with DNI \( 5^\circ \) measured by pyrheliometer.

Figure 9. DNIs for different FOV (the numbers are CSRs at that moment)

Figure 9 shows DNIs (different FOV) calculated using DNI \( 5^\circ \) and CSR measured on November 11, 2019. At 12 o’clock, CSR is 0.28 and the difference between DNI \( 1.36^\circ \) and DNI \( 5^\circ \) is 81 W/m2, accounting for 10.5% of DNI \( 5^\circ \), which is enough to influence the simulation result of the parabolic trough solar power plant mentioned above. So the calculation method of DNI for different FOV should be adopted to improve the accuracy of CSP simulation.

7. Conclusion

In this study, a method of measuring CSR and sunshape using the CCD camera with filters is developed, and the feasibility of the method is verified by the data measured by the illuminometer. The measured sunshape with Buie sunshape model is well consistent under different CSR conditions. The method has the advantages of intuitive, reliable, low accuracy of solar tracking and low overall cost, but the camera cannot meet the needs of solar power plants in terms of rain and dust resistance. It can only be used for experimental research. Also a calculation method of DNI for different FOVs is
proposed, which is mainly based on sunshape model and measured DNI5°. The calculation method can improve the accuracy of the CSP simulation, in which the concentrators have different acceptance angle.

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