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基于光锥耦合的分光谱辐射表入射系统设计

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摘　要:为了实现直接辐射的太阳能量的耦合,设计了一种分光谱辐射表入射系统。根据气象辐射理论对直接辐射表的尺寸进行约束,利用几何光学理论设计导光锥,使收光筒与光纤部分实现低损耗连接,解决光纤与收光筒直接耦合时能量较弱的问题.通过在太阳模拟器下模拟的真实辐照度,测试整个入射系统不同波长处的耦合效率,以及不同跟踪角度误差下耦合效率的变化.理论分析表明,导光锥和光纤两轴线的横向偏移是引起耦合损耗的主要因素.实验结果表明:系统的耦合效率为 66.24%,在太阳跟踪器完全跟踪不到太阳直接辐射时,耦合效率为 12.8%,反映了环日辐射和散射辐射水平.该系统可满足太阳直接辐射观测的入射系统要求.

关键词:分光谱辐射表;收光筒;直接太阳辐射;导光锥;耦合效率;影响因素分析

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Design of Spectroradiometer Incidence System Based on Lightcone Coupling

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Abstract: A spectroradiometer incidence system was designed to realize the coupling of direct irradiance. In order to reduce energy loss between light-collecting barrel and fiber, and solve the problem of low energy level in direct coupling, the characteristic dimensions of the barrel were restrained, the lightcone parameters were calculated according to the geometrical optics theory. The coupling efficiency in different wavelengths and change of efficiency under different tracking angle errors were tested by solar simulator. The theory analyses indicate that axis's lateral offset of lightcone and fiber is the main factor that caused coupling efficiency loss. Experimental results indicate that the coupling efficiency of the whole system is 66.24%, the efficiency is 12.8% when the sun tracker miss the sun completely, which reflects the level of circumsolar radiation and scattered radiation. The system can satisfy the requirements for the observation of direct solar irradiation.

Key words: Spectroradiometer; Light-collecting barrel; Direct normal irradiance; Lightcone; Coupling efficiency; Analysis of influence factors

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0 Introduction

The measurement of direct normal irradiance is mainly used to confirm the atmospheric turbidity and the depth of aerosol[1]. Besides, it is also applied into medicine, biology, agriculture and solar energy[1]. The atmospheric turbidity can express the degree of the solar radiation weakened by the atmospheric aerosol, and indicate the atmospheric transparency, which is an important parameter in climate change study. EKO Instrument proposed a kind of compact all-weather spectroradiometer, Full Width at Half Maximum (FWHM) of spectral resolution is 10 nm[2]. The Eppley laboratory in the United States focus on the development and research of ultraviolet spectroradiometer, infrared radiometer and sunshine intensity meter, its 240-8111 hemispherical total spectroradiometer can receive net radiation of short wave and long wave radiation precisely, with 180° field of view and wavelength ranging from 0.3～30 μm[3]. CE318 sun photometer produced by France CIMEL ELECTRONIQUE has a good performance in sun spectrum monitor, and is applied into meteorological observation of many regions over the world [4].

In this paper, a kind of incident optical system is designed. It includes light-collecting barrel, lightcone and fiber. Using lightcone as the coupling component can solve the contradiction between enlarging incidence energy and achieving pupil docking. To maximize the coupling efficiency, geometrical optics theory is applied to designing the lightcone[5], the coupling efficiency under different wavelengths and tilt angles is tested.

1 The design of spectroradiometer incidence system

The system of spectroradiometer is shown as Fig. 1, it is consisted of incidence system, spectral separate system and detector system. Light received from incidence system is separated by grating, then imaged on the surface of detector. Thus, it realizes the separation of different wavelengths. The transmitting efficiency of the incident system greatly affects the resolution of the whole instrument. So, coupling the solar energy adequately into the optical system is an important factor in the design of spectroradiometer.

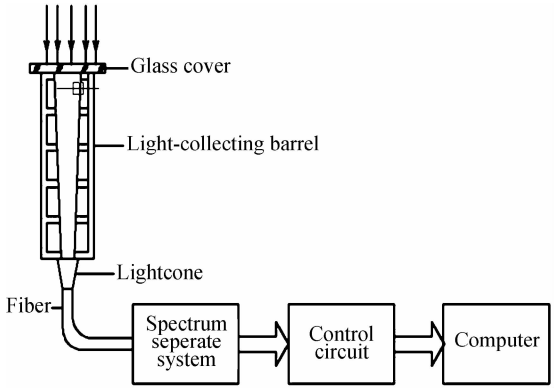

Fig. 1 The components of spectroradiometer

In normal meteorological pyroelectric instrument, fiber is usually directly coupled with light-collecting barrel. It's coupling efficiency is about 30%～40%. For spectroradiometer, the incident energy is decided by the dimension of light-collecting barrel. If the direct coupling method, is adopted to achieve pupil docking, the small end of the light-collecting barrel will be the same diameter with fibercore. In this case, dimension of light-collecting barrel will be small. Thereby, the energy into the system will be very weak, besides, coupling efficiency of direct coupling is very low. So the resolution decreases significantly in this way.

1.1 Design of light-collecting barrel

The measurement of Direct Normal Irradiation (DNI) is defined in the World Meteorological Organization (WMO) Guide (WMO 2010), direct solar radiation is measured by means of pyrheliometers, the receiving surfaces of which are arranged to be normal to the solar direction[6]. By means of apertures, only the radiation from the sun and a narrow annulus of sky is measured, the latter radiation component is sometimes referred to as circumsolar radiation or aureole radiation. [6]

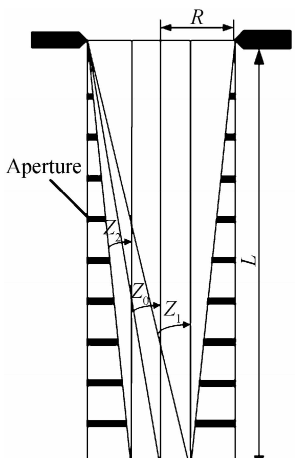

Fig. 2 Sketch of light-collecting barrel

Circumsolar radiation is generated by the effect of atmospheric scattering. The radiation level, of which the detector can detect, affects the accuracy of direct normal irradiation. While, circumsolar radiation is restricted by the characteristic dimensions of light-collecting barrel. The solid angle of circumsolar radiation is 5°, but the DNI is only 0.5°. To separate such a small angle, the light-collecting barrel will be too long to alignment and use. Besides, with the sun rose and fell, light-collecting barrel needs to be installed on the sun tracker to alignment the sun all the times. The WMO guide recommends an opening half-angle of 2.5° and a slope angle of 1° [7]. Fig. 2 shows the sketch of light-collecting barrel, where R, r, L are the characteristic dimensions of light-collecting barrel. The slope angle is defined as

$$\begin{cases} a=\dfrac{R}{r} \\ b=\dfrac{L}{r} \end{cases} \tag{1}$$

Half open angle Z_0 is

$$Z_0=\arctan(a/b) \tag{2}$$

Bevel angle Z_2 is

$$Z_2=\arctan[(a-1)/b] \tag{3}$$

Constraint condition is

$$\begin{cases} Z_0=2.5° \\ Z_2\leqslant 1° \end{cases} \tag{4}$$

As the front of the whole incidence system, light-collecting barrel is a tube with a series of apertures. Apertures are used to ensure the instrument's field of view, and to prevent the effect of stray radiation on tube wall and weaken the influence of airflow.

1.2 Design of lightcone

The design of lightcone can be analyzed by geometrical optics theory, its diameter varies linearly with the length of the fiber. Fig. 3 is the meridian ray transmitting in the lightcone. Locating δ is cone angle ψ, which decreases with the increase of reflection times, is reflecting angle on core-skin interface[8-9]. From the geometrical relationship and refraction law, the reflection angle is

$$\psi_n=90°-\frac{n_0}{n_1}\arcsin\varphi-(2m-1)\frac{\delta}{2} \tag{5}$$

where m is the reflection time number, φ is the incidence angle, the same to Z_0, n_0 and n_1 are the refractive indices of air and core respectively. When the light incident into the big end, due to the decreases of reflection angle ψ_n with the increases of reflecting number, total reflection condition can be destroyed, until the total reflection condition does not satisfied[10].

According to the total reflection condition, in order to make all the incident lights exit from the other end of lightcone, it should be satisfied that

$$\sin\left(\xi+\frac{\delta}{2}\right)\leqslant\frac{a_1}{a_2}\left[1-\left(\frac{n_2}{n_1}\right)^2\right]^{1/2} \tag{6}$$

The Eg. (6) can be expanded as

$$\sin\xi\cos\frac{\delta}{2}+\cos\xi\sin\frac{\delta}{2}\leqslant\frac{a_1}{a_2}\left[1-\frac{n_2}{n_1}^2\right]^{1/2} \tag{7}$$

where a_2 and a_1 is the radius of the incident and the exit end of the fiber, n_2 is the refractive index of cladding. Because the cone angle is very small, $\cos(\delta/2)\approx 1$, it can be obtained that

$$\sin\left(\frac{\delta}{2}\right)\leqslant\frac{\frac{a_1}{a_2}\left[1-\left(\frac{n_2}{n_1}\right)^2\right]^{1/2}-\sin\xi}{\cos\xi} \tag{8}$$

From the geometrical relationship in Fig. 3

$$\sin\left(\frac{\delta}{2}\right)=\frac{a_2-a_1}{l} \tag{9}$$

where l is the length of the lightcone as

$$l\geqslant\frac{1}{2}\frac{2(a_2-a_1)\cos\theta}{\frac{a_1}{a_2}\left[1-\left(\frac{n_2}{n_1}\right)^2\right]^{1/2}-\sin\theta} \tag{10}$$

Meanwhile, the parameters r, R are decided by the small end radius of light-collecting barrel and fiber core radius separately.

When connects fiber and lightcone, the matching of the characteristic parameters of each other needs to be considered. Suitable core diameter and refractive index of core and cladding and Numerical Aperture (NA) are important to fiber.

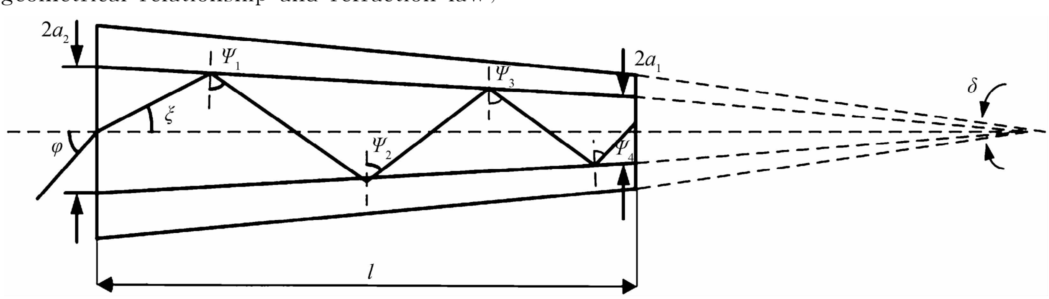

Fig. 3 Light transmit in the lightcone

2 Coupling experiment

2.1 System parameters and experimental apparatus

According to Eg. (4), parameters of light-collecting barrel are shown in Table 1.

Table 1 Light-collecting barrel

Parameters	Values
Material	Aluminum alloy
Big end dia. ($2R$)/small end dia. ($2r$)	10 mm/6 mm
Length	114.5 mm

The lightcone in experiment is produced by drawing bundles of fused silica fiber into cone. Out of the cone, there is black protective glass, which protects the fiber, it also can prevent stray light. The outermost is encased by aluminum shell. Based on constraint conditions in Eg. (2), its basic parameters are shown in Table 2.

Table 2 Light cone parameters

Parameters	Values
Core material	Fused silica
Core/cladding refractive index	1.62/1.49
Big end dia. /small end dia.	6 mm/1 mm
Length	50 cm

The max coupling efficiency can be obtained, when the diameter of lightcone's small end is the same with fiber core diameter, and these two objects have the same refractive index[11]. So, fiber in this system has a 1.62 core refractive index, 1mm core diameter and 0.3 m length.

The experimental device includes solar simulator, spectrometer and rotary working table. The solar simulator is high collimation, and its spot uniformity can reach 1%, besides, its irradiance is adjustable ranging from 100 ~ 1200 W/m^2 [12-13]. Fig. 4 is the experimental device. The tilt angle is achieved by rotary working table, the model of spectrometer is Avantes company's AvaSolar-1.

Test result of coupling efficiency experimental is shown in Fig. 5. The test wavelength ranges from 350 nm to 1100 nm. The coupling efficiency is 66.24%. Both in the grating system and detector system, incident signal level should be higher than stray light level, so that, recording value could be effective. For example, the lowest response irradiance of pyrheliometers is 120 W/m^2. After the incidence system, the irradiance on the grating is 79.48 W/m^2, which can satisfy spectral separation and detector.

Fig. 4 Experimental apparatus

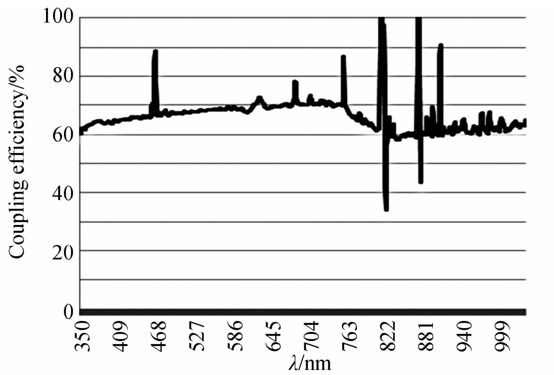

Fig. 5 Coupling efficiency in different wavelength

Solar spectrum has different distribution regularities in different wavelength. So the incidence system needs to deliver solar spectrum truly[14]. Meanwhile, reasonable integration time can ensure good Signal to Noise Ratio (SNR). From the Fig. 5, the average coupling efficiency in different wavelength is about 65%. It is a little higher between 620 nm and 740 nm. Due to the fluctuation of the solar spectrum, the coupling efficiency of the near infrared band can be relatively volatile[15]. This fluctuation can be eliminated by large cardinal number experiments. This experiment proved that, the energy loss in different wavelength changes little after the incidence system and can transfer the energy veritably.

Direct normal radiation spectroradiometer is working coordinated with solar tracker. When the collecting-light barrel align the sun in different tilt angle, each coupling efficiency is tested, the result is shown in Fig. 6. Tracking accuracy of solar tracker can be reduced in extreme weather or by equipment trouble. As shown in the Fig. 6, the coupling efficiency decreases almost linearly with the increase of the tilt angle, the barrel′s incidence half angle is 2.5°. So no direct normal irradiance enters into the system when the barrel tilts 2.5°, then energy detected is absolutely circumsolar scattered radiation. The coupling efficiency 12.8% shows the energy level of circumsolar radiation and scattered radiation.

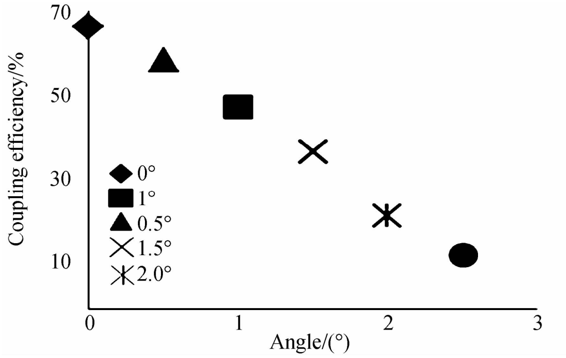

Fig. 6 Coupling efficiency in different angel

3 Analysis of affecting factors of coupling efficiency

The coupling efficiency test shows the average coupling efficiency is 66.24%, about one-third energy loss on the incidence system. The following is the loss analysis. There are four main effecting factors: Fresnel Effect on the face of fiber and lightcone; axes of light-collecting barrel, lightcone, and fiber are not consistent; axes angle deviation and offset between each of the three objects. Because the contact area of light-collecting barrel and lightcone is far bigger than lightcone and fiber, the loss caused by the former can be ignored. The following contents focus on the energy loss on lightcone and fiber coupling[16].

Although analysis of direct coupling loss in geometrical method is not preciser than Fluctuation theory, it accurately provides useful information for the loss and impact factors. The Fresnel Effect of the fiber and lightcone end face can be expressed as the Fresnel formula

$$\rho=\left[1-\left(\frac{n_1-n_0}{n_1+n_0}\right)^2\right] \tag{11}$$

where n_1 is refractive index of fibercore, n_0 is refractive index of air.

In theory, as to multimode fiber, θ represents incidence angle of light. When $\cos\theta=\cos 2.5°\ll 1$, refractive index difference between fibercone and surrounding medium is Δ, here $\Delta=8\%$. Assuming matching coefficient is $p=n_1/n_0$, the optical transmittance τ is

$$\tau\approx\frac{16p^2}{(1+p)^4}[1+F(\varepsilon^2)] \tag{12}$$

Based on the hypothesis above, the influence of various errors on the coupling efficiency of the lightcone and fiber can be discussed. Fig. 7 shows the influence factors coupling efficiency.

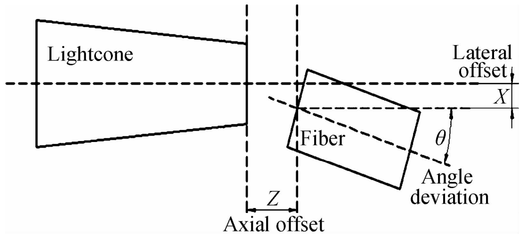

Fig. 7 Sketch map of coupling loss

3.1 Axial offset

Assume the diameter of fibercore and small end of lightcone are both r, the distance between two objects is z. From geometrical optics theory, the coupling efficiency is

$$\eta=\frac{16p^2}{(1+p)^4}\left[1-\frac{z}{4r}p(2\Delta)^{1/2}\right] \tag{13}$$

The relationship between coupling efficiency and x is given in Fig. 8. The solid line is the theoretical value. As the fibercore in the experiment is homogeneous, the numerical difference Δ of core and cladding is 8%. In practical use, we can add fiber matching liquid between the two end. $p=1$ is the condition of adding fiber matching liquid, $p=2$ is in the air. The coupling efficiency is significantly improved.

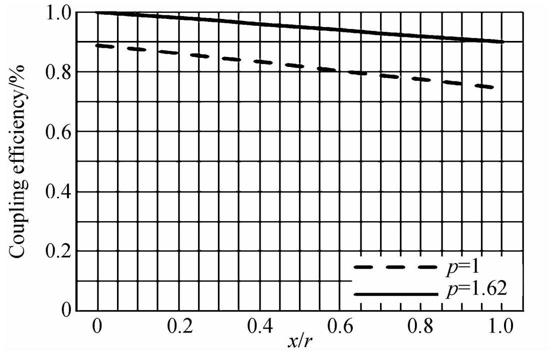

Fig. 8 The relationship between coupling efficiency and x/r

3.2 Lateral offset of fibercore

Lateral offset of two axes is X. In this case, only the light on the overlapping part of lightcone and fiber can be transmitted, so that

$$\eta=\frac{16p^2}{(1+p)^4}\left[2\arccos\left(\frac{X}{2r}\right)-\left(\frac{X}{r}\right)\left[1-\left(\frac{X}{2r}\right)^2\right]^{1/2}\right] \tag{14}$$

The relationship between coupling efficiency and z/r is given in Fig. 9. Contrast Fig. 8 and Fig. 9, it can

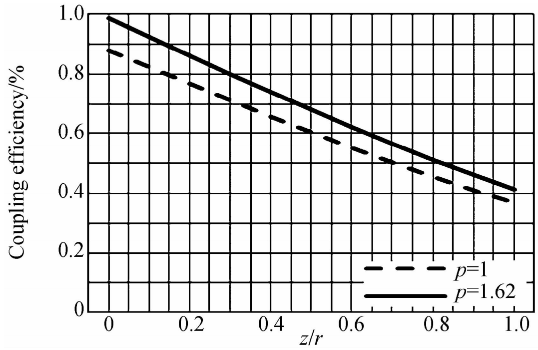

Fig. 9 The relationship between coupling efficiency and z/r

be seen, adjustment precision of lateral offset z is much higher than axial offset x. Adding fiber matching liquid can also improve the coupling efficiency.

3.3 Angle deviation of axes

The deviation angle between the two optical axes is θ, so the coupling efficiency is

$$\eta=\frac{16p^2}{(1+p)^4}\left[1-\frac{\theta}{\pi p(2\Delta)^{1/2}}\right] \tag{15}$$

The relationship between coupling efficiency and is given in Fig. 10.

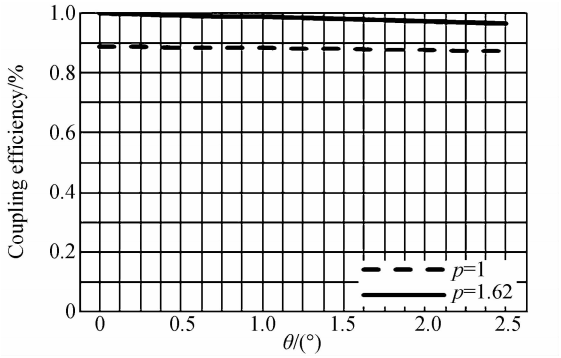

Fig. 10 The relationship between coupling efficiency and θ

The coupling efficiency is most sensitive to the lateral offset, the second is the axial offset, and then the angle deviation. In practical, the axial offset can be removed by closing the two end face, and bonding with fiber matching liquid instead of air. The biggest factor of the coupling loss is the lateral offset of the fiber and the lightcone axis. It needs high precision mechanical loading and processing technology to realize. Moreover, the effect of fiber bending should not be ignored. The longer the wavelength is, the more sensitive to the fiber blending. So trying to avoid the bending of the fiber in large angle should be noticed.

4 Conclusion

In this paper, the lightcone is used to coupling the solar energy into the whole radiance system to maximize the coupling efficiency. The lightcone is designed based on the theory of geometrical optics. Energy test in the incidence shows the coupling efficiency is 66. 24%. The experiment in different wavelengths and tilt angles indicates that coupling efficiency changes greatly in near infrared band. Finally, factors that affect the coupling efficiency are analyzed. As the suggestion, the later prototype test can use lightcone melting on the fiber to decrease Fresnel effect and optical axis inconsistency. This paper also has reference significance on the design of the direct normal radiance spectroradiometer.

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