Design of divergence solar simulator with large irradiated surface and high uniformity

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Abstract: To achieve solar irradiation with large spot diameter, the divergent solar simulator with large irradiated surface was designed. The short arc xenon lamp was selected as light source based on the characteristics of solar spectrum distribution. The mathematical model for light source was built. Considering imaging ratio and peak brightness xenon arc point relative to defocus, the optical filter and condenser system was designed, the irradiate uniformity of the solar simulator was improved. At the same time, based on the spectral characteristics of short arc xenon lamp, a spectral matching model was established, the optical filter transmittance at different wavelengths was designed. Experimental results show that the divergent solar simulator has large irradiation area about $\Phi2\,\mathrm{m}$, When the working distance is 6, 8, 10 m, the irradiation non-uniformity of the simulator is superior to 3.33%, 3.51% and 4.3% respectively, and the spectra match A level standard of the AM1.5 solar spectrum.

Key words: solar simulator; divergence; large spot; high uniformity

大光斑高均匀度发散式太阳模拟器设计

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摘　要：为了实现大光斑直径高均匀度太阳辐照模拟，设计了大光斑发散式太阳模拟器。根据太阳光谱分布特性选取短弧氙灯作为光源，建立光源功率计算模型；基于成像倍率和氙弧峰值点离焦量之间的关系，优化设计聚光系统和光学积分器，提高太阳模拟器的辐照均匀度；同时，结合短弧氙灯的光谱特性，建立光谱匹配模型，设计光学滤光片在不同波长的透过率。实验结果表明：设计的发散式太阳模拟器辐照面积为 $\Phi2\,\mathrm{m}$，当工作距离为 6、8、10 m 时，辐照不均匀度分别优于 3.33%、3.51% 和 4.3%，且光谱与 AM1.5 太阳光谱 A 级标准相匹配。

关键词：太阳模拟器； 发散式； 大光斑； 高均匀度

0 Introduction

The solar simulator is a kind of experiment and test equipment that simulates sunlight on the ground. It uses the light collecting system and the uniform light system, work with the light source and the filter close to the solar spectrum to simulate the solar radiation characteristics. The existing solar simulator is classified into collimated solar simulator and divergent solar simulator according to the exit mode. The collimated solar simulator has a collimator in optical system, it can simulate solar radiation distance and solar radiation angles[1-2]. But the effective irradiation area is limited by the collimator lens diameter, usually only $60-300$ mm; and divergent solar simulator optical system does not contain collimator lens, although can not achieve the sun′s radiation distance and solar radiation angle simulation, but the radiation area is no longer subject to collimator lens diameter limit, it can simulate a larger irradiation area, if use the optical splicing method, the radiation area can up to ten meters[3-5].

In order to meet the needs of solar radiation measurement instruments, spacecraft, new materials, new space environment simulation experiments, precision calibration and performance testing, in recent years, many scholars at home and abroad have carried out divergent solar simulator research. In 2008, IES-UPM was designed to develop a solar simulator for converged photovoltaic systems, compared with the conventional solar simulator, it has a radiation angle similar to the sun, which increases the area of the photovoltaic cell [6]. In 2013, Changchun Institute of Optics, Precision Mechanics and Physics, Chinese Academy of Sciences designed a AM0 solar simulator with a large irradiated surface, and the work distance is 4 m, the irradiation surface diameter is 1 m, non-uniformity is superior to 5%, and irradiance is 0.8 solar constant, and the spectrum matched the C level of AM0 solar spectrum[7]. In 2014, Beijing Aerospace Long March Institute of Aircraft Research published a patent, used the five-way xenon lamp projection optical system composed a large-scale spot divergent

solar simulator, spot diameter is 5 m, irradiance reached the $0.7-1.3$ solar constants[8]. In 2015, Beijing Institute of Environmental Properties and the Optical Radiation Key Laboratory, by optical splicing technology, designed a solar simulator with the effective spot diameter is 2.43 m, working distance is 5 m, non-uniformity is 2.8%, spectral mismatched error reached C Level[9]. In 2017, Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, using the four xenon lamp arrays as light source to design a projection solar simulator and irradiation area is 1 m×1 m, irradiance reached a solar constant and the non-uniformity is 4.82%[10].

In this paper, the optical system of the large light spot divergent solar simulator is studied, the light source analysis and selection method are discussed, and the concentrating system and the optical integrator are designed. The calculation method of the optical filter transmittance is studied and verified by experiments. The solar simulator optical system is designed, and the sun simulator irradiance up to 0.1 solar constant, irradiation surface diameter is $\Phi 2$ m, when the working distance between $6-10$ m changing, the uniformity of the surface is superior to 4.3%. At the same time, the spectral matching error is superior to the A-level requirement specified in GB/T12637-90.

1 Composition of the optical system

Divergent solar simulator optical system mainly contains the light source, condenser system, optical integrator and optical filter and other components[11-14].

Using the light source as solar simulator light source, which radiation spectrum energy distribution close to real sunlight the light source[15]. We placed the light source in the first focus of the condenser system, after the role of the condenser system, the beam issued by the light source with axis symmetry is converged to the second focal point of the concentrating system, and form a minimum spot. At the same time, the optical integrator is placed at the second focal point of the converging system, and the smallest spot converged by the converging system is superimposed on the symmetrical division by each

channel of the optical integrator. And the beam imaged at the working distance to form a imaging surface which irradiance distributed uniformly, thus realized the simulation of sunlight.

2 Design of the component

The design of the divergent solar simulator optical system focuses on improving the energy efficiency, the uniformity of the radiation surface and the spectral matching, and the requirement for the aberration of the system is not high. In the design, according to the requirements of the emission irradiance, we calculated the power of the light source and selected the light source type. For the light source characteristics, optimized and designed the ellipsoid condenser and the optical intergrator with a certain axial imaging magnification and inclusion angle, ensured the effective irradiation surface diameter is $\Phi 2$ m. The irradiance is $0.1S_0$ (S_0 refers to solar constant. The solar constant refers to the solar radiation per second per unit area perpendicular to the sun's rays over the average distance between the sun and the sun($D=1.496 \times 10^8$ km)), the non-uniformity of the irradiation surface is superior to 4.3%. At the same time, the optical filter is designed to match the A level of AM1.5 solar spectrum.

2.1 Design and selection of light source

Combined with the requirements of the light source of the divergent solar simulator, this paper chooses the short arc xenon lamp as the solar simulator light source. The radiation spectrum energy distribution of the short arc xenon lamp is close to the solar irradiation spectrum, and the spectral energy distribution does not change with the input power, and the spectral distribution is almost unchanged during the working cycle. At the same time, short arc xenon lamp work to form a very small area of the cathode spot, xenon lamp anode and cathode shape is different, the cathode is a certain angle of the triangular pyramid shape, the head of the vertex for the small cross-sectional area, it can be seen as point

material, that is conducive to optical system design. In addition, the stability of shine characteristics of the cathode spot is subject to the external environment smally, photoelectric parameters have good consistency and light efficiency is high.

According to the requirements of the solar simulator for irradiance, the light efficiency and shine characteristics of the short arc xenon lamp, the focusing efficiency and reflectance of the concentrating system, the aperture utilization and transmittance of the optical integrator, the diameter of the irradiated surface and the energy loss in the beam transmission, we established the power calculation model for the short arc xenon lamp, which is shown in equation (1).

$$E = \frac{4PGNK_eK_cK_aK_r^nK_t}{\pi D_0^2} \qquad (1)$$

Where K_e is the photoelectric conversion rate of xenon lamp; K_c is the concentrating efficiency of ellipsoidal condenser; K_a is the optical integrator aperture utilization; K_r is the reflectivity of ellipsoidal mirror (reflectivity of steering plane mirror); K_t is the optical integrator (field mirror and projection mirror) transmittance; K_w is the transmissivity of converging optical systems; E is irradiance; P is xenon lamp power; N is the number of lamps; n is the number of reflection; D_0 is the diameter of the radiation surface.

Calculated, we need xenon lamp power is $P = 8$ kW. Taking into account the xenon lamp after a long time working, there is a phenomenon that power reduction caused by aging, the actual xenon lamp power is higher than the power of theoretical calculation, select the short arc xenon lamp as shown in Fig.1.

Fig.1 Object pictures of short arc xenon lamp

2.2 Condenser system design

Usually used condenser elements are lenses, photonic sieve and mirrors. Among them, the lens and photonic sieve not only manufactured difficult and energy wasted, compared, the mirror can effectively improve the utilization of light. In order to converge the radiation flux emitted by the short arc xenon lamp more fully, select the ellipsoid condenser as the condenser system of the divergent solar simulator.

The concentrating efficiency of the ellipsoid condenser is the ratio of the total light energy emitted by the xenon lamp and the energy of the second focal plane which the ellipsoid condenser converged to, it expressed by K_c, as shown in equation (2).

$$K_c = \frac{2\pi \int_{u_0}^{u_m} t(u)\sin u \, du}{2\pi \int_{0}^{180°} t(u)\sin u \, du} \quad (2)$$

In the formula, $t(u)$ −xenon lamp irradiance relative distribution in different directions, $t(u) = I/I_0$; u −xenon lamp axis with the angle; I −xenon lamp shine intensity into the u angle direction of the axis; I_0 −luminous intensity of arc xenon lamp.

The imaging magnification M_0 of the ellipsoid condenser mainly depends on the ratio of the first focal length f_1 of the ellipsoid and the second focal length f_2, the convergence angle of the main ray of the converging beam, the outline of the simulator, and the uniformity of irradiation. Using the ellipsoid condenser vertex as the coordinate origin, the optical axis as the x −axis, radius y axis to establish the Cartesian coordinate system, as shown in Fig.2.
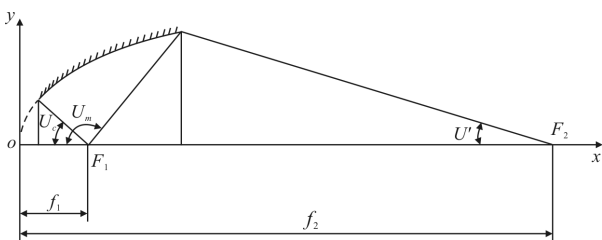

Fig.2 Overall dimension schematic diagram of condenser

According to the luminous characteristics and structural parameters of the short arc xenon lamp, we used the equation (3) to design the main parameters of the ellipsoidal condenser.

$$y^2 = 2R_0 x - (1 - e^2)x^2 \quad (3)$$

In the formula, R_0 −vertex radius of curvature, $R_0 = 2f_1 f_2/(f_1 + f_2)$; e −eccentricity, $e = (f_2 - f_1)/(f_1 + f_2)$; U' − image aperture angle of ellipsoid condenser. The inclusion angle of the ellipsoid condenser is $(U_0 - U_m)$.

It can be calculated the first focal length $f_1 = 57.35$ mm, $M_0 = 23X$(Imaging magnification is 23), $U' = 55°$, the second focal length $f_2 = 1\,319$ mm, the vertex radius of curvature $R_0 = 109.92$ mm, the eccentricity $e = 0.916\,66$, the top opening diameter is $\Phi 62.8$ mm, the pupil diameter of $\varphi 310.36$ mm. The physical map is shown as Fig.3.
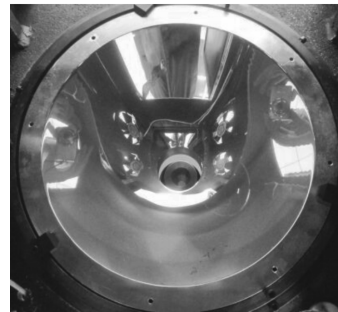

Fig.3 Object picture of consider

2.3 Design of optical integrator

The optical integrator is a key component to improve the uniformity of the radiation of the divergent solar simulator. It is mainly composed of field mirror, projection mirror, additional mirror I and additional mirror II, the structure of the optical integrator as shown in Fig.4.
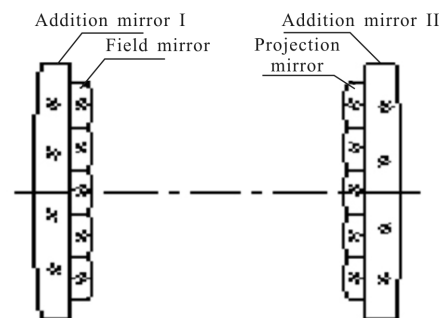

Fig.4 Structure of optical integrator

In which, the field mirror is placed at the second focal plane of the ellipsoid condenser, used unit lens

with a plurality of juxtaposed ax−symmetric optical channels to image segmentation xenon lamp spot which energy is gathered and is Gaussian distributed. And projected into the corresponding unit lens′ optical channel of projection mirror, after the projection mirror aperture, the unit lens exit and enlarge the light source, achieving energy superposition in working plane, thereby improved the uniformity of light irradiation.

From the relationship (4) between the annulus of the ellipsoid condenser and the aperture angle u and the imaging magnification M_u, it can be seen that the value of M_u is ranging from 15× to 16× when the aperture angle u changes from 0 to 600, when the aperture angle u is 55°, M_u can be 15.1×, xenon lamp spacing pole is 10.5 mm, optical integrator diameter is from 90.6 mm to 96 mm.

$$M_u = \frac{e^2 + 2e\cos u + 1}{e^3 - 1} \quad (4)$$

Select the circum-circle of the optical integrator is φ90.60 mm, the field mirror is composed by the 19−regular hexagon flat convex element lens, each element lens inner diameter is φ24 mm, circumscribed circle diameter is 27.78 mm, focal length is 120.00 mm. The 19−regular hexagonal flat convex lens is attached to the plane of the additional mirror I to form an array of optical integrator projection mirrors. Among them, the additional mirror II placed in the optical integrator projection mirror rear, the focal length is 10 000.00 mm, thickness is 8.00 mm, radius of curvature is 4 585.00 mm.

The projection lens unit lens has the same optical parameters (aperture and focal length) with the field mirror unit lens. According to the requirement (take 8 m as the design distance) of the working distance, in order to make the arc xenon lamp image on the irradiation surface, according to the geometric imaging relationship between the optical integrator field mirror element lens. The distance between the projection lens and the element lens is 120.00 mm. A 19−regular hexagonal flat convex lens is attached to the plane of

the additional mirror I to form an array of optical integrator projection mirrors. The shape of the additional mirror II is a plano-convex lens, it is placed in the optical integrator field mirror, the focal length is 1 199.30 mm, the thickness is 8.00 mm, the radius of curvature is 550.00 mm.

2.4 Design of optical filter

Spectrum energy distribution curve of xenon lamp and AM1.5 solar as shown in Fig.5. The comparison shows that when the wavelength range is 300−800 nm, the spectral distribution of the xenon light source is close to the standard curve. The energy distribution curve is almost the same in the wavelength range of 300−450 nm. In the wavelength range of 450−650 nm, the measured spectrum curve is lower than the standard spectral energy distribution curve; In the range of 700−800 nm, it is very consistently; In the wavelength range of 800−1 100 nm, the spectral distribution of the xenon light source has much spikes. Among them, the most obvious is 900, 950, 1 000 nm, compared with the AM1.5 standard spectrum curve they are higher than 100, 170, 70 $\mu W/(cm^2 \cdot nm^{-1})$.
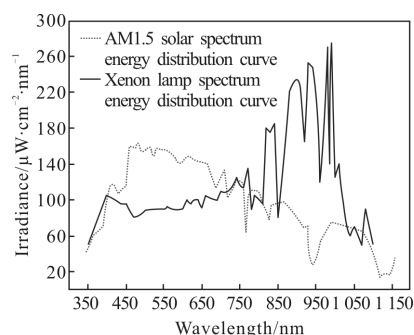

Fig.5 Spectrum energy distribution curve of xenon lamp and
　　　 AM1.5 solar

Spikes lead to the loss of solar simulator spectrum relative energy seriously, so we designed the optical filters to correct the xenon lamp spectral distribution. According to the test results in Fig.7, compared with the relative energy distribution curve of AM1.5 solar spectrum, we established the spectral correction model, as shown in equations (5)−(11).

$$T_{\max}=\left(\int_{300}^{500}T_1f(x_1)\mathrm{d}x_1+\int_{500}^{600}T_2f(x_2)\mathrm{d}x_2+\int_{600}^{700}T_3f(x_3)\mathrm{d}x_3+\right.$$

$$\int_{700}^{800}T_4f(x_4)\mathrm{d}x_4+\int_{800}^{900}T_5f(x_5)\mathrm{d}x_5+$$

$$\left.\int_{900}^{1100}T_6f(x_6)\mathrm{d}x_6\right)\Big/\sum_{j=1}^{6}A_j \qquad (5)$$

$$14.8\%\leqslant\int_{300}^{500}T_1f(x_1)\mathrm{d}x_1\Big/\sum_{j=1}^{6}A_i\leqslant22.20\% \qquad (6)$$

$$16.08\%\leqslant\int_{500}^{600}T_2f(x_2)\mathrm{d}x_2\Big/\sum_{j=1}^{6}A_i\leqslant24.12\% \qquad (7)$$

$$14.64\%\leqslant\int_{600}^{700}T_3f(x_3)\mathrm{d}x_3\Big/\sum_{j=1}^{6}A_i\leqslant21.96\% \qquad (8)$$

$$11.84\%\leqslant\int_{700}^{800}T_4f(x_4)\mathrm{d}x_4\Big/\sum_{j=1}^{6}A_i\leqslant17.76\% \qquad (9)$$

$$9.68\%\leqslant\int_{800}^{900}T_5f(x_5)\mathrm{d}x_5\Big/\sum_{j=1}^{6}A_i\leqslant14.52\% \qquad (10)$$

$$12.88\%\leqslant\int_{900}^{1100}T_6f(x_6)\mathrm{d}x_6\Big/\sum_{j=1}^{6}A_i\leqslant19.32\% \qquad (11)$$

In the formula, $T_{\max}$ −the maximum transmittance of the system after the optical filter; T_i −the transmittance of the corresponding wavelength range; $\sum_{i=1}^{6}A_i$ −the sum of the area values of the irradiated curve in all wavelength range.

When using the spectral correction model to calculate the spectral distribution rate corresponding to different wavelength ranges, in order to meet the standard spectral distribution rate, the Ti value of the energy transmittance should be selected as large as possible to ensure the irradiance of the solar simulator. The calculated spectral transmittance values corresponding to different range are shown in Tab.1.
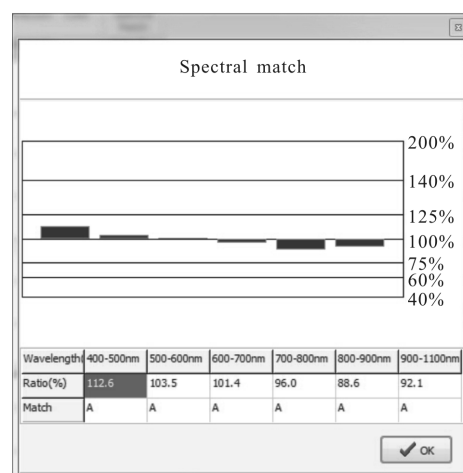
Tab.1 Spectral distribution on different wavelength range

Wavelength range/nm	Spectrum distribution of AM1.5		
	Lower than standard 20%	Standard value	Higher than standard 20%
400−500	85.2%	81.5%	77.8%
500−600	83.92%	79.9%	75.88%
600−700	85.36%	81.7%	78.04%
700−800	88.16%	85.2%	82.24%
800−900	90.32%	87.8%	85.48%
900−1 100	87.12%	83.9%	80.68%

According to the range of spectral distributions corresponding to the different range in Tab.1, we used H4 with high refractive index and stable optical performance, SiO_2 matched with H4 and with low refractive index and improved film stability, and used the Al_2O_3 with wear resistance and chemical inertia as the membrane material, used the wide transmission band method to design the periodic film system. We also used the electron beam and the ion source assisted evaporation technique to design the optical filter. The total transmittance of the system is 19.15%. Figure 6(a) shows the match between the sun simulator measured spectrum and the solar spectrum after using the optical filters. Figure 6(b) shows the spectral transmittance values of different wavelength ranges at the time of measurement.
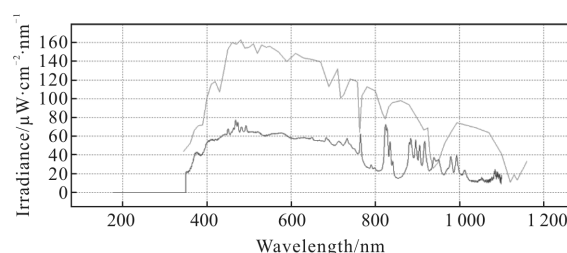
(a) Spectral energy distribution curve of xenon lamp after the optical filter

(b) Spectral distribution on different wavelength range

Fig.6 Spectral energy distribution curve and spectral measured value

It can be seen from Fig.6 that by optimizing and designing the optical filter, we solved the problem,

inconsistency between the spectral distribution of the xenon lamp and the distribution of the solar spectrum, effectively. Which ensures that the spectrum of the solar simulator is matched with AM1.5 class A standard of sun spectrum distribution in the range of $0.4-1.1\ \mu m$.

3 Experimental verification

We measured the irradiance, the irradiate uniformity and the radiation instabilities of the divergent solar simulator with large light spot. The physical map of the solar simulator is shown in Fig.7.

Fig.7 Physical map of the solar simulator

When we are testing the irradiance, in the vertical optical axis direction is divided into test grid as shown in Fig.8, test grid diameter is 2 m, every 0.1 m distribute a test circumference, the total is eight. In the circle, select test points as the distribution of "meter".
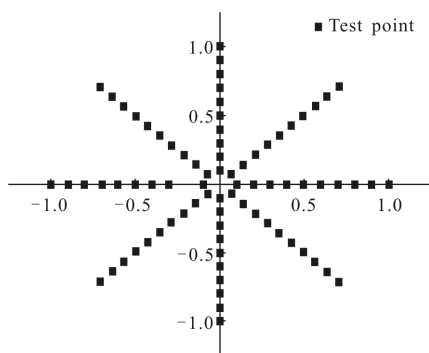
Fig.8 Distribution schematic of the tested points on the effective irradiation area

The test grid was placed at 6, 8, 10 m from the exit of the optical system, respectively, we tested the feature points.

We sorted out the test data, used the equation(12)

to calculate the non-uniformity of radiation, and draw the radiation distribution shown in Fig.9.

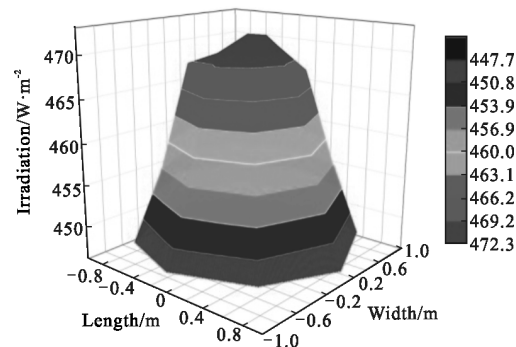$$\frac{\Delta E}{\overline{E}}=\pm\frac{E_{\max}-E_{\min}}{E_{\max}+E_{\min}}\times100\% \qquad (12)$$

In the formula, E−irradiance; $E_{\max}$−the maximum value of irradiance in-plane irradiance; $E_{\min}$-the minimum value of irradiance in-plane irradiance; $\overline{E}$− average irradiance.
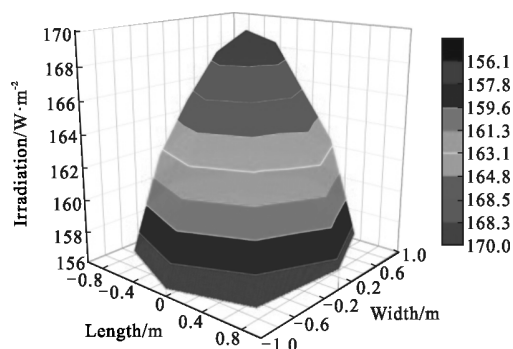
(a) Non-uniformity of the test results when the distance is 6 m from the exit of optical system
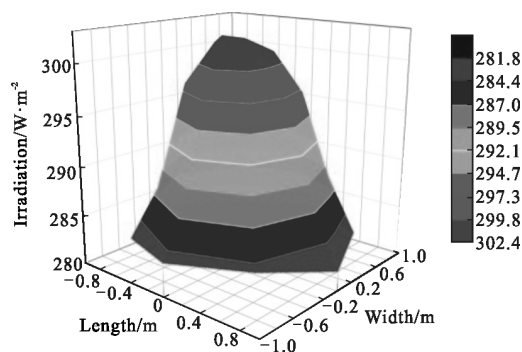
(b) Non-uniformity of the test results when the distance is 8 m from the exit of optical system

(c) Non-uniformity of the test results when the distance is 10 m from the exit of optical system

Fig.9 Test results of radiation intensity

It can be seen from the map of irradiance distribution, when the distance is 6 m from the exit of optical system, the minimum irradiance is 447.74 W/m², the irradiation non-uniformity is 3.33%; when the distance is 8 m, the minimum irradiance is 281.90 W/m². And the irradiation non-uniformity is 3.51%. When the distances is 10 m from the exit of optical system, the minimum irradiance is 156.12 W/m² and the irradiation unevenness is 4.3%.

Irradiation instability test, we treat the feature points as the test object, which the distance is 10 m from the exit of optical system, continuous measurement time is 60 minutes, we used the equation (13) to calculate the radiation instability, the measured results is shown in Fig.10. It can be seen from the figure: divergent solar simulator radiation instability is superior to 0.96%.

$$\frac{\Delta E}{\overline{E}}/T = \pm \frac{E_{\max}-E_{\min}}{E_{\max}+E_{\min}} \times 100\%/T \qquad (13)$$

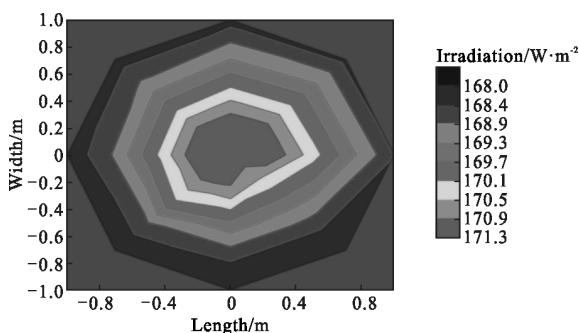In the formula, T—time interval.

Fig.10 Test results of irradiation instability

In conclusion, the irradiance of the divergent solar simulator with high uniformity is better than $0.1S_0$. When the distance from the exit of the optical system is 6, 8, 10 m, the non-uniformity of irradiation is superior to 3.33%, 3.51% and 4.3%, conform to the design requirements of the simulator.

4　Conclusion

According to the requirements of irradiation surface, irradiation uniformity, irradiation instability and spectral simulation of the divergent solar simulator, we designed a solar simulator optical system with large spot diameter, high irradiation uniformity and spectral matched level is A. We used the short-arc xenon lamp as the light source, established the power calculation model and calculated the power the short-arc xenon lamp required. Considering the concentrating efficiency, the imaging magnification and the xenon arc peak brightness point with respect to the defocus amount of f_1, we designed the condensing system. At the same time, we designed a 19−channel optical integrator as a uniform optical device, which consists of a field mirror, a projection mirror, an additional mirror I and an additional mirror II. At the same time, according to the spectral characteristics of the short arc xenon lamp, we established a calculation model o filter transmittance, designed and made optical filter. The experimental results show that the irradiation area of the divergent solar simulator we designed is $\Phi 2$ m. When the working distance is 6, 8, 10 m, the irradiance non-uniformity of the simulator is superior to 3.33%, 3.51% and 4.3% in the range of $\Phi 2$ m, and the simulation spectrum matched with the AM1.5 solar spectrum class A standard, conform to the design requirements of simulator.

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