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DEVELOP UV RADIATION SOURCE FOR CALIBRATION BASED ON THE INTEGRATING SPHERE

Dejin Yin [1], *Ming Xia* [1], *Fangsheng Lin* [1], *Tiecheng Li* [1] *Junan Ye* [1]

[1] Shanghai Institute of Measurement and Testing Technology, Shanghai, China, yinlaoshuang@icloud.com

Abstract – A UV radiation source based on the integrating sphere has been developed by means of theoretical calculation and computer simulation. The radiation source can meet the requirements of intensity and uniformity in the calibration of ultraviolet irradiance meters. By monitoring the intensity changes of the radiation source itself during the measurement, its stability can be recorded and corrected, thereby reducing the measurement error introduced by UV radiation source itself.

Keywords: UV radiation, integrating sphere, uniformity, stability

1. INTRODUCTION

UV (ultraviolet) light is electromagnetic radiation whose wavelength range is from 10nm to 400nm. UV light source and UV irradiance meters are now widely used in many areas such as materials testing, semiconductor packaging, meteorological and environmental monitoring, medical treatment and epidemic prevention. Comparison is mainly used in the calibration of UV irradiance meters. We usually choose a standard UV irradiance meter as a standard device, and then measure the tested device and the standard under the same irradiation conditions. We obtain the measurement error of the tested device by the comparison of measurement results. Low-pressure mercury lamp or high-pressure mercury lamp is chosen to be used as standard UV light source to provide the input signal. Therefore, to enhance the performance of UV light source is of great significance for reducing the system error generated in calibration[1].

Integrating sphere is used in various kinds of optical radiation measuring instruments, especially the calibration equipment of optical imaging system. The inner wall of integrating sphere should be a good spherical surface, which usually requires that deviation from the ideal spherical should be less than 0.2% of inner diameter. The whole inner wall is coated with ideal diffuse material, commonly used magnesium oxide or barium sulfate, whose reflectivity is usually close to 100%[2]. After multiple reflections in integrating sphere, the light forms uniform illumination on the inner wall. We can obtain uniform Lambert illumination anywhere on the outlet plane of integrating sphere theoretically. As a uniform diffusion light source, integrating sphere has a history of scores of years for radiometric calibration. It is shown in much past research that different geometry and occlusion conditions effect the illumination uniformity on the inner wall. In the optical experiments for the outlet of an integrating sphere, the spherical illuminance distribution given by theoretical calculation and the actual measurement results are in good agreement.

2. EFFECTS OF STANDARD UV RADIATION PROPERTIES ON CALIBRATION

A UV light source with good uniformity and stability plays an important role in calibration.

2.1. The calibration of UV meters

There are several methods we can use to calibrate UV meters. The most convenient way is to measure the tested detector and the standard detector under the same irradiation conditions, and then we can calculate the testing error of the tested detector by comparison. In order to guarantee the accuracy of the testing result, we have to maintain the consistency of the irradiation conditions. Both the tested detector and the standard detector are put at the same position relative to the irradiance source during the test.

However, it usually has to take tens of seconds or even several minutes to accomplish the calibration. Both the short term stability and the long term stability will be significant influence factors to the testing result. The diameter of the detectors of UV meters are very different. It can be from 1mm to 20mm(Fig. 1), even though we can strictly put both the tested detector and the standard detector at the same position on the same vertical plane relative to the incident light. Extra testing error still can not be avoided because of the uniformity of the UV radiation source

Fig. 1. Several tested detectors of different UV meters

2.2. The uniformity of UV radiation source

There are differences and changes in surface uniformity In Fig. 2, it is the spot photo of high-pressure mercury lamp used in the calibration of UV radiation, emitting in 2π space. It can be observed visually that the centre is brighter than the surroundings, which means the uniformity of the spot is not ideal.

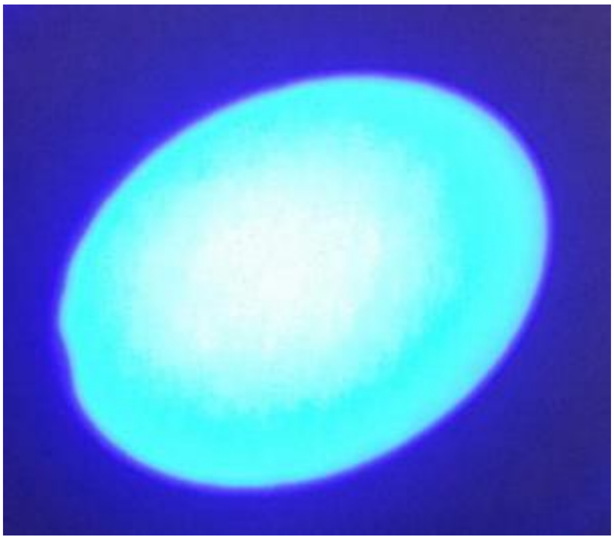


Fig. 2. The spot photo of a standard UV light source

By analysing the image in Fig. 2, it reflects the stability of radiation source from another perspective. The analysis results in Fig. 3 show that the intensity of centre spot is significantly higher than the surrounding area. We can not take the photo of the spot exactly vertical to the incident direction because the camera will block the radiation, so the spot is ellipse, which will bring error to the analysis result. But the profile of the intensity curve still seemed like Gaussian distribution.

Different UV detectors have different sizes, diameter of which ranges from 1mm to 20mm or more as shown in fig. 1. The calibration process is bound to be effected by the nonuniformity of spot radiation intensity, resulting significant measurement error[3].

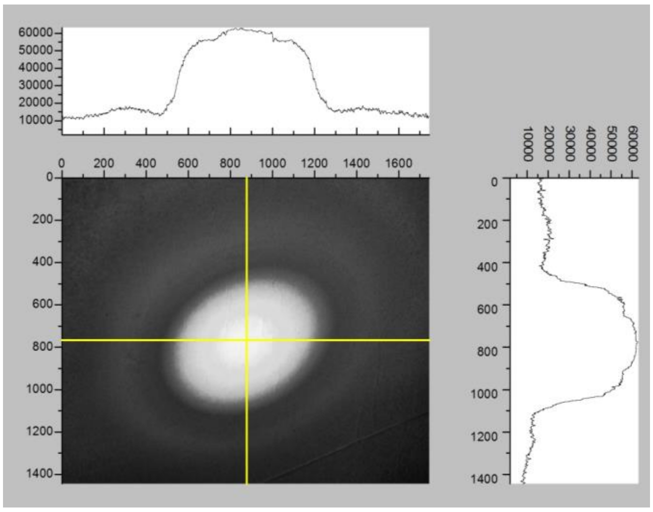


Fig. 3. The analysing data of standard UV light source spot in Fig. 2

Though we can not take the photo of the spot from the vertical direction, we still can analyze the intensity distribution of the spot by using the standard UV irradiance meter to measure the uniformity. We measure the spot intensity which is 50cm from the source. The diameter of spot is about 125mm. The measurement data and analysis results are shown in Fig. 4.

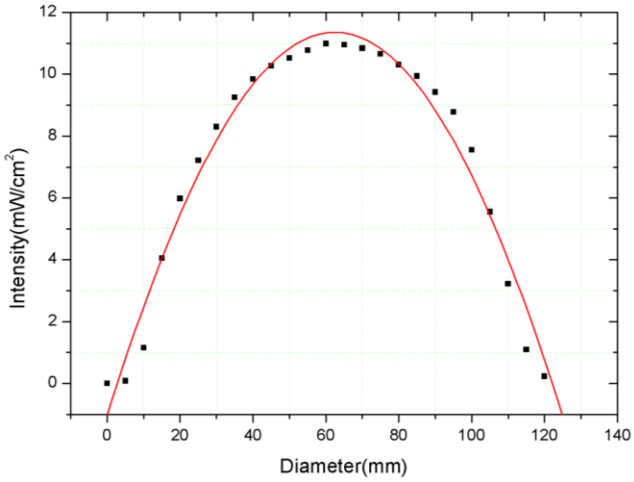


Fig. 4. The uniformity data and analysis results of a UV radiation source

The central intensity of the spot is about 11mW/cm^2, while the edge is only about 2mW/cm^2. Even in the area 125mm from the centre of the spot in diameter, the uniformity is ±5.5%, which is obviously not satisfying. As seen in Fig. 4, the spot intensity distribution showed significant Gaussian. Gaussian function:

$$y = y_0 + \frac{A}{w \times \sqrt{\pi / 2}} \times e^{-2\times(\frac{x-x_c}{w})^2} \tag{1}$$

Measurement results such as parameter, value and standard error are shown in Table 1 by curve fitting.

Table 1. The uniformity fitting results of UV radiation source in laboratory data

Parameter	Value	Standard Error
y_0	-103.3	240.8
x_c	62.4	0.5
w	261.3	289.1
A	37555.5	120388.3

2.3. The stability of UV radiation source

In many calibration labs, standard UV light sources are used frequently, together with their own aging curve, so the short-term and long-term stability are always far from satisfactory (shown in Fig. 5). The experiment is conducted after the radian source preheating to stable state. As shown in Fig. 5, within 10 minutes of monitoring time, it maximum output intensity is 18.8mW/cm^2 and the minimum is 18.4mW/cm^2, which means the variation reaches up to 2%. But the time of calibration for a UV irradiance meter is usually far beyond 10 minutes. During this process, the change of light source intensity itself is a significant source of measurement error.

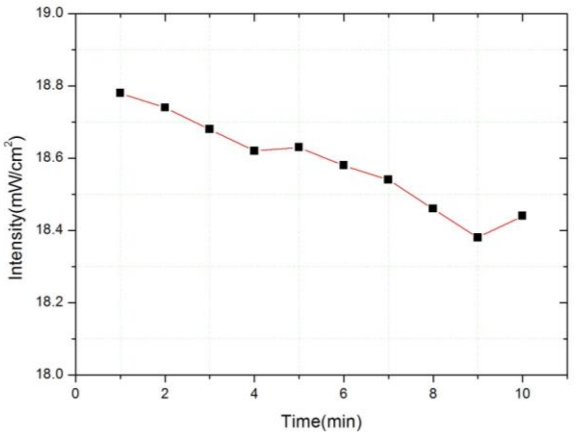


Fig. 5. The stability data of a UV radiation source

It usually has to take tens of seconds or even several minutes to accomplish the calibration, if the radiation source is not stable enough, it will cause significant testing error to the calibration results. Usually, these UV light sources are commercial and hard to improve by calibration labs. We have to find other way to reduce the testing error introduced by the stability of UV radiation source itself.

3. IMPROVEMENT IN PERFORMANCE OF STANDARD UV RADIATION

3.1. The introducing of integrating sphere

By the analysis above, we find that the standard UV radiation source currently used have much space to improve in uniformity and stability. Since the manufacture of such a light source needs to meet the requirement of emission intensity and spectral matching, it is difficult to improve stability and uniformity merely from the manufacturing process. By introducing the integrating sphere structure, we can effectively improve the uniformity of UV radiation source meanwhile its stability can be monitored.

To obtain higher measurement accuracy, integrating sphere should be as small as possible. The aperture ratio is defined as the ratio of aperture area to the entire inner wall area of integrating sphere. Integrating sphere radiatinn source is a good light source for calibration, with the good uniformity on radiating surface beyond ordinary light source[4].

There is a point light source in the centre of integrating sphere with the radiation flux Φ. The radiant illumination on surface A in integrating sphere is E_A and the reflectance ratio of the material of the inner wall of integrating sphere is ρ(λ). The radiance L_A on surface A is:

$$L_A = \rho(\lambda)\frac{E_A}{\pi} = \frac{\rho(\lambda)}{\pi}\frac{d\Phi}{dA} \qquad (2)$$

A can be seen as a new point light source in integrating sphere and can it also be regarded as Lambert. So the irradiance E_{B1} of another point B in integrating sphere is:

$$E_{B1} = \oiint dE_{B1} = \oiint_A \frac{L_A dA}{4R^2} = \oiint_\Phi \frac{\rho(\lambda)d\Phi}{4\pi R^2} = \frac{\rho(\lambda)\Phi}{4\pi R^2} \qquad (3)$$

However, the irradiance of B is provided by more than A point, which also includes the diffuse reflection from other parts of sphere. In this case, if the aperture and the baffles inside the integrating sphere are ignored, the secondary diffuse irradiance E_{B2} of B can be obtained according to"(3)"

$$E_{B2} = \frac{\rho^2(\lambda)\Phi}{4\pi R^2} \qquad (4)$$

Similarly you can also get the contribution of three, four and multiple diffusion to the irradiance of B. Thus the total irradiance E_B of point B is:

$$E_B = E_{B1} + E_{B2} + ... = \frac{\rho(\lambda)}{1-\rho(\lambda)}\frac{\Phi}{4\pi R^2} \qquad (5)$$

We assume in "(5)" that the sphere is a complete hollow sphere without any aperture or baffle inside, which is impossible in practice. Considering the modifications, in the condition of single aperture on the inner wall, we can obtain the irradiance of aperture E:

$$E = \frac{\rho(\lambda)}{1-\rho(\lambda)(1-f)}\frac{\Phi}{4\pi R^2} \qquad (6)$$

In"(6)", f is the ratio of the area of all the apertures to that of sphere. It shows in "(6)" that if ρ and f are constant, we can obtain the diffuse radiation with appropriate intensity for calibration at the outlet plane as long as introducing the radiation in the centre of the sphere [5][6][7][8].

In experiments, the inner wall of integrating sphere is coated with high reflectivity paint-coat in UV wavelength band. Its reflectivity is measured by UV spectrophotometry and results are shown in Fig. 6. We can see that in the wavelength range of from 200nm to 400nm, the average of reflectivity of paint- coat is higher than 99% and remains static with the change of wavelength.

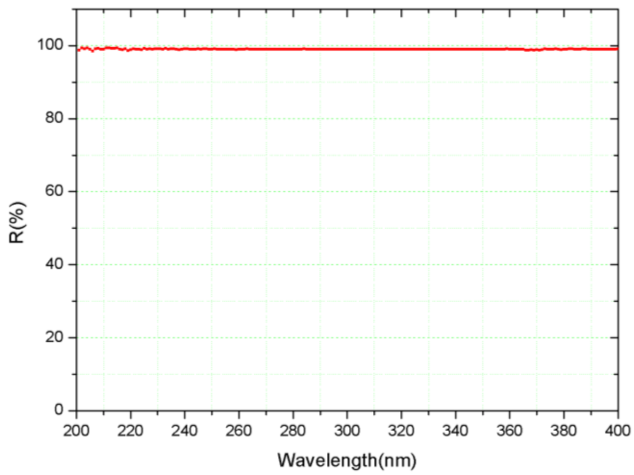


Fig. 6. The reflectivity data of the integrating sphere inner wall

Equation (6) can be approximated to "(7)" :

$$E = \frac{\rho}{1-\rho(1-f)}\frac{\Phi}{4\pi R^2} \qquad (7)$$

3.2. The relative spectral distribution of the new UV radiation source

After the introduction of the integrating sphere, the relative spectral distribution of the radiation from the outlet of the integrating sphere could be different from the incident radiation, because the reflectivity of the coating on the inner wall of the integrating sphere is usually related to the wavelength of the incident UV radiation. The high reflectivity of the inner wall could cause great difference in the relative spectral distribution, even though the variation of the reflectivity curve is not obvious.

We need to minimize the influence of the reflect coating on the inner wall of the sphere, which can change the relative spectral distribution of the incident radiation. After repeated experiments, we finally find the appropriate material to coat the inner wall of the integrating sphere. The reflectivity curve of the coating is shown in fig. 6. As we can see, the reflectivity is almost a constant from 200nm to 400nm, covering the whole UV band. The relative spectral distribution of the original UV radiation source and the relative spectral distribution of the radiation from the outlet of the integrating sphere are shown in fig. 7 and fig. 8. The profiles of the two curve are almost same. The only different is that the intensity of the radiation from the outlet of the integrating sphere is lower.

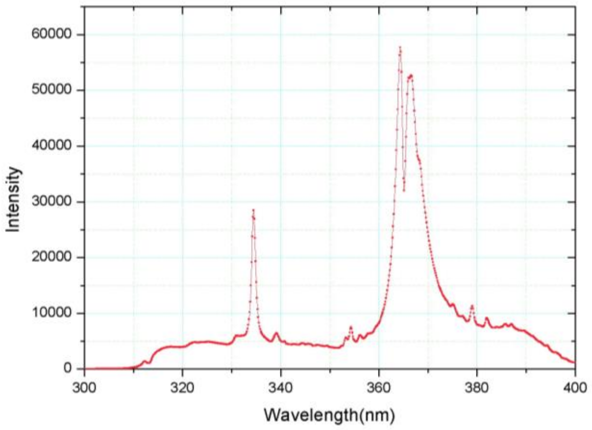


Fig. 7. The relative spectral distribution of the original UV radiation source

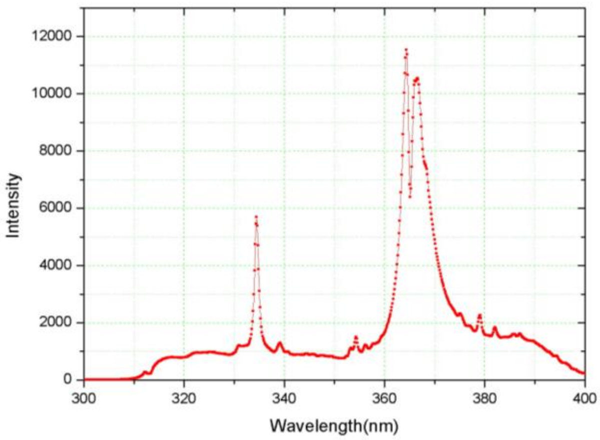


Fig. 8. The relative spectral distribution of the radiation from the outlet of the integrating sphere

3.3. The radiation intensity of the new UV radiation source

In experiment, the total amount of incident radiation in integrating sphere is about 650mW. In order to carry out the calibration experiments conveniently, the aperture diameter is taken as 3cm. As shown in Fig. 6, the reflectivity of the inner wall of integrating sphere is taken as 99%. Then the radiation intensity at the outlet plane changes with the diameter of integrating sphere, which is modeled as the graph in Fig. 9. Without changing the aperture diameter, the larger diameter of integrating sphere is, the better uniformity of radiation will be, while the radiation intensity will decrease with the increase of diameter. So we need to choose the appropriate diameter of integrating sphere, which can fully guarantee the uniformity of irradiance and also ensures that the radiation intensity at the outlet plane can meet the calibration in laboratory. After repeated experiments, we select an integrating sphere with a diameter of 10cm, the aperture diameter 3cm, and then f is 0.6% by calculation, which will not significantly damage the radiation uniformity inside the integrating sphere. And we obtain the radiation intensity at the outlet plane is about $20mW/cm^2$ through measurements, which meet the intensity requirements of the UV radiation source in UV irradiance meter calibration.

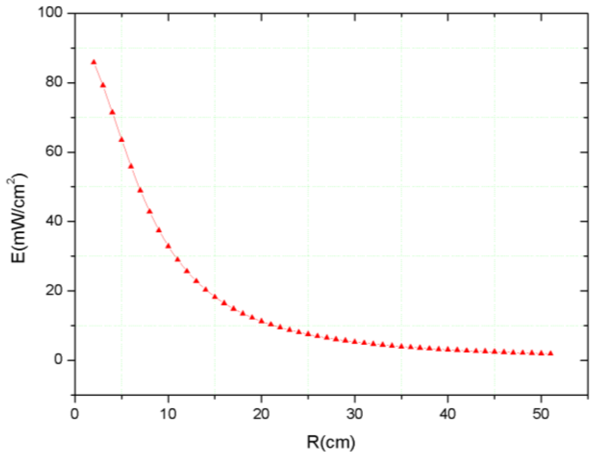


Fig. 9. The simulation results of radiation intensity at the outlet plane of integrating sphere

According to the above analysis and experiments[9], we have designed a radiation source system to measure UV light based on integrating sphere. The entire system is shown in Fig. 10.

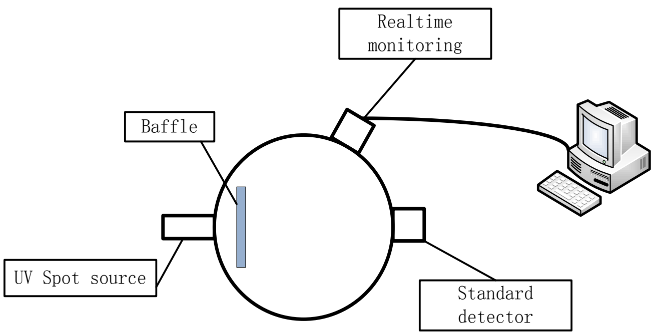
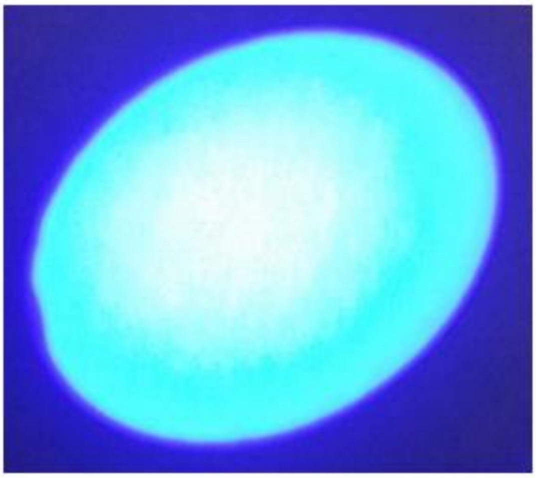


Fig. 10. The design of the radiation source system based on integrating sphere

3.4. The uniformity of the new UV radiation source

Before and after the introduction of integrating sphere, the comparison of spot photos is shown in Fig. 11. Without the integrating sphere structure in Fig. 11(a), the spot is with bright center and darker edge, which is obviously Gaussian-shaped distribution. The radiation of the UV source is too strong, we can not take the photo of the incident beam directly because the CCD will be saturated. So we project the beam on a piece of white paper and take a photo of the spot on the paper, the phosphors contained in the paper can be excited by UV radiation, that is why the color of spot photo is blue. After the introduction of integrating sphere, in Fig. 11(b), the spot is under good uniformity.

We use software to analyze the spot photo of Fig. 11(b) and the results are shown in Fig. 12. It can be seen that the spot intensity curve is smooth, uniform and without obvious raised or sunken area.



(a) The spot photo of a standard UV light source

(b) The spot photo of the outlet of the intetrating sphere

Fig. 11. The comparison of two spot photos before and after the introduction of integrating sphere

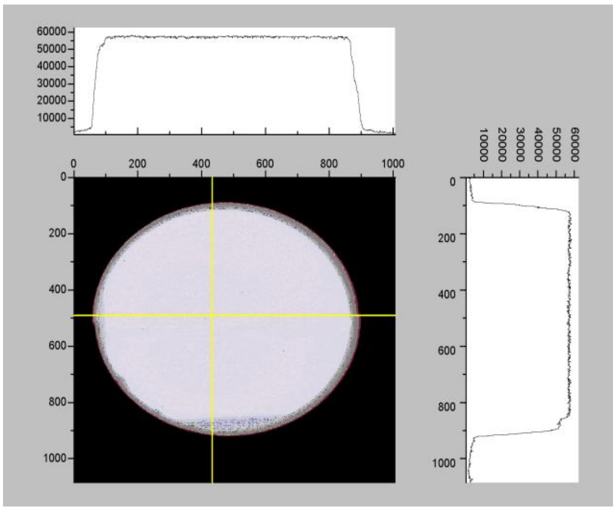


Fig. 12. The analysis results of the spot with the integrating sphere

3.5. The stability correction of the new UV radiation source

The system can monitor the stability of radiation source, meanwhile operate compensation for the source band through a set of calculations. The detector is mounted on the integrating sphere to monitor and record UV intensity changes in calibration process caused by the input radiation intensity changes in integrating sphere. By real-time monitoring and recording, we can evaluate the stability of the radiation source and correct the impact of the instability of radiation source. A UV detector with high accuracy and good stability needs to be selected in experiments which is less affected by the visible light (especially with excellent performance in visible light cutoff).

The real-time monitoring detector we choose is calibrated and linear corrected in order to minimize the testing error introduced by the detector itself during the experiment. The testing error of the tested detector is:

$$\sigma = (\frac{\overline{E}}{E_s} - 1) \times 100\% \qquad (8)$$

δ is the testing error of the tested detector, $\overline{E}$ is the average of it's testing result, E_s is the standard integrating energy during the calibration of the tested detector. If the radiation source is stable, E_s will be equal to the integrating energy E_s' recorded by the standard UV detector. However, the radiation source is not stable enough, so E_s will drift from E_s'.Thus correction need to be introduced.

In our system, a real-time monitoring detector is placed on the integrating sphere, which can monitor the variation of the incident radiation. Correction can be made according to the data recorded by this detector during the two test:

$$\sigma = (\frac{\overline{E}}{E_s} - 1) \times 100\% = (\frac{\overline{E} \cdot E_{m1}}{E_s' \cdot E_{m2}} - 1) \times 100\% \qquad (9)$$

E_s' is the standard integrating energy recorded by the standard detector. E_{m1} is the average intensity recorded by the real-time detector when E_s' is tested, E_{m2} is the average intensity recorded by the real-time detector when $\overline{E}$ is tested.

We take the average voltage collected during the process as monitoring signal intensity of this test, do this same operation with standard UV radiation meter. Comparing the ratio of two average value called correction factor. If the correction factor is very close to 1, it means that the UV light source is stable and no correction is in need. If the correcton factor is not close to 1, then it meas the UV light source is not stable enough and we need to introduce correction to the testing results.

We adopt data acquisition card (DAQ) to collect and record the electrical signal generated by the UV sensor and then send to PC for analysis. In PC we can observe the data points (voltage value) collected real-time in Labview DAQ program. We set 10 seconds same with UV energy test time as sampling period and DAQ sampling frequency is set to 100Hz.

4. CONCLUSIONS

The uniformity and stability of the standard UV radiation source is critical for calibration, which directly effects the accuracy of measurement. In this experiment, we take use of technology to optimize the UV radiation source in order to improve the uniformity of the radiation intensity. Meanwhile, we monitor the real-time intensity change of the radiation source during measurement process, so that the stability of it can be evaluated. By processing measurement data and introduce correction factor, we can reduce the impact introduced by the instability of radiation source during measurement process.

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