Dust Concentration Test Methods and Its Light Energy Distribution Characteristics

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Abstract
To improve the detection performance of the atmospheric dust concentration detector, this paper proposes an atmospheric dust concentration measurement method network-based by a rectangular array LED and receiver detector, and establishes atmospheric dust concentration measurement models, researches luminescence properties and optical properties of the matrix LED, sets up a detection screen by matrix LEDs and receiver detector probes, study photoelectric properties of the detection screen and the light energy distribution of the screen, gives the digital model of the LED transmitting power and output of detection circuit, analyses light energy distribution of the dust concentration detecting area formed by LED and optical current trends of the detection area with the light current characteristics of LED. Through the simulation calculation and experiment, the results shows the change rule of detection sensitivity by the distance from matrix LED to photoelectric detector and the LED transmitting power, and the relationship between the atmospheric dust concentration and the LED power.
Key words: DUST CONCENTRATION, LIGHT-EMITTING DIODE (LED), PHOTOELECTRIC DIODE, LIGHT ENERGY DISTRIBUTION CHARACTERISTIC

Introduction

The dust concentration or the atmospheric particulates concentration is an important indicator of air pollution detection, and detection of dust concentration is directly related to people's health. Various industrial sectors will encounter a variety of dust pollution troubles, resulting in increasingly importance of the dust concentration monitoring[1-2]. It is meaningful to research the dust concentrations detection in other areas like environmental protection, fire safety, industrial production and scientific experiments. There are two methods mainly to detect dust particles emission, sampling and non-sampling in the blackness. Blackness measurement method is very simple, but the measurement results will be affected by subjective factors such as the weather and the operator's other objective factors to a large extent [3].

With the increasing global demand for controlling dust pollution monitoring, according to more stringent requirement proposed for online measurement of the soot particles concentration[6], the relevant departments are developing high-precision testing equipment. For example, the light-scattering theory and laser absorption measurement technology has been widely applied to the analysis of the concentration of dust particles [4-5]. The key laboratory of combustion and clean coal power generation technology in Ministry of Education in China is just making use of light scattering method to monitor the concentration of dust particles emissions on-line. The Automation Instrumentation Institute of Northeastern University developed a kind of online detect instrument by using the principle of optical smoke density to achieve real-time measurement of dust concentration. Harbin Institute of Technology uses two-optical laser detection system to monitor the change in the concentration of particles real-timely[6]. These detection methods are non-contact measurement, and the instrument calibration conditions will change with the variation of the dust particles size, which will cause additional measurement error.

Therefore, the detection system need to be improved by the utilizing of laser scattering when transmit dust, the absorption properties, diffusion concentration of dust, dust particles size and the related environment characteristics to achieve the online real-time monitoring of concentration of dust particles. To solve this problem in traditional measure method, a new method of non-sampling method to measure the dust concentration in the air is proposed and the dust concentration monitor is achieved according to the optical properties of the dust particles.

1. Optical test methods of dust concentration

1.1 Dust concentration measurement principle

Dust concentration test system uses the principle of the light transmission method, which adopts the principle that light energy occurs attenuation due to scattering and absorption when light transmit through the medium of dust. When the light beam passes through the tested dust particles, the outgoing light energy is reduced to a certain extent due to the absorption and scattering of light through dust particles, and using the degree of attenuation of the outgoing light energy, the variation and the value of the dust particle concentration in the measured region can be obtain. In this method, the light received is the transmitted light rather than the scattered light, as a result, the light energy is relatively strong, while the measured light source is mostly white light instead of monochromatic laser[7]. Apart from the particle size, it is also easily to get the particles concentrations with the light transmission method. The light source in dust concentration test system is matrix light source composed by $N \times N$ super-bright white luminous diodes at a constant arrayed pitch. The matrix area is $0.5m \times 0.5m$, and the optical receiver diodes arrange in the same pitch with the same area as the matrix light source. The detection range of the atmospheric concentration measurement instrument equals to the distance between the luminous diodes and optical receiver diodes. When a light beam emitted from the light source transmit through the air with the particles, the received transmitted light energy gets a attenuation due to the scattering and absorption of light through particles, and this attenuation could be sensed by optical receiver diodes on the opposite, which output changed current signal, this signal vary as the size and concentration of the particles in the air. The atmospheric dust concentration measuring system with the light emitting diodes matrix and receiver-sensor is shown in Figure 1.

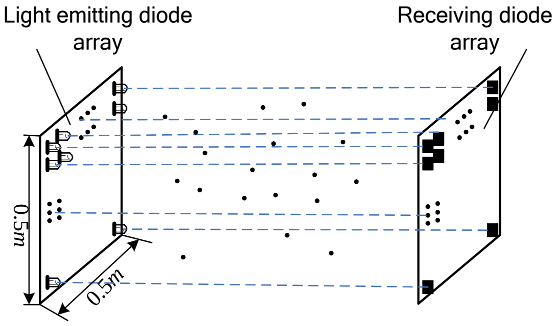


Figure 1. The dust concentration photovoltaic test system diagram

1.2 Dust concentration measurement method

The light transmission method has many positive characters, like with a fast measurement speed, great repeatability, which is suitable for online measurement. When the light beam passes through the dusty air, absorption and scattering occurs, which result in a certain degree of attenuation in the original propagation direction. Assuming the original light energy is I_0, the light energy by attenuation is I, and according to the *L-B* law[8].

$$I = I_0 e^{-\frac{1}{4} N_v \pi L D^2 E(\lambda, m, D)} \quad (1)$$

Then the concentration of dust is:

$$N_v = \frac{4 l_n (I_0 / I)}{\pi L D^2 E(\lambda, m, D)} \quad (2)$$

The actual dust particles is usually composed by particle groups with a certain distribution, and the particles have a poly dispersity character with a N(D) distribution, and assuming n_r(D) stands normalized frequency distribution function of the group of particles, then the dust particle concentration can be gained[9-10].

$$N_v = \frac{8\pi^2 r^2 I / I_0}{\lambda^2 SL \sum (i_1 + i_2) n_r \Delta D_i}$$

(3)

According to the characteristics of the measuring system, it is necessary to analysis the energy distribution of the detection area, with the request of improvement of detection performance and accuracy, under the premise of a reliable operation with this system. If the output light energy of the luminous diodes is too strong, the output will beyond the saturation[11]. Meantime, the uniformity and stability of the light source is also related to the voltage of luminous diodes and space between the luminous diodes, therefore, it is essential to analyze the characteristic of luminescence.

2. Light energy distribution of dust concentration detector in detection area

According to the design of dust concentration test system, due to the large detection area, it is impossible to escape of a difference of light energy in different area. The light energy attenuation caused by scattering and absorption will result in a light energy variation in the photosensitive surface of photoelectric diode. Therefore, the light energy distribution has a impact on detection sensitivity of the detection system. In order to analyze the optical characteristics of the detection area more effectively[12], the light emitting diode matrix in probe area and the light energy distribution in photoelectric diode should be analyzed effectively to improve the design of the dust concentration test system.

Actually, there is a light energy decrement in probe area in dust concentration test system, and this decrement will increase with the detection distance. According to the principle of the LEDs and the LEDs matrix, the light energy decrement of the system mainly due to two aspects, one reason is not all of the implantation energy can be converted to photons; the other is only a small portion of the light can radiate within total reflection angle. As a result, it is necessary to study the light energy distribution in probe area.

Ideally, one LED is an approximately Lambertian source, which means the light energy distribution of the LED is a cosine function of the observation angle. But in fact, due to the shape of the chip and packaging[13], the result is, the luminance actual distribution should be approximately:

$$E(r,\theta) = E_0(r)\cos^m \theta \qquad (4)$$

θ is the emitting angle of LED, $E_0(r)$ is for luminance value at a distance of r in the axial direction. The value of m depends on the distance between the chip and the package lens surface center of light emitting diode[14]. If the location of the chip corresponds to the package lens surface center, then $m \approx 1$, Some typical value of m would be greater than 30, the light energy distribution from the center to the boundary decrease very quickly. The value of m can be determined simply by $\theta_{1/2}$.

$$m = \frac{-\ln 2}{\ln(\cos\theta_{1/2})} \qquad (5)$$

As the modification to the equation (4) in Cartesian coordinate system, and assuming the distance from the surface of dust particles to light source, then the luminance at each point of the probe area in this system could be expressed as

$$E(x,y,z) = \frac{z^m L_{LED} A_{LED}}{\left[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2\right]^{(m+2)/2}}$$

(6)

L_{LED} is LED radiation brightness, while A_{LED} is LED emitting area.

For dust concentrations optical test system, the light source is formed by square LED arrays. The illumination distribution of $N \times M$ square LED arrays in optical test system is:

$$E(x,y,z) = z^m A_{LED} L_{LED} \times \sum_{i=1}^{N}\sum_{j=1}^{M}\left\{\left[x-(N+1-2i)\frac{d}{2}\right]^2 + \left[y-(M+1-2j)\frac{d}{2}\right]^2 + z^2\right\}^{-(m+2)/2}$$

(7)

Take a secondary differential for E, and make $x = 0, y = 0$ and $\partial^2 E / \partial x^2$, as can gain:

$$f(D) = \sum_{i=1}^{N}\sum_{j=1}^{M}\{[(N+1-2i)^2 + (M+1-2i)^2](D^2/4)+1\}^{-(m+6)/2}$$
$$\times\{1-[(m+3)(N+1-2i)^2 - (M+1-2i)^2]\cdot D^2/4\}$$

(8)

Thus, the light energy of the dust concentrations optical test system is related to the illumination of light source *E*, radiation energy of LED L_{LED} and light-emitting area of the light emitting diode A_{LED}. Therefore, fully considering the impact of these factors, to design a uniform and stable light source, it will help improve the performance of the dust concentration optical testing system.

3. Simulation calculation and Experiments analysis

3.1 Simulation calculation

According to current characteristics of the LED, it is easy to obtain that light emitting power is proportional to the radiation recombination rate. Under certain conditions, the optical power level is mainly determined by the ratio of composite current and diffusion current, and this ratio is also related to the forward bias voltage of the LED. With the formula (8), (9), it is not difficult to obtain: the size of N_t directly affects the diffusion current ratio, the higher the value of N_t, the lower of the radiation recombination ratio of LED; Different applied voltage directly influent the light power of LED. Figure 2 is a schematic diagram of relationship between the applied voltage in probe area and the output current in detection circuit.

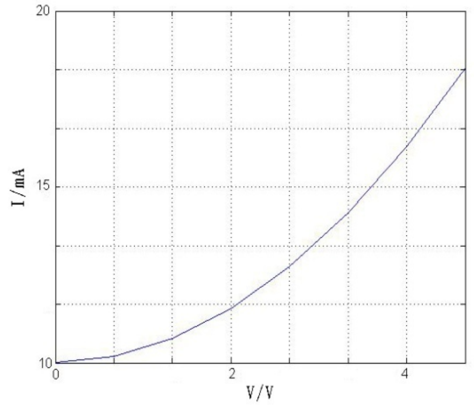


Figure 2. The schematic diagram of relationship between the applied voltage in probe areaand the output current in detection circuit

From Figure 2, the output current in receiving circuit increases with the applied voltage in LED. Considering the formula (7) - (9), this is due to the increased radiation recombination rate leads to an increased LED emitting power, a rising carrier excitation inside, and a bigger output current in detection circuit. According to formula (9), when the applied voltage increases to a certain value, the value of light power decreases by the junction temperature. Therefore, output current in detection circuit is proportional to applied voltage in probe area of the dust concentration detector.

In order to visualize the luminous energy distribution of the LED, figure 3 is 7×7 array LED matrix model of LEDs, figure 4 is light energy distribution of LED matrix in 3-dimensional graphics. Set the relevant parameters of the LED matrix in optical design software, evaluate the light energy distribution, as a result, the emission situation of the light in the entire system reflects the space energy distribution. According to the calculation parameters in formula (17), formula (18) and (19), and with the simulation of the optical design software, the illumination distribution through a lens convergence in illumination region is shown in Figure 5.

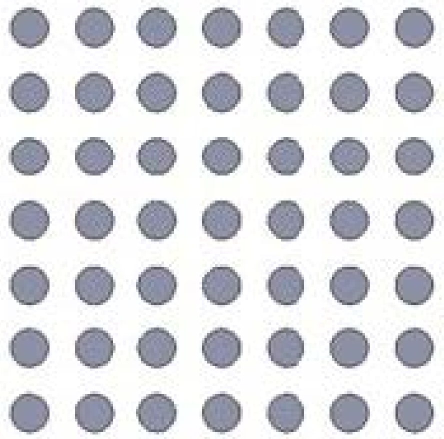


Figure 3. 7×7 array LED matrix model

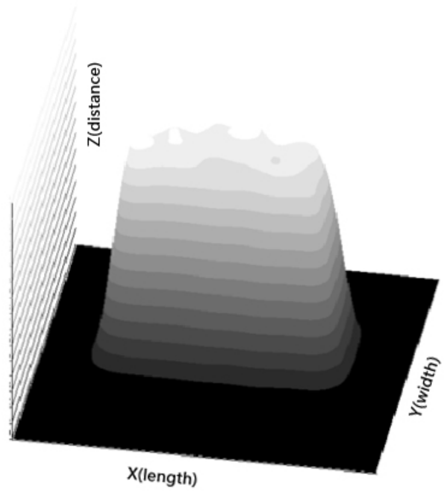
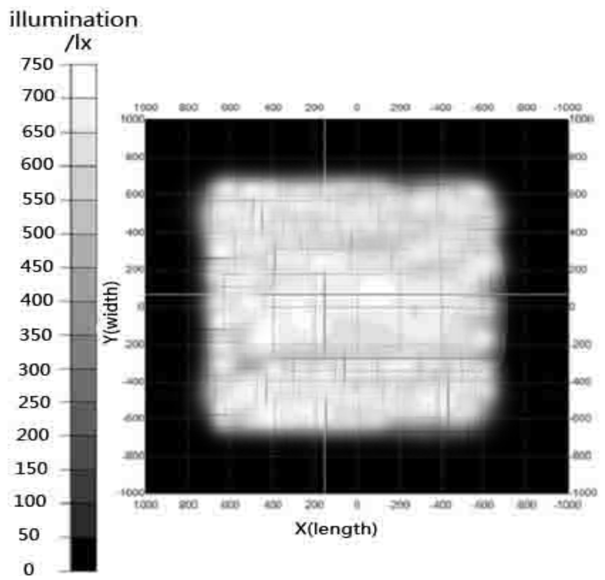
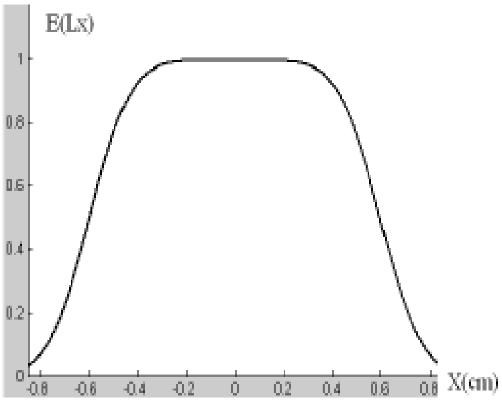


Figure 4. Light energy distribution of LED matrix in 3-dimensional graphics



(a) LED matrix light energy distribution (top)



(b) Light energy distribution curve in X-axis direction

Figure 5. LED matrix model simulation

Figure 5 shows the light energy distribution of light source matrix formed by a plurality of LEDs. It is clear to see the light energy distribution of the LED matrix. The theory results validate light energy distribution in probe area of dust concentration test system, which means the uneven distribution of light energy in the edge detection area, the evenly distributed in the intermediate area.

3.2 Experiment and analysis

This experiments are performed in a sealing wooden with a certain volume, using a hair dryer blown a certain quality of dust into the inside of box, $d = 10\mu m$, $\rho = 2.6\text{g}/cm^3$, $m = 1.48g$. When the dusts disperse substantially and uniformly, measure the voltage value, and complete quantitative tests.

With different quality of dust particles inside the box, we measure the output voltage in detection system, Table 1 is measure result.

Table1 denotes output voltage in detection system in six kind quality dust particles, A and B denote the quality of dust particles is 4-5g, C denotes the quality of dust particles is 9-11g, D denotes the quality of dust particles is 15g, E and F denote the quality of dust particles is 20-25g. From table 1, we know if the larger dust particles quality, the larger the output voltage, it means the larger of dust particles concentration; this is the same to the theoretical calculation.

Table 1. The output voltage under different quality of dust particles

Num	A	B	C	D	E	F
1	1.56	1.37	3.29	5.48	10.04	12.60
2	1.09	1.28	3.25	5.54	9.89	12.05
3	1.14	1.43	3.21	5.66	10.23	11.56
4	1.19	1.36	4.45	5.71	11.02	11.37
5	1.67	1.65	3.69	5.52	10.32	11.66
6	1.08	1.33	4.06	5.67	10.91	11.98
7	1.21	1.23	4.28	5.56	9.76	12.27

According to the experimental method, with the same environment, metered dust quality, we measure three times repeatedly, and obtained three groups of voltage values vary as the concentration, such as figure.6.

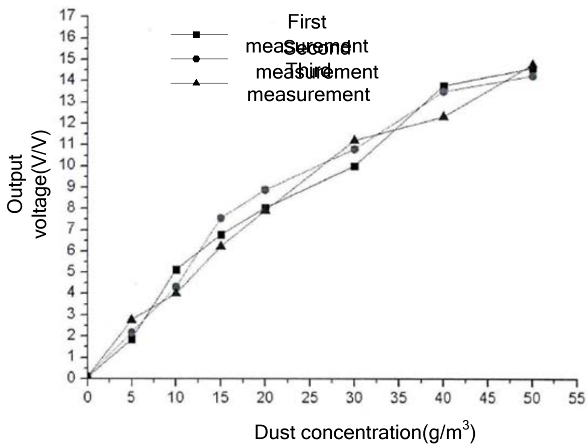


Figure 6. Measured voltage value of three times

From the above analysis, the greater the concentration of dust particles, the greater of the measured voltage signal value; the measured three groups value of voltage showed the same trend, and with a high stability of the system; By data fitting, a direct proportion relationship between dust particle concentration and voltage was obtained, which further validate the theoretical analysis.

4. Conclusions

This paper researches the dust concentration measurement method based on light transmission method, through the decay principle of laser propagation in dust particles, analyzes the light emitting performance of LEDs matrix in dust concentration test system and the impact of the photoelectric diode performance on detection performance. Bias voltage indirectly impact luminous power by influencing the number of carriers in the LED carriers. Photoelectric diode current is proportional to light power of light source in dust concentration test system. The larger of the light emitting power, the greater of the current generated in photoelectric diode, and the more obvious changes in its performance, with the improvement of detection sensitivity. This paper analyzes the light energy distribution in probe area, and calculates energy calculation algorithms. Finally, this paper uses experiments and simulations to verify the feasibility of the theoretical analysis. This paper has a great significance for the study of luminescence properties of dust concentration measurement system, and establishes the theory and practice foundation for effectively improvement of the detection performance in actual environment, and has a strong practical meaning.

Acknowledgements

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