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The design of a small flow optical sensor of particle counter

Yongbo Zhan [a], Jianwei zhang [a], Jianxiong Zeng [a], Bin Li [a], Lu Chen [b,*]

[a] *Guangdong Huankai Microbial Sci.&Tech. Co., Ltd., Guangzhou 510663, China*
[b] *Guangdong Institute of Microbiology, Guangzhou 510070, China*

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ABSTRACT

Based on the principle of Mie scattering, we design a small flow optical sensor of particle counter. Firstly, laser illumination system was simulated and designed by ZEMAX optical design software, and the uniform light intensity of photosensitive area was obtained. The gas circuit structure was also designed according to the related theory of fluid mechanics. Then, the method of combining with MIST scattering calculation software and geometric modeling was firstly used to design spherical reflection system, on the basis of the formula of object-image distance. Finally, the test was conducted after the optical sensor placed in self-designed pre-amplification and high-speed processing circuit. The test results show that the counting efficiency of 0.3μm gear is above 70%, 0.5μm gear and 1.0μm gear are both reached more than 90%, and the dispersion coefficient of each gear is very nearly the same, compared with the standard machine of Kanomax 3886 under the particle spraying flow of 2.5SCFH, 3.0SCFH, 3.5SCFH.

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1. Introduction

Laser dust particle counter (LPC) is an important instrument that can monitor the particle size and concentration in the air. It has the properties of fast detection speed, wide measuring range, high sensitivity, good reliability, and has been widely used in the industry of food, medicine, textile, semiconductor and so on [1,2]. The light source of LPC has gone through three stages of white light [3,4], He–Ne laser [5] and semiconductor laser diode [6]. The detector has also changed from photomultiplier to photoelectric diode [7]. These changes make the volume of LPC miniaturization and the performance also improving greatly. The related researches of LPC were mainly focused on the particle scattering characteristics, counting performance and calibration methods etc. In abroad, for example, W.W. Szymanski et al. reported the particle scattering strength as a function of particle size and the refractive index for the different scattering collection angle [5]. Miton Kerker introduced forward and vertical angle collection of scattering optical signal [8]. The resolution of the particle size was discussed respectively by A. vander Meulen and Robert Finsy from different perspectives [9,10]. A. Trampe et al. put forward a method for improving the signal-to-noise ratio of the particle counter, simultaneously reducing the detection sensitivity threshold and counting error rate by using electronic digital signal processing [11]. The calibration procedure of particle counter was also discussed by P. Jani, which had important significance for the definition of measurement range of particle size and size resolution [12]. In China, J. Yang, G. Peng et al. of Nanjing University of Science and Technology, elaborated the essence of signal transmission of LPC [13] and the characteristics of probability distribution of counting signal amplitude [14]. Y.J. Ji, B.M. Bian et al. also have a research on performances of LPC with different lamp-houses [15]. In addition, the luminous flux of transducer [16] and the mathematical model of LPC [17] were also reported by domestic scholars.

At present, although the performance of domestic LPC has been improved greatly, there is still a gap compared with the foreign one [17,18], especially the development of the optical sensor has many imperfect places. In fact, a slight variation of the scattering solid angle can lead to larger difference of particle scattering coefficient when particles go through the different positions of photosensitive area. Design a spherical reflection system combining with Modeled Integrated Scatter Tool (MIST) and geometric modeling method, it can control particle scattering coefficient of photosensitive area efficiently.

In this letter, a LPC optical sensor was designed based on Mie scattering theory. The uniform photosensitive area was obtained by the methods of optical design. On the basis of this photosensitive area, the gas circuit structure was designed which satisfied laminar flow condition of Renault equation. Then we firstly used the method of combining

* Corresponding author.
E-mail address: luchen898@163.com (L. Chen).

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with MIST and mathematical modeling to design the spherical reflection system. At last, the light trap was also designed by the actual observation of Knife-Edge Beam Profiler. The designed optical sensor reflects better stability and higher counting performance in the actual detection of polystyrene latex particles (PSL) of 0.3 μm, 0.5 μm and 1.0 μm.

2. The design method of optical sensor

The optical sensor of LPC is designed based on Mie scattering theory. Generally, there are two ways to collect the scatter light. The theoretical calculations are as follow.

i. The system collecting the light scattered in nearly forward direction (Fig. 1(a)).

For the incident plane-polarized light, the scattered luminous flux within the solid angle between θ_1 and θ_2 can be described as

$$F = \frac{\lambda^2 I_0}{4\pi} \int_{\theta_1}^{\theta_2} \int_0^{2\pi} \left[i_1(\theta)\sin^2\phi + i_2(\theta)\cos^2\phi \right] \cdot \sin\theta d\phi d\theta = \frac{\lambda^2 I_0}{4\pi} \int_{\theta_1}^{\theta_2} \left[i_1(\theta) + i_2(\theta) \right] \sin\theta d\theta. \tag{1}$$

ii. The system collecting the light scattered in orthogonal direction (Fig. 1(b)).

For the incident plane-polarized light, the scattered luminous flux within the solid angle between θ_1 and θ_2 can be described as

$$F = \frac{\lambda^2 I_0}{4\pi} \int_{\theta_1}^{\theta_2} \frac{i_1(\theta) + i_2(\theta)}{2} \left(\phi_2 - \phi_1\right) \sin\theta d\theta + \frac{\lambda^2 I_0 \cos\left(2\phi_0\right)}{4\pi^2} \int_{\theta_1}^{\theta_2} \frac{i_1(\theta) - i_2(\theta)}{2} \sin\left(\phi_2 - \phi_1\right) \sin\theta d\theta. \tag{2}$$

In the orthogonal direction, $\theta_1 + \theta_2 = 180°$, so

$$\phi_2 - \phi_1 = 2\cos^{-1}\left[\frac{\cos\left(\frac{\theta_2-\theta_1}{2}\right) - \cos\left(\frac{\theta_1+\theta_2}{2}\right) \cdot \cos\theta}{\sin\left(\frac{\theta_2+\theta_1}{2}\right) \cdot \sin\theta} \right] = 2\cos^{-1}\left[\frac{\cos\left(\frac{\theta_2-\theta_1}{2}\right)}{\sin\theta} \right]$$

where I_0 is incident light intensity, $i_1(\theta)$, $i_2(\theta)$ are scatter light intensity functions, λ is incident wavelength.

From Ref. [6], $i_1(\theta)$, $i_2(\theta)$ can be describe as

$$i_1(\theta) = \left| \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} a_n \pi_n + b_n \tau_n \right|^2 \tag{3}$$

$$i_2(\theta) = \left| \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} a_n \tau_n + b_n \pi_n \right|^2 \tag{4}$$

where π_n, τ_n are scattering angle functions, a_n, b_n are Mie scattering coefficients.

The a_n, b_n are both the functions of refractive index n and particle size parameter α ($\alpha = \pi d/\lambda$, d is particle diameter). In the orthogonal direction, for small particles ($\alpha < 1$), scattering light intensity attenuates quickly as a function of particle diameter, so the particle resolution will be better than the one nearly forward. Besides, it is conductive to eliminate the optical noise for the incident light perpendicular to the receiving surface of detector. Therefore, the orthogonal direction was used to collect the scattered light in this letter.

Optical sensor is the core component of LPC, its composition mainly includes laser illumination system, gas circuit system, scattering system and extinction system, the main designs of each part are as follow:

① The ZEMAX design of uniform photosensitive area.

The photosensitive area of optical sensor is the vertical intersection of laser beam and sampling gas, the uniformity of light intensity of which is related to the counting accuracy of LPC. In order to reduce

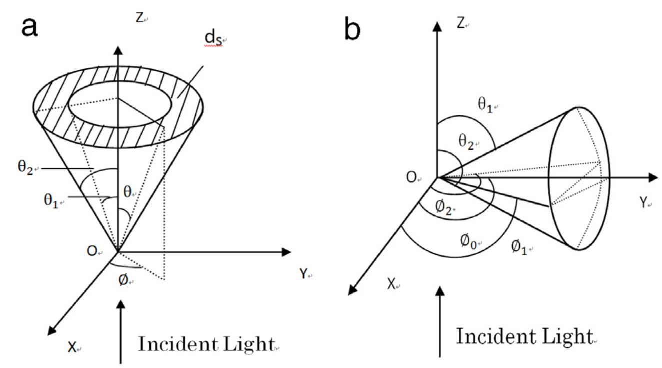

Fig. 1. Collecting system of scattering light (a) nearly forward direction (b) orthogonal direction.

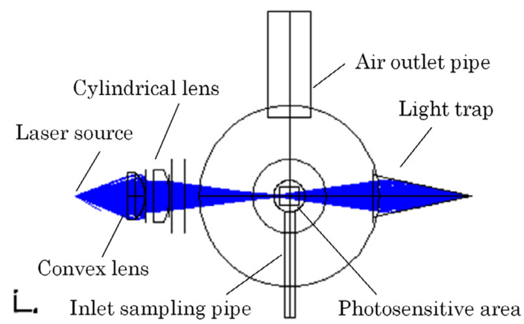

Fig. 2. Laser illumination system.

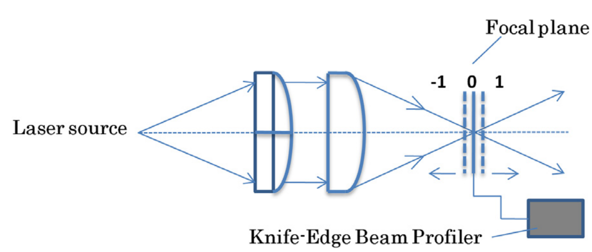

Fig. 3. Spot test using Knife-Edge Beam Profiler.

the design cost and size, we used semiconductor laser diode as the light source. The reasonable photosensitive area was obtained near the focal plane after the laser beam was collimated and compressed. The marginal intensity of photosensitive area must account for more than 80% of the central intensity according to the national standard of GB/T 6167-2007. After optimizing the optical path, the focal lengths of plane-convex lens and cylindrical lens are 12 cm and 25 cm respectively . Laser illumination system is shown in Fig. 2.

② The measurements of light spot parameters near the focal plane.

Fig. 3 shows the spot test schematic. The parameters and position relationship of the laser diode and lens are both consistent with the model of ZEMAX software design. The actual test values of spot width, thickness and optical power are listed in Table 1. From the point of optical power, the light intensity near the focal plane is uniform that the average value is about 99.78 mW. The light spot width near the focal plane is also uniform that the average value is about 4050.75 μm. The cross-section diameter of sampling flow must be smaller than this value, otherwise, some of the particles would not go through the photosensitive area. The thickness of photosensitive area is no more than 469.6 μm of the 10% maximum thickness. This thickness can be used to estimate the overlapping error [18] and upper limit concentration of LPC.

③ The design of gas circuit system.

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