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RESEARCH ARTICLE

Small particle detection method based on laser feedback

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Abstract In order to overcome the shortcomings of traditional particle measurement, a new method for the detection of small and single particles through laser feedback phenomenon is presented. This method is based on the laser feedback caused by radiation scattered back from a moving particle in the external cavity of the laser. The parameters of the single particle, such as the diameter, velocity, and quantity, can be measured and calculated from the change in output laser power. In the experiment, the confocal external cavity composed of a concave reflector and a positive lens is designed. This device is able to obtain the corresponding variety curve of standard particles passing through the confocal area, and then the parameters of the particles can be measured and calculated by combining the experimental data and standard curves. Experimental results show that this method is an easily operated and reliable way for particle detection. The measurement ranges from 0.2 to 2000 μm, resolution is 0.2 μm, and measurement error is within 2%. This device may have wide application in areas such as atmosphere particle detection and calibration of a single particle producer.

Keywords small particle detection, laser feedback phenomenon, confocal external cavity

1 Introduction

In recent decades, a lot of research has been put forward for measuring particle size and concentration of light-scattering methods and apparatuses, especially in small particle measurement. There are now a variety of fine particulate concentration measurement technologies and analysis methods [1], such as the measurement of suspended small particles in the medical field, the measurement of air pollution in environmental engineering, and the measurement of silicon surfaces in the semiconductor industry. Current methods for particle sizing include: sieving, sedimentation, laser diffraction [2], electric halo-counting, resistance method, and static images. Sieving is very simple, but low resolution requires higher skills, and long-term maintenance of measuring instruments is needed. Laser diffraction, which is based on the Fraunhofer diffraction, yields the particle formation by diffraction signals in the focal plane. This method is rapid, simple, and reproducible, but the measurement resolution is low. Halo-counting can be achieved with high-resolution measurements, but can not be used for the flow of air particles. The traditional method of imaging is by means of optical microscopy, graphics capture cards, and equipment using computer software acquisition and image processing, thus gaining particle size and shape parameters. However, the problem with the above single measurement is the limitation of the number of particles and the cumbersome process. The general resolution is to take a number of measurements through a mock field to enhance the authenticity of the test results.

At present there are two main methods for single particle sizing.

1) Coulter [3]: The particles are dispersed uniformly in the electrolyte. The electrolyte flows through a glass tube with holes, passing through by one particle at a time. Measuring the corresponding voltage pulse, the total number of particles and particle size are calculated. The weaknesses of this method include: a complex processing system; it is easy to plug the holes; the holes must conform to the size of the particles, with certain ratio requirements; and, equipment and operating costs are high, with no on-line measurements available.

2) Angle scattering: The filtered laser passes through a lens to gather at the waist, which acts as a measurement area. The particles in the area are measured. The accuracy can be improved by involving more receivers. Optical instruments are large in size, with complex installation and debugging. Further, the light scattering particle size and the relationship with the curve calculation is cumbersome and complex. Some companies enhance the products' sensitivity using a dual light path design, however, the system is relatively more complicated and the vast

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majority of products are used to measure particles in liquid only.

In light of the difficulties in detection of gaseous fine single particles parameters [4–7], a small particle detection method based on laser feedback is proposed in this paper. This method is based on laser feedback caused by the radiation scattered back from a moving particle in the external cavity of the laser. The parameters of the single particle, such as the diameter, velocity, and quantity, are measured and calculated from the change in output laser power. In the experiment, the confocal external cavity composed of a concave reflector and a positive lens is designed. This device can obtain a corresponding variety curve of standard particles passing through a confocal area, and then the parameters of the particles can be measured and calculated by a complex of experimental data and standard curves. The method, which is simpler compared to the other optical scattering measurement methods, is applicable to low-density particle dispersion measurements, and can also be used for removable indoor air particle measurement and calibration of the single-particle generator, with a wide range of practical applications.

2 Theory

Laser feedback effect refers to the output of laser light reflected or scattered by the external reflection, which is part of the optical feedback to a laser resonator. As the feedback and the original light in the resonator interact, the output characteristics of the laser light field are modulated by the change in feedback, a concept first introduced by King in 1963 [8] and also known as the laser self-mixing effect. Laser self-mixing is similar to dual-beam interference. It is usually applied in displacement measurements, Doppler velocity tests, vibration, surface morphology and scattering medium objects imaging research. Researchers have established various theoretical models for various laser self-mixing phenomena, and have deduced the expressions of laser output power under the conditions of feedback [9–16]. In this paper, the particles are placed in the laser resonator surcharge, and the single particle parameters are measured using the laser feedback effect. When the particle passes through a confocal sensitive area, the forward and backward scattering of the particle affects the laser feedback output amplitude, which in turn affects the laser output power.

The theory of the effect caused by laser feedback based on particle scattering is shown in Fig. 1. Considering the beam propagation in the one-dimensional direction, the measurement of small particles, including the laser system of the laser resonator mirrors R1, R2, and R3, the mirror resonators constitute a surcharge (external cavity). In the absence of any particles, the right transmission laser couples to the cavity, and reflects the laser resonator again. When the laser spreads into the right and left fields, we assume that the laser is in a single transverse mode with "+" and "−" values.

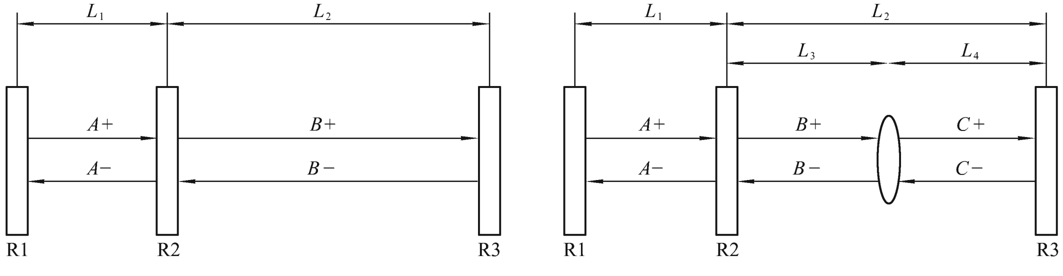
On the assumption that the single-particle does not diffract the laser field, only the scattering coefficient of the system is considered. For those lasers with no particle feedback, a complex amplitude of the light field $E_0(z)$ is set up at the first mirror R1, and the light field complex amplitude of the output is expressed as

$$\begin{aligned} E(z) = {} & E_0(z) r_1 r_2 e^{i\frac{4\pi}{\lambda}d} \\ & + E_0(z) r_1 (1-r_2)^2 r_3 e^{i\frac{4\pi}{\lambda}(d+L_2)}, \end{aligned} \tag{1}$$

where r_1 and r_2 are the refractive indexes of mirrors R1 and R2 reflectivity, respectively, d is the product of the refractive index medium in the cavity, the length of the laser cavity is L_1, and the length of the laser resonator is L_2.

For additional existing resonant cavity laser scattering of particles, the expression of the complex amplitude is more complex. Assuming that the particle's left and right scattering coefficients are S_1 and S_2, respectively, the output amplitude of the rehabilitation field can be divided into the following parts: the complex amplitude of the laser reflected in the resonant cavity is

$$E_1(z) = E_0(z) r_1 r_2 e^{i\frac{4\pi}{\lambda}d}; \tag{2}$$



(a) (b)

Fig. 1 Particle scattering in external cavity causes laser feedback phenomenon. (a) Laser cavity and external cavity without a small particle; (b) small particle scattering in external cavity of the laser the complex amplitude of the laser through the mirror R2 is left-scattered to R1 by the particles:

$$\begin{aligned} E_2(z) &= E_0(z) r_1 (1-r_2) e^{i\frac{2\pi}{\lambda}d} e^{i\frac{2\pi}{\lambda}L_3} S_1 e^{i\frac{2\pi}{\lambda}L_3} (1-r_2) e^{i\frac{2\pi}{\lambda}d} \\ &= E_0(z) r_1 (1-r_2)^2 S_1 e^{i\frac{4\pi}{\lambda}(d+L_3)}; \end{aligned} \tag{3}$$

the complex amplitude of the laser through the mirror R2 is right-scattered by the particle and later is reflected by mirror R3, and then returns to the main resonator by scattering the particles:

$$\begin{aligned} E_3(z) &= E_0(z) r_1 (1-r_2) e^{i\frac{2\pi}{\lambda}d} e^{i\frac{2\pi}{\lambda}L_3} S_2 \\ &\quad \cdot e^{i\frac{2\pi}{\lambda}L_4} r_3 e^{i\frac{2\pi}{\lambda}L_4} S_1 e^{i\frac{2\pi}{\lambda}L_3} (1-r_2) e^{i\frac{2\pi}{\lambda}d} \\ &= E_0(z) r_1 (1-r_2)^2 r_3 S_1 S_2 e^{i\frac{4\pi}{\lambda}(d+L_2)}. \end{aligned} \tag{4}$$

With the laser complex amplitude of the coherent superposition, the optical field complex amplitude is distributed in the surface of R1:

$$\begin{aligned} E(z) &= E_0(z) r_1 r_2 e^{i\frac{4\pi}{\lambda}d} + E_0(z) r_1 (1-r_2)^2 S_1 e^{i\frac{4\pi}{\lambda}(d+L_3)} \\ &\quad + E_0(z) r_1 (1-r_2)^2 r_3 S_1 S_2 e^{i\frac{4\pi}{\lambda}(d+L_2)} \\ &= E_0(z) r_1 e^{i\frac{4\pi}{\lambda}d} \left[r_2 + (1-r_2)^2 S_1 \left(e^{i\frac{4\pi}{\lambda}L_3} + r_3 S_2 e^{i\frac{4\pi}{\lambda}L_2} \right) \right]. \end{aligned} \tag{5}$$

From Eqs. (1) and (5) of the light field complex amplitude, when the single-particle is in the external cavity, the changing complex amplitude of the laser results in the changing laser powers and the corresponding pump currents. Different particle sizes and velocities result in the different scattering coefficients S_1 and S_2. By measuring the laser output voltage pulse signal, the parameters of the particle, such as particle diameter, can be calculated.

Although the single particle size, velocity and other parameters cannot be measured by laser feedback effect directly, this effect can be used to measure the unknown particle parameters in accordance with the calibration spectra after testing by standard particle calibration. Further, the measurement error can be offset from the error of the apparatus itself.

3 Experiment setup

Based on the laser feedback effect, a single particle measuring device design is shown in Fig. 2. A single-mode He-Ne laser operating at 632.8 nm, with an output power $P_{\max} = 5$ mW and an output beam diameter of 0.81 mm, is used as the coherent source. The surcharge resonator cavity is built up by the laser resonator cavity, a concave mirror and a condenser lens which is all-confocal. As shown in Fig. 2, R is a concave mirror, L is the focusing transform lens, the focal length $f = 20$ mm, optical aperture $D = 70$ mm, the all-concave mirror focal length is 30 mm, and F is the focus for the confocal length. When the output laser is in the focus F confocal region of the surcharge resonator cavity, the emergence of the measured particles becomes very sensitive and the scattering light generated by the optical feedback laser results in an obvious change of laser power output. PD (photo diode) is a photodetector with high sensitivity and good linearity; A is the amplification and conversion of the high speed data acquisition card device, recording equipment from two parallel directions. OS (oscilloscope) used Tektronix oscilloscope's 5104 B, C for data recording.

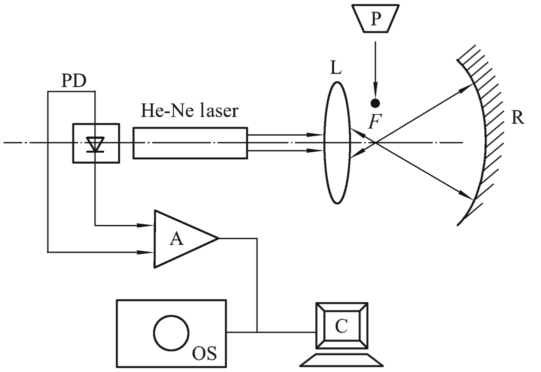


Fig. 2 Single-particle measurement system based on laser-feedback phenomenon (PD—photo diode; L—focus lens; *F*—focus point; P—printer; R—concave reflector; A—amplifier; OS—oscilloscope; C—computer)

Compared to the additional resonator made directly by a plane mirror, the particle can be captured more sensitively in the confocal region with the lens confocal cavity used, which can improve the measurement accuracy and reliability. Lasers and lenses coated with the internal part of a high absorption of sleeve material will be closed to avoid the interference of stray light from the outside world. At the same time, the large aperture of a short focal length lens is used to improve the resolution, shorten the optical path, and raise particle measuring stability. For the lens with $\varphi = 70$ mm and $f = 20$ mm, the focus of the spot size can be achieved at 0.2 μm resolution.

The slowly moving single particle whose diameter is between 2–35 μm is produced by a piezoelectric inkjet printer P, which is of good characteristic repeatability, has accurate mechanical positioning, large drop absorption and scattering coefficients, and an obvious laser feedback effect [17]. In addition, through precise and controllable speed rotating machinery filaments driven by confocal measurements, the single particle which is faster and has a greater diameter measured can be simulated. At present, majority of countries have classed standard particles into two grades by accuracy and production: one is the standard error of particles at 1%–2%, mainly for the evaluation and measurement of the two fixed-value uses; the other is the particle standard field measurements which are required to meet measurement errors in the 5%–10% range. Large particles are produced from metal material processing with errors more than 20 μm to 1 μm below the basic standards of a particle.

The motion and direction of the particle produced by the printer are to ensure a vertical axis direction and an error within ± 5°. The inkjet printer which produces the particles, using the removable or pressure control system, can meet the basic constant current, constant speed requirements by measuring the sensitive area.

The sensitive areas usually installed in particle measurement equipment are very small, and in some equipment may be reduced to as small as 3 μm × 3 μm × 3 μm, to guarantee the accuracy of measurement. The feedback effect of a laser particle, which measures the confocal sensitive areas in the experiment, will be under the direction of particle motion within the lens focal plane, usually within a ± 2 mm error, which is more than the total coke measurement. The effect can be ignored, causing the current generated by the pulse signal change to be significantly reduced. The limit of the size of a single-particle measurement can be up to 2000 microns.

4 Experimental result

Using a feedback laser measuring device for single-particle measurement of particle parameters is done with on-line information of the laser output power to meet the conditions of stability on the basis of standard size and speed in standard particle measurement by using criterion-referenced maps. This is called a scaling experiment. The results are then acquired by calibrating experimental results with actual on-line measurement results entered into computer processing algorithms. It is the assumption that the particle approaching the standard inkjet requirement is characterized by its size D_s and by its surface area. Before conducting the experimental calibration, the system needs more than 20 minutes of thermal stability in order to get the enlarged DAC voltage value with particle-free passage. Then a new voltage value is measured by letting particles through using the standard measurement of coke. The difference is the feedback laser pulse voltage value.

Calibration experiments are used to study single particle spectrum measurement standards according to the law. The main conclusions of the study are:

1) In constant velocity, the particle size is proportional to the voltage feedback. In Fig. 3, particles are shown moving in single file at $v = 0.5$ m/s, with a diameter less than 30 μm, the linear relationship between the particle diameter, d, and the measured pulse voltage. For the speeds of particles at 5 and 20 m/s, the related diameter of the particles in the 30 to 120 μm range and with the voltage pulse, these are shown in Fig. 4. The experimental data show that regardless of the small particle size, high-speed movement or larger-sized particles, the linear relationship between the feedback voltage pulse and the diameter is significant, and smaller particle size has a greater slope in the experimental results.

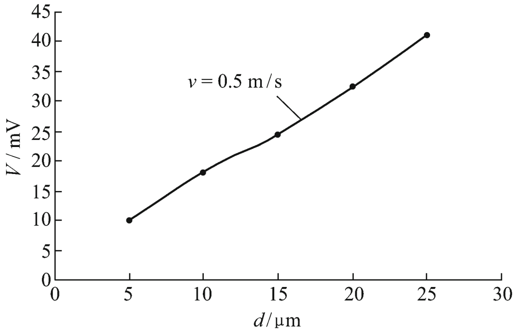


Fig. 3 Measured voltage pulse of laser feedback signal as a function of particle size at $v = 0.5$ m/s

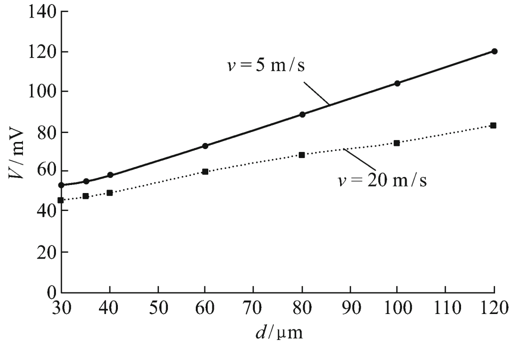


Fig. 4 Relation between voltage pulse and a comparatively larger particle size at $v = 5$ m/s and $v = 20$ m/s

2) For a certain size of single standard particles, the velocity which is perpendicular to the optical axis through the sensitive areas of the confocal lens is linear with the voltage, but the particle size determines the ratio of the slope. Figure 5 indicates moving particles with diameters of 5, 10, 30, 80 and 120 μm and a velocity less than 20 m/s as measured by a voltage pulse diagram. From the experimental contrast, it is not difficult to find that the smaller the particle size is, the smaller the relationship between the speed and the feedback effect of the measured voltage

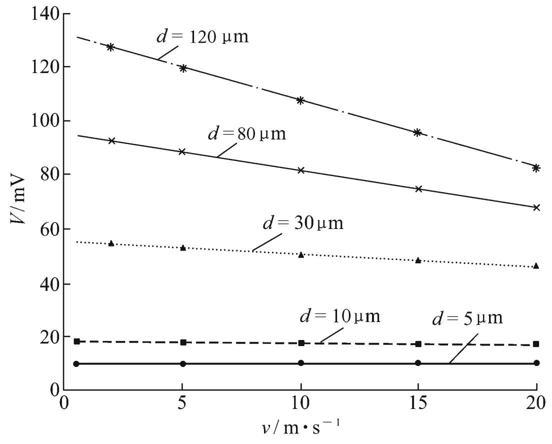


Fig. 5 Relation between voltage pulse and velocity of moving particles with different sizes

pulse is, and the slope is almost 0. However, if the particle size is over 100 μm, speed is obviously linear with the voltage measurement. The slopes of the curves of speed and voltage are negative, indicating that when the particles move along the optical axis perpendicular to the direction of the minimum velocity, the feedback effect of the laser pulse voltage has the greatest value. Therefore, it is inferred that a particle with a size less than 10 μm is very easy to detect in this system, but the velocity of particles can not be determined. For a larger particle size, the size and velocity can be identified from feedback voltage pulse numbers.

3) To achieve single-particle measurement calibration test repeatability and good stability, the experiments are performed with four single particle groups. Group 1: $d = 5$ μm, $v = 0.5$ m/s; Group 2: $d = 10$ μm, $v = 0.5$ m/s; Group 3: $d = 35$ μm, $v = 5$ m/s; Group 4: $d = 40$ μm, $v = 10$ m/s. These four single particle groups are measured on 10 occasions respectively, and the received voltage measurement results as shown in Table 1. The number of particles can be counted in accordance with the number of voltage pulses. From Table 1 below, each measuring system repeatability error is less than 0.15% (the difference between the maximum and minimum divided by the average), and measurement repeatability and reliability are good. The single particle generated has less than 2% of the accuracy of a standard measurement, and the repeatability error is less than 0.15%. The ratio of the standard to determine the particle-particle size is good and is able to avoid the error of the measuring equipment. Further, the precision level can achieve on-line measurement accuracy requirements. Measuring range can be from 0.1 to 2000 μm.

5 Stability of laser output

Generally speaking, the unstable laser output power will impact on the feedback effect. In this experiment using the highly stable single-mode helium-neon laser light source, light stability of the former is confirmed in experimental measurements. In the experiment, the construction of device structures is done at the temperature of 27°C. Then after 20 minutes of being in stable status, one sample will be taken every 10 minutes, and each is done in accordance with different magnifications, consecutively and rapidly sampling data three times. At the beginning, the standard is set for the admission average of stability; if numerical changes are more than 1%, there will be an alarm. After about 7 h of measurements, there are 13 alarms and the biggest change is 1.4%.

Table 2 shows the data at 27°C: series 1, 2 and 3 systems are at different magnification settings, considering an integrated system error. In the final experiment, 220 mV is used for benchmarks in the system. The results show that the stability of the laser output is quite good. And because the particles move fast, laser power has a long cycle of change. In the system, the effect of laser power is almost negligible.

6 Conclusion

Particle parameter measurement based on the feedback effect of laser can improve the conventional optical scattering method in terms of the inadequate measurement of a single particle. The design, combined with the additional confocal optical resonator, improves the sensitivity of the measuring system. The measurement system is designed to be simple as well as applicable to single particle measurement, with repeatability and good stability. Measured by the standard particle, laser feedback effect and single particle size, velocity must exist between the associations. Although reasonable theoretical analysis has not been made on such an inevitable association, experimental data has been given on the reliability and stability of measurement results. The map of received statistical data through the particle calibration voltage feedback method can be measured for single particle parameters to make projections and forecasts. Under normal circumstances, the experimental device can measure about 600 single-particles per second continuously. With the focus error within ± 2 mm, the requirement of environmental testing is low, and the operation is simple. The device can achieve 0.2-μm optical resolution, particle size measurement in the range of 0.2–2000 μm, data repeatability error at less than 0.15%, and measurement accuracy error within 2%. The measuring system is expected to be used in the measurement of particles in air and toward single-particle generators. There are also a variety of applications, such as calibration. The next step is to adopt PD semiconductor lasers to replace the laser and gas detection instruments, such as oscilloscopes, and produce a small online portable single-particle measuring instrument.

Table 1 Repetition measurements to test reliability of the system (mV)

	1	2	3	4	5	6	7	8	9	10
Group 1	10.010	10.016	10.011	10.021	10.006	10.018	10.013	10.018	10.011	10.013
Group 2	18.001	18.033	18.045	18.050	18.023	18.052	18.042	18.030	18.023	18.045
Group 3	55.053	55.109	55.078	55.101	55.089	55.072	55.113	55.035	55.056	55.121
Group 4	62.082	62.138	62.114	62.123	62.100	62.056	62.079	62.040	62.116	62.093

Table 2 Stability output of the laser system at 27°C (mV)

	0 min	10 min	20 min	30 min	40 min
1	220.30	220.31	220.31	220.38	220.32
2	300.0	301.2	300.9	302.3	301.9
3	150.0	149.1	150.8	151.0	151.2

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