The Optimized Design of Aerosol Mass Measurement System based on Information Entropy

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Abstract. In this paper, the relationship between the signal amplitude counting distribution's information entropy and the channel division is analyzed firstly. According to the character of information entropy, when the channel number is given, if the channel division way is equip-probability division, then the maximum of information entropy occurs, the mass distribution information should be also the biggest. Besides, the more the channel number is divided, the bigger the information entropy. Based on these, the signal amplitude counting distribution is divided by three ways to analysis and calculation, which are equip-probability division, uniform division, geometric proportion division. The experimental results show that the aerosol mass measurement system with the equip-probability division has the highest accuracy and good stability, which matches with the theoretical analysis. This study provides a theoretical guidance for the circuit design of aerosol mass measurement system.

Introduction

With the development of industrial production, the environmental pollutions become very serious. More and more aerosols appear in the air, which can affect the global climate and reduce atmospheric visibility[1,2]. There are also evidences that aerosols have a negative effect on human health[3]. Therefore, it has become a hot issue in the current research on how to monitor the mass concentration and the number concentration of aerosols. The light scattering method is widely used method, due to high precision, fast speed and suitable for on-line measurement. It includes an ensemble-measuring technique and a single particle counting technique. The former based on a simultaneous occurrence of an ensemble of particles in sensing volume can only measure mass concentration, and has been widely employed [4-6]. However, the single particle counting method is simple and reliable. It is usually used to measure the number of particles, besides it also can be used to measure the mass concentration of the particles.

Single particle scattering method usually inverse the particles' mass through dividing channel and calibrating the volume equivalent particle size. However, how to select the channel number is a big problem. If the channel number is big, then the workload is large and the inversion equation is ill posed. If the channel number is small, it is not good to extract the structure of the object. Therefore, it exists great significance to study how to rationally divide the counting channels of the particle counter, which can provide theoretical guidance for the circuit optimization design of the particle counter.

So, this paper analyzes the relationship between information entropy and channel division based on information theory. According to the theory of information entropy, if the channel number is given, the information entropy is the biggest when the channel is equal-probability divided. But in the case of the given channel division method, the more channel number is, the more information entropy is. Then, the three division ways are given and calculated by voltage uniform division, geometric proportion division and equal-probability division for the channel number of signal amplitude distribution. The results indicate that the equal-probability division can provide the highest inversion precision and stability.

The Information Transmission System of Aerosol Mass Measurement

Aerosol mass measurement system

A schematic diagram of an OPC(Optical Particle Counter) system, which includes an optical sensor and a signal collecting and processing system, is shown in Fig. 1. The optical sensor is the kernel assembly, which directly affects the capability of the OPC. Aerosol flows through an optical sensing volume within the optical sensor, and the light scattered by a single particle is collected and focused by a mirror in the angular range, and then converted to an electrical pulse by a photo-detector. Through pre-amplification and multichannel collection, the voltage pulse of the particle is obtained. Note that the magnitudes of voltage pulses are correlated to the particle sizes, and the number of voltage pulses recorded in each channel is the number of particles. The relationship between the number of voltage pulses and the amplitudes of voltage pulses in each channel is the light scattering pulse height distribution of particles, which is used to inverse aerosol mass concentration in this paper.

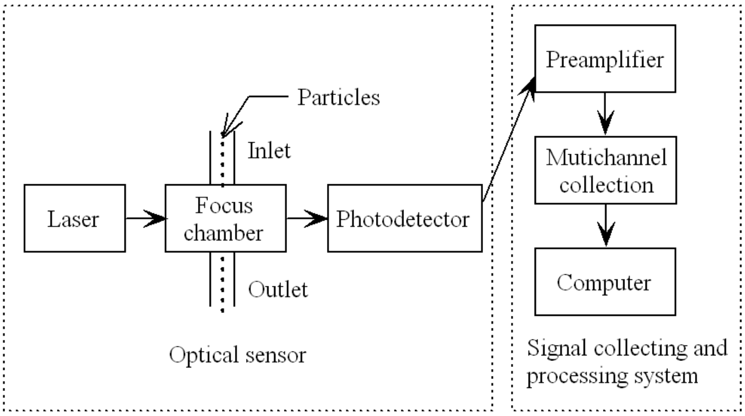


Fig.1 Schematic diagram of optical particle counter system

The information transmission system of aerosol mass measurement

Measurement is a process which use the numerical value of the empirical and objective measurements to describe the characteristics of objects in the real world. In essence, the measurement system is an information transmission system, which includes information source, information sink and information channel[7].

Information is the most basic and most important concept in information theory. Shannon defined as: information is a description of the uncertainty for the movement state or the existence way of the things [8]. Hence, information content can be defined by the use of information uncertainty.

Obviously, aerosol mass measurement is a measurement process. Therefore, the optical particle counter for the aerosol mass measurement is an information transmission system. The input of the aerosol mass counting distribution can be seen as the information source, the output signals' amplitude distribution can be seen as the information sink, and the sensor is taken as the information channel. Then, the particle counter mass measurement process corresponds as the information transmission system, as shown in Fig. 2.

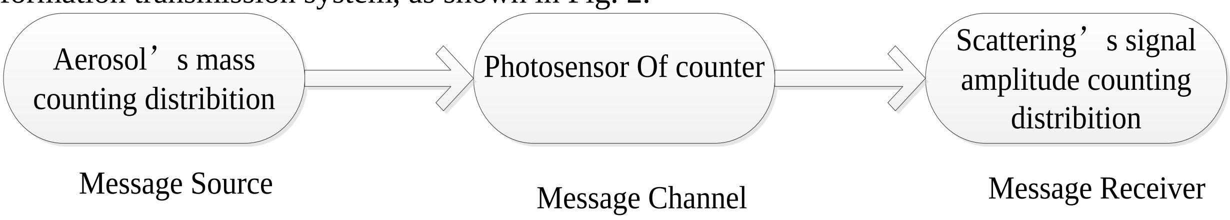
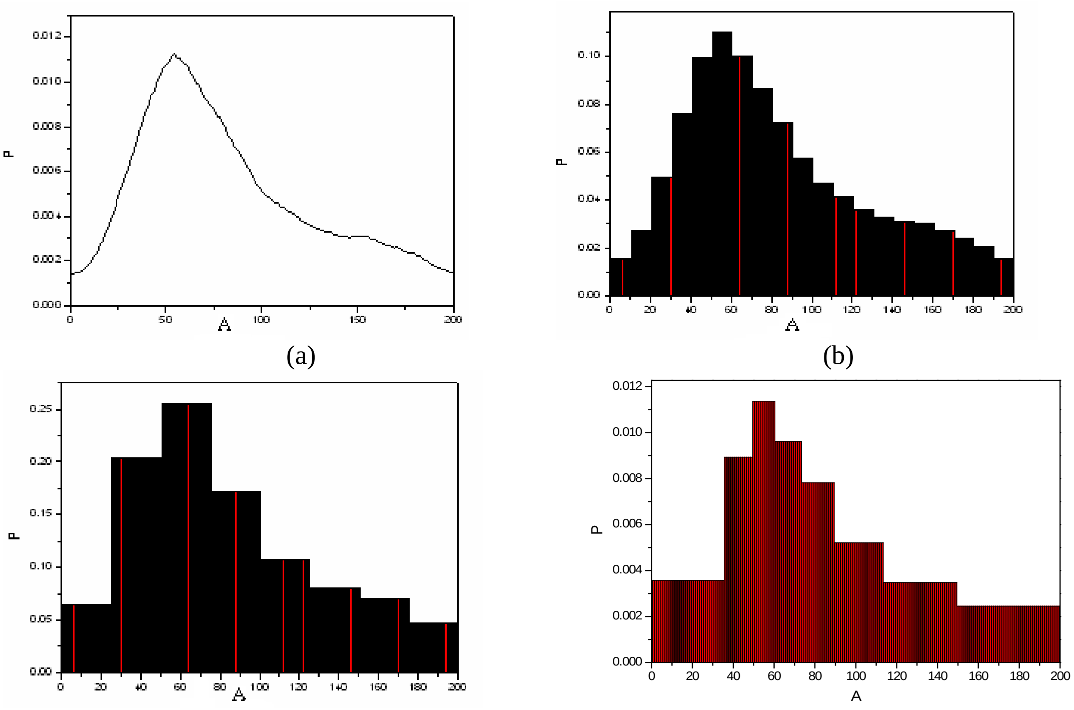


Fig.2 The information transmission process of optical particle counter system

Information Entropy and Channel Division

The signal amplitude distribution of a given particle set usually needs to be discretized and divided data channel. For the same distribution, the channel has many division ways , such as the independent variable uniform division (Fig. 3(b), 3 (c)), The equip-probability division (Fig. 3(d)), and so on.



(a) (b) (c) (d)

Fig.3 The probability histogram of different division mode (a). The continuous probability distribution; (b). The uniformly division histogram with channel number is 20; (c). The uniform division histogram with channel number is 8; (d).The equip-probability division histogram with channel number is 8.

From Fig. 3, we can see that the division way of the probability distribution is different, the probability value $p(a_i)$ of each interval is different, then the size of the information entropy is different and the amount of obtained information is also different. In the same division way, if the channel number is more, the quality of the information obtained is more, as shown in Fig. 3 (b) and 3 (c). But if the channel number is same, the information obtained by different division methods is obviously different. When the channel number is given, the information entropy is the largest under the equip-probability division way, and the quality of the obtained information is the largest, as shown in Fig.3 (c) and 3 (d).

The Information Entropy of Particle Signals' Amplitude Counting Distribution and Inversion Precision

In order to validate the above analysis, in the following experiments we will use three representative method to divide the signal amplitude of aerosol mass measurement: voltage uniform division and geometric proportion division, equal-probability division. We will compare the inversion accuracy and stability of the three division ways under different channel number.

1. equal-probability division

In order to achieve maximum entropy, according to the nature of information entropy, the equal-probability division method of the signal amplitude distribution is used. Then we can be obtained: $p(a_i) = 1/q$, $H = \lg q$, which $q = 2^n$ 。

2. voltage uniform division

By the order of the signal amplitude, the particle counter is merged into q sub sets. The formula for counting the channel voltage of the uniform division method is:

$$u_{li} = u_{l\min} + i \cdot \frac{u_{l\max} - u_{l\min}}{q} \tag{1}$$

Where, u_{li} is the lower voltage of i-th counting channel, and $u_{l\max}$ =5V, $u_{l\min}$ =0V, $i = 1, 2, \cdots q$.

3. geometric proportion division

Because small particles is major in aerosol, the large particles are easy to settle and the content is lower, so the small signals of signal amplitude counting distribution is larger and the big signal is relatively smaller. For as much as possible extraction of particle mass distribution information, according to the characteristics of signal distribution, the arithmetic progression method in Eq.(1) can be changed as follows:

$$u_{li} = (1-\varepsilon)^{i-1} u_{l\max}, \quad i = 1, 2, \cdots q \tag{2}$$

In the formula ε is a coefficient, the smaller the value ε is, the more the channel number q is, the more information obtained from the voltage pulse signal amplitude distribution is.

By using the above three ways, the voltage counting channels are divided into q counting channels. So, the amplitude distribution of the particle's voltage pulse signal $N(a_i)$ is divided into q signal subsets. Taking the smoke's signal amplitude distribution with the mass concentration of $4.964\, mg/m^3$, the information entropy of the signal amplitude is calculated by the three methods. As shown in fig. 4.

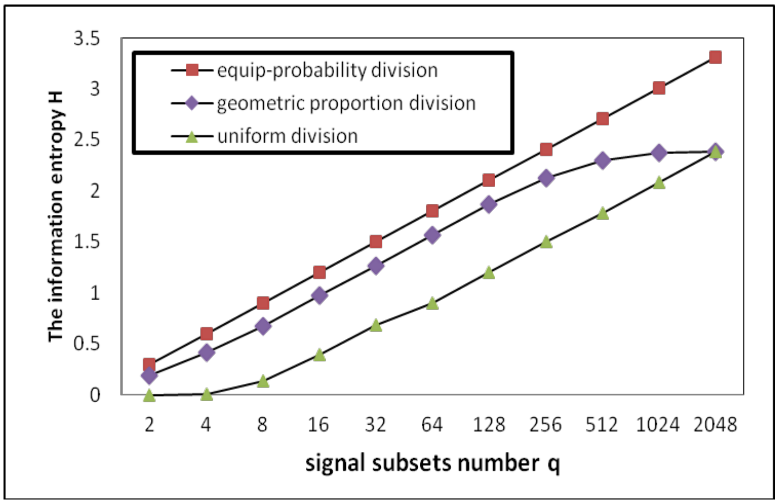


Fig.4 The information entropy of signal amplitude distribution for uniform division, geometric proportion division and equip-probability division.

From the above, we can see that the information entropy of the signal amplitude distribution increases with the increase of the channel number q. The more the signal subsets are, the greater the signal's irregularity is. At the same time, because the information entropy reflects the uncertainty of the signal, so the value of information entropy also increases. But the largest information amount of aerosol mass distribution is a certain value $I(M;A)$, then when the channel is divided into a certain degree, the extracted information quantity of aerosol mass distribution can reached the maximum. Here, if we increase the channel number, although the information entropy increases, but the information amount of aerosol mass distribution does not increase, and the increased information is the instrument itself.

When the channel number is given and the signal amplitude is equal-probability divided, the information entropy is the maximum value $\lg q$. Smoke signal amplitude distribution information entropy with the geometric proportion division is more than the uniform division under the same number of subsets, as Fig.4 shows. Fig.4 also indicates that the missing information of geometric proportion division method is smaller than the uniform division method.

Because the inversion accuracy is best and in steady state when the signal amplitude counting distribution is divided with equal-probability division way, so we consider only uniform and geometric proportion two division ways to verify the inversion accuracy and stability. By using the calibration characteristic parameters and the extraction of signal amplitude distribution, the aerosol mass concentration can be inversed. Then the inversion accuracy r_{esa} will be calculated through comparing the aerosol mass concentration and standard reference instrument measurement values C_{TSI}, its expression as follows[9]:

$$r_{esa} = \sqrt{\frac{\sum_{t=1}^{T}[\frac{1}{C_{TSI,t}}(C_{TSI,t} - C_t)]^2}{T}} \quad (3)$$

Where T is the number of experimental data points, $C_{TSI,t}$, is the actual mass concentration of standard reference instrument at t-th measurement, C_t is the mass concentration measured by OPC at t-th measurement.

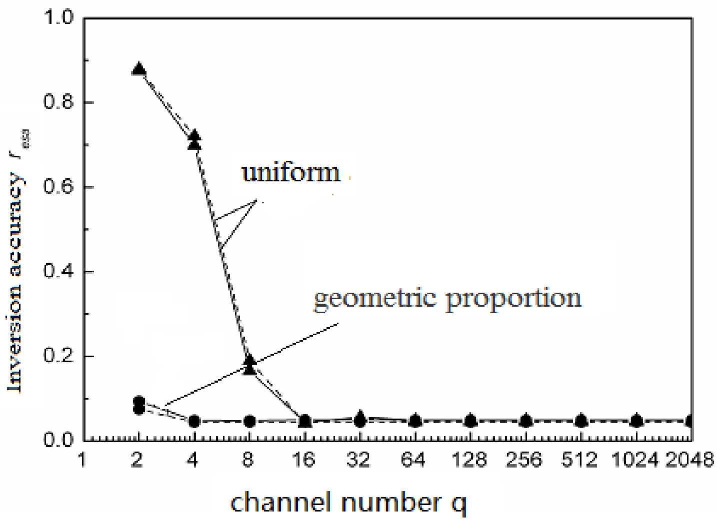


Fig.5 Inversion accuracy of the uniform and geometric proportion division for different signal subsets number

Fig. 5 shows the inversion accuracy of mass concentration for different numbers of signal subsets. For the uniform division method, when subsets are few, inversion accuracies are low, and it trends to stability with the increase of q. When subsets divided by the uniform division way is up to 16, the inversion accuracy of mass concentration has been stable. But if we combine signal amplitude distributions extracted by the geometric proportion division way, mass concentrations measured by an optical particle counter can be attained using the inversion algorithm mentioned in Ref.9. From Fig. 5 we can see that inversion accuracies rapidly trend to stability. When subsets divided by the geometric proportion division way is up to 4, the inversion accuracy of mass concentration has been stable.

From above it can be seen that the mass concentration inversion accuracy and stable speed of two division ways exist significant difference. The mass concentration inversion accuracy and stability of the geometric proportion division way is obviously superior to the uniform division way when the channel number is smaller than 16. However, when the channel number is more than 16, the channel division way is no significance because we can use any method to achieve the same accuracy. This accuracy is also the maximum inversion accuracy that the optical particle counter can achieve.

Conclusion

The relationship between the information entropy and the channel division way is analyzed. Based on these, the signal amplitude counting distribution is divided by the three ways to analyze and calculate, which include voltage uniform division and geometric proportion division, equal-probability division way. The experimental results demonstrate that equal-probability division way has the highest precision and stability. This result provides a theoretical guidance for the circuit design of the mass measuring system of the particle counter.

Acknowledgement

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