

Measurement of Particle Velocity, Particle Size Distribution and Concentration in Particulate Suspension by Transmission Fluctuation Correlation Spectrometry

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Abstract

In coal-fired power generation industry, parameters such as particle size affect combustion efficiency. Especially in the application of two-phase flow clean energy, the parameters such as particle velocity, particle size distribution and concentration are very important, because the coal particle velocity, concentration or size range have an impact on the whole combustion process. This paper introduces an optical measurement setup based on the transmission fluctuation correlation spectrum measurement technique, which realizes the simultaneous measurement of particle velocity, particle size distribution and concentration. Compared with image method, ultrasonic spectrum method and other methods, the experimental device is simple and low-cost.

Keywords

On-Line Measurement, Two-Phase Flow, Transmission Fluctuation Correlation Spectrum, Energy and Power

1. Introduction

Based on the statistical characteristics of transmission fluctuation in flowing particle suspensions, transmission fluctuation spectrometry (TFS) as a new particle measurement method has been used to measure and analyze the particle parameters [1] [2] [3].

When the particle passes through the laser beam at a constant velocity, the transmitted light signal fluctuates with time due to the particle flow. The fluctuation is expressed by transmittance $T(t) = I(t)/I_0$, where $I(t)$ is the transmit-

ted light intensity when the particle passes through the light radiation area at a certain time, I_0 is the incident light intensity, the transmission fluctuations are expressed in terms of the expectancy of the transmission square (ETS). By changing the averaging parameters, the ETS is obtained as a spectrum, which is related to the physical properties of the flowing particle suspension and the process of signal averaging.

Due to the low resolution of ETS for particle size distribution, so different TFS have been developed according to different signal average processing methods, such as transmittance fluctuation spectrum method of low-pass filter based on band-pass filter technology, transmittance fluctuation spatial average method, transmittance fluctuation time average method and their combination [4] [5].

Particulate two-phase flow is widely used in many industrial processes, such as energy, environmental, processing, and power engineering. In order to improve process efficiency, reduce pollutant emission and improve product quality, it is necessary to measure and control the particle size distribution in particle two-phase flow. In the power generation industry, the particle size distribution of pulverized coal and biological objects is an important parameter related to combustion efficiency and greenhouse gas emission. Too large pulverized coal particles will lead to uneven flow distribution between burners and related combustion problems, while very fine particles will be taken away by wind during blowing, resulting in waste of raw materials. Keeping pulverized coal fed at a certain speed and concentration and ensuring particles with a certain particle size range in the combustion chamber will contribute to the improvement of combustion efficiency and heat transfer efficiency. Therefore, the particle size distribution and feed concentration should be kept within an acceptable range to ensure the optimal combustion process, maximize energy conversion and minimize pollutant emission [6] [7]. At present, the particle size measurement of pulverized fuel is mainly realized through regular manual sampling and subsequent off-line analysis, which will lead to the lag of information and can not meet the requirements of real-time control and process optimization. Moreover, it is impossible to monitor the combustion of particles in the combustion chamber. Therefore, a technology that can simultaneously measure multiple parameters of pulverized coal particles is proposed, which can effectively improve the industrial process and make a certain contribution to promoting clean energy.

The transmission fluctuation spectrum may also be obtained with correlation techniques [8] [9] [10]. One of these is the transmission fluctuation spectrometry with spatial correlation (TFS-SC) in which two parallel narrow beams with a variable separation between each other are employed and the expectancy of the transmission product (ETP) is measured as a function of the beam separation. The advantage of this version of TFS-SC is not care about particle velocity and hence it is not strongly influenced by the velocity fluctuations in the measurement zone. However, the mechanical operation on the beam separation becomes challenging, especially for the measurement on small particles. The beams and the detectors should be able to move synchronously and fast enough in a micrometer

scale, what's more, the beams should be consistent with each other both in the beam diameters and in propagating directions, which is very difficult to realize in the actual measurement processing. Therefore, in order to overcome these disadvantages, transmission fluctuation spectrometry with autocorrelation (TFS-AC) is proposed, TFS-AC uses the transmittance of a single beam to calculate the autocorrelation, and changes the autocorrelation time to obtain the functional relationship between ETP and correlation time to obtain the autocorrelation spectrum of transmittance fluctuation. This method does not need to adjust the beam distance repeatedly, and the experimental operation is very simple, but it needs additional means to obtain the particle velocity.

In our work, we propose to use two pinholes to generate a pair of parallel beams, and then cross-correlation the two transmittance signals to obtain the particle flow velocity [11]. By performing autocorrelation calculation on any one of the transmission fluctuation signal, the transmission fluctuation autocorrelation spectrum (TFAS) would be obtained. The particle size distribution and concentration information will be obtained by using appropriate inversion algorithm [12] [13] to inverse TFAS.

In Section 2.2, the theory of TFS-SC and TFS-AC are simply reviewed. Section 3 introduces the experimental setup in detail and the measurement results are given. It is found that the TFS-AC can give reasonable results for certainly concentrated particle suspensions. In Section 4 we further discuss the application prospect of on-line measurement of TFS-AC technology and Section 5 is the conclusion.

2. Principle of the Measurements

The test principle of transmission fluctuation correlation spectrometry (TFCS) method is shown in **Figure 1**. Two narrow beams of the same thickness are parallel to each other, and the particle flow direction is in the plane of the beam and perpendicular to the beam propagation direction. The diameter of both narrow beams is D . The beam center spacing is L , and two PIN tubes are used to detect the light intensity signal and amplify it. When there are no particles in the beam, the detected light intensity signal is the incident light intensity $I_{1,0}$ and $I_{2,0}$.

2.1. Principle of Velocity Measurement

Particle velocity can be obtained by cross-correlation calculation of two transmission fluctuation signals [11], where the cross-correlation calculation is defined as

$$ETP_{L,\tau} = e\{T_1(t)T_2(t+\tau)\} = \lim_{t_s \rightarrow \infty} \frac{1}{t_s} \int_0^{t_s} T_1(t)T_2(t+\tau) dt \quad (1)$$

with the change of correlation time τ , when the cross-correlation signal $ETP_{L,\tau}$ reaches the maximum and the correlation time is recorded as τ_{\max} , which can be combined with the distance L between the two beams to obtain the particle velocity

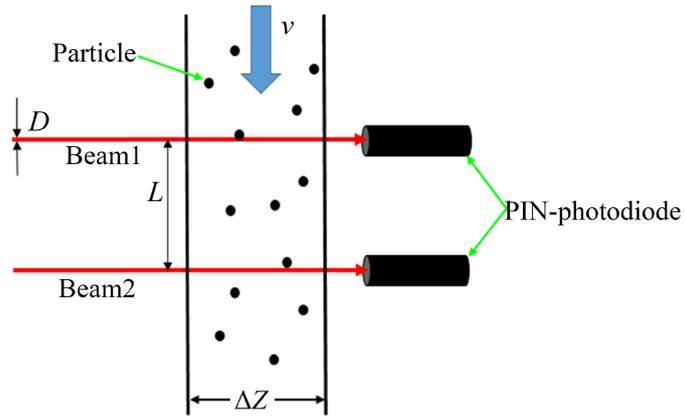


Figure 1. Measurement principle diagram of transmittance fluctuation correlation spectrum.

$$v = \frac{L}{\tau_{\max}} \tag{2}$$

2.2. Principle of Particle Size and Concentration Measurement

2.2.1. Transmission Fluctuation Spectrometry with Spatial Correlation (TFS-SC)

In the technique of TFS-SC, the expectancy of the transmission product *ETP* is defined a

$$ETP = e\{T_1 \cdot T_2\} = \lim_{t_s \rightarrow \infty} \frac{1}{t_s} \int_0^{t_s} T_1(t) \cdot T_2(t) dt \tag{3}$$

where t_s is the sampling time, $T_1(t)$ and $T_2(t)$ are the fluctuating transmission signals of the beams.

The theory of the TFS-SC is developed on the basis of a layer model [9] [10]. When the particle concentration is not too high, a three-dimensional particle system can be taken as a stack of independent monolayers. The *ETP* of the particle suspension is approximately a product of those through the single layer and hence the whole particle system can be described based on the layer model theory, so the *ETP* is expressed as

$$ETP = e\{T_1 \cdot T_2\} \approx \prod_{i=1}^{N_{ML}} e\{T_{ML,i,1} \cdot T_{ML,i,2}\} = (ETP_{ML})^{N_{ML}} \tag{4}$$

where $N_{ML} = \frac{1.5}{P} \cdot \frac{\Delta Z}{x}$ is the number of layers in the particle system, x is the particle size, ΔZ is the thickness of the measurement zone. P is the structural parameter, and it has a value not less than 1.5, which is dependent on the flow field conditions.

With assumptions of geometrical ray propagation and completely absorbent spherical particles, an analytical expression of the *ETP* through the monolayer is expressed as

$$ETP_{ML} = 1 - \beta \cdot [2 - \chi(\Gamma, \Lambda)] + o(\beta^2) \tag{5}$$

where $o(\beta^2)$ is the higher-order term of layer density, describing the monolayer density effects, β is the fraction of the monolayer projected area covered by the particles, which is called the monolayer density. For spherical particles $\beta = PC_V$ and C_V is the particle volume concentration. $\chi(\Gamma, \Lambda)$ is transition functions, which is expressed as

$$\chi(\Gamma, \Lambda) = \int_0^\infty F_T \cdot F_S \cdot F_p \cdot du \quad (6)$$

Here, Γ is the dimensionless beam separation defined as the ratio of the beam distance L to the particle diameter x

$$\Gamma = \frac{L}{x} \quad (7)$$

and Λ is the dimensionless beam diameter. Defined as the ratio of the beam diameter D to the particle diameter x

$$\Lambda = \frac{D}{x} \quad (8)$$

F_T is the spatial correlation factor of two beam transmission fluctuation signals

$$F_T = J_0(2u\Gamma) \quad (9)$$

F_S is the Fourier transform of the beam profile, describing the properties of spatial averaging on the transmission signal over the cross section of the beam

$$F_S = \left[\frac{2J_1(\Lambda \cdot u)}{\Lambda \cdot u} \right]^2 \quad (10)$$

F_p is the particle shape factor and for spherical particles

$$F_p = \frac{2J_1(u\Gamma)}{u} \quad (11)$$

2.2.2. Transmission Fluctuation Spectrometry with Autocorrelation (TFS-AC)

The principle of TFS-AC is much similar to that of TFS-SC, but the operation is a little different. The transmission fluctuation signal $T(t)$ of a single beam is recorded in a quite long period of sampling time t_s . The *ETP* is then calculated with a autocorrelation time τ

$$ETP = e\{T(t)T(t+\tau)\} = \lim_{t_s \rightarrow \infty} \frac{1}{t_s} \int_0^{t_s} T(t)T(t+\tau) dt \quad (12)$$

By changing the autocorrelation time τ , the *ETP* is obtained as a spectrum.

When the particle are passing through the incident beam vertically at a constant velocity v , the product of particle velocity and autocorrelation time is equal to the beams separation.

$$L = v \cdot \tau \quad (13)$$

So Equations (5)-(11) can be fully applied to the TFS-AC. The only difference

is that the variable parameter Γ in Equation (7) is no longer the dimensionless beam separation, but the dimensionless correlation time and it is expressed as

$$\Gamma = \frac{v \cdot \tau}{x} \tag{14}$$

when the particle concentration is not too high, the higher-order term of the layer density $o(\beta^2)$ has little effect on the *ETP*, so Equation (5) is re-expressed as

$$\ln ETP_{ML} \approx \ln(1 - \beta \cdot [2 - \chi(\Gamma, \Lambda)]) = -\beta \cdot [2 - \chi(\Gamma, \Lambda)] \tag{15}$$

and hence the logarithm of the *ETP* of a three-dimensional system of mono-dispersed particles can be obtained.

$$\ln ETP = \ln\left(\prod_{i=1}^{N_{ML}} ETP_{ML}\right) = N_{ML} \cdot \ln ETP_{ML} = -\frac{1.5\Delta Z}{x} \cdot C_V \cdot [2 - \chi(\Gamma, \Lambda)] \tag{16}$$

Equation (16) shows that for parallel beam, the beam diameter remains unchanged in the beam propagation direction.

The discussions above are for a mono-dispersed spherical particle system. For a dilute poly-disperse suspension steric interactions between the particles which are independent of each other. The poly-disperse suspension can be modeled as a number of monodisperse suspensions. So the logarithm of *ETP* is the sum of the contributions from each fraction \bar{x}_j of particles

$$\ln ETP(\tau_i) = -\sum_{j=1}^n \frac{1.5\Delta Z}{\bar{x}_j} \cdot C_V(\bar{x}_j) \Delta x_j \cdot [2 - \chi(\Gamma_{ij}, \Lambda_j)] \tag{17}$$

Here, $\tau_i (i = 1, 2, \dots, m)$ is the variable time difference for signal correlation, $\bar{x}_j (j = 1, 2, \dots, n)$ is the mean particle diameter in the j^{th} fraction of particle size and $C_V(\bar{x}_j)$ is the corresponding volume concentration. $\Gamma_{ij} = v\tau_i/x_j$ is the dimensionless correlation time.

Equation (17) shows that the logarithm of *ETP* is linear with respect to the particle concentration, and the effect from the different particle size fractions superimpose linearly to form the logarithm of *ETP*. Therefore, the particle size distribution and volume concentration information can be retrieved simultaneously by inverse calculation the logarithm of *ETP* with Chahine iterations inversion algorithm [12] [13].

According to Equation (17), we can construct a linear vector equation

$$M \cdot X = Y$$

$$\sum_{j=1}^n M_{i,j} \underbrace{\frac{1.5\Delta Z}{x_j} C_V(\bar{x}_j) \Delta x_j}_{X_j} = \underbrace{-\ln ETP(\tau_i)}_{Y_i} \tag{18}$$

where, $\{M_{i,j}\}$ is the theoretical interpolation matrix, corresponding to the test principle.

For a uniform beam with constant diameter, the theoretical matrix is calculated as follows

$$M_{i,j} = 2 - \chi \left(\Gamma_{ij} = \frac{v\tau_j}{x_j}, \Lambda_j = \frac{d_B}{x_j} \right) \quad (19)$$

$$\chi(\Gamma, \Lambda) = \int_0^\infty J_0(2u\Gamma) \cdot \left[\frac{2J_1(u\Lambda)}{u\Lambda} \right]^2 \cdot \frac{2J_1^2(u)}{u} du$$

$\{-\ln ETP(\tau_i)\}$ is the transmittance fluctuation correlation spectrum obtained by correlation calculation to experimental data. $\{X_j\}$ is particle size distribution with an appropriate inversion algorithm to solve Equation (18), the particle size distribution can be retrieved. In addition, the volume concentration C_V of the poly-dispersed particle system can be obtained simultaneously

$$C_V = \sum_{j=1}^n C_V(\bar{x}_j) \cdot \Delta x_j \quad (20)$$

3. Experiment

Experimental Setup

The experimental setup is schematically shown in **Figure 2**. The illuminating beam, from a He-Ne laser ($\lambda = 0.6328 \mu\text{m}$), was expanded and collimated by a beam expander and vertical irradiation to the sample cell. There is a light barrier behind the sample cell, which has two holes and their diameter is $D = 850 \mu\text{m}$ and distance is $L = 1.4 \text{ mm}$. The transmitted beam intensity or transmission of passing through the two holes are received by photodiode (PBX65) with effective areas are $2 \text{ mm} \times 2 \text{ mm}$ respectively. The transmitted beam intensity or transmission passing through the two small holes are detected by the photodiode and amplified by the signal amplifier and acquired by a high-speed data acquisition card (PCI-50621). The final data processing includes correlation calculation and inversion, which can be executed by a computer.

The measurements are performed on spherical, transparent particles glass beads and on non-spherical and white opaque particles silica sand. The nominal particle sizes of glass beads are $500 \mu\text{m}$, $700 \mu\text{m}$ and $1000 \mu\text{m}$, respectively and their density is 2.45 g/cm^3 , the nominal particle size of silicasand particles is $800 \mu\text{m}$ and its density is 2.65 g/cm^3 . In order to ensure constant measurement conditions during experimental measurement, the circulating speed of

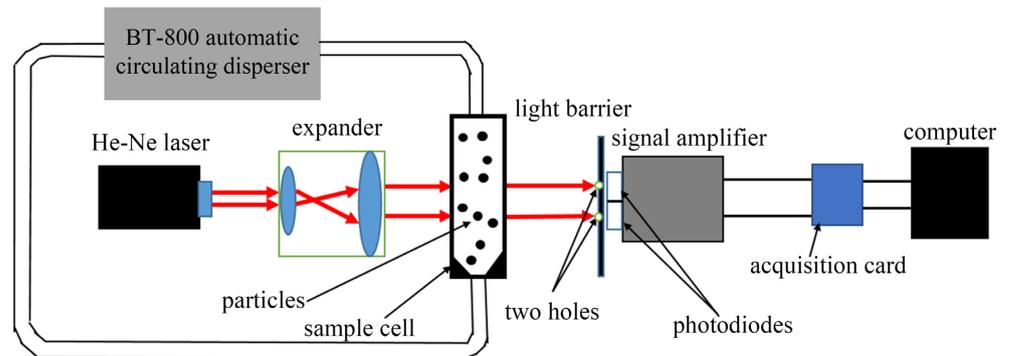


Figure 2. Experimental setup.

the circulating disperser is set to 600 rpm, the particle flow velocity is 1.13 m/s, which is measured by a laser velocimeter. **Table 1** shows the measured velocity values of four particle samples.

In **Table 1**, the concentration of the test from group 1 to group 10 increases gradually. When the concentration increases, the particle velocity decreases slightly, which is mainly because some particles settle when the concentration increases, but the velocity changing is very little. So we believe that the velocities of glass bead particles and silica sand particles obtained by cross-correlation processing of transmittance signals are consistent with the results measured by laser velocimeter.

Figure 3 shows the cumulative distribution curves Q_3 of spherical glass beads particle and non-spherical silica sand particle under different concentrations. It can be seen that most of the particle distribution curves obtained under different concentrations have good repeatability. There are obvious deviations in the test results of silica sand particles at different concentrations, this is because silica sand belongs to non-spherical particles, and its test results are related to the spatial orientation of particles when they pass through the measurement area.

Figure 4 show the results of measurements on the particle volume concentration for spherical glass beads (a) and non-spherical particles (b). The horizontal axis represents the volume concentration obtained from the particle mass and density, and the vertical axis represents the volume concentration measured by TFS-AC technology. When we compare the concentration relationship of spherical particles, the results obtained by the two methods are basically the same. However, when the particles are non-spherical, the volume concentration measurement result C_{V_TFS-AC} is slightly larger than C_{V_mass} . This is mainly because the theoretical model of transmission fluctuation autocorrelation spectrum method is based on spherical particles.

Table 1. Velocity test results of particle samples with four different particle sizes (m/s).

	Glass bead (500 μm)	Glass bead (700 μm)	Glass bead (1000 μm)	Silica sand (800 μm)
1	1.1824	1.1589	1.1437	1.2411
2	1.1589	1.1513	1.1438	1.1667
3	1.1667	1.1363	1.1667	1.1589
4	1.1363	1.1218	1.1513	1.1744
5	1.1363	1.1290	1.1218	1.1290
6	1.1363	1.1076	1.1218	1.1147
7	1.1363	1.1218	1.1147	1.1147
8	1.1076	1.1218	1.1076	1.1076
9	1.1218	1.1076	1.1076	1.2903
10	1.0803	1.1076	1.1006	1.1076

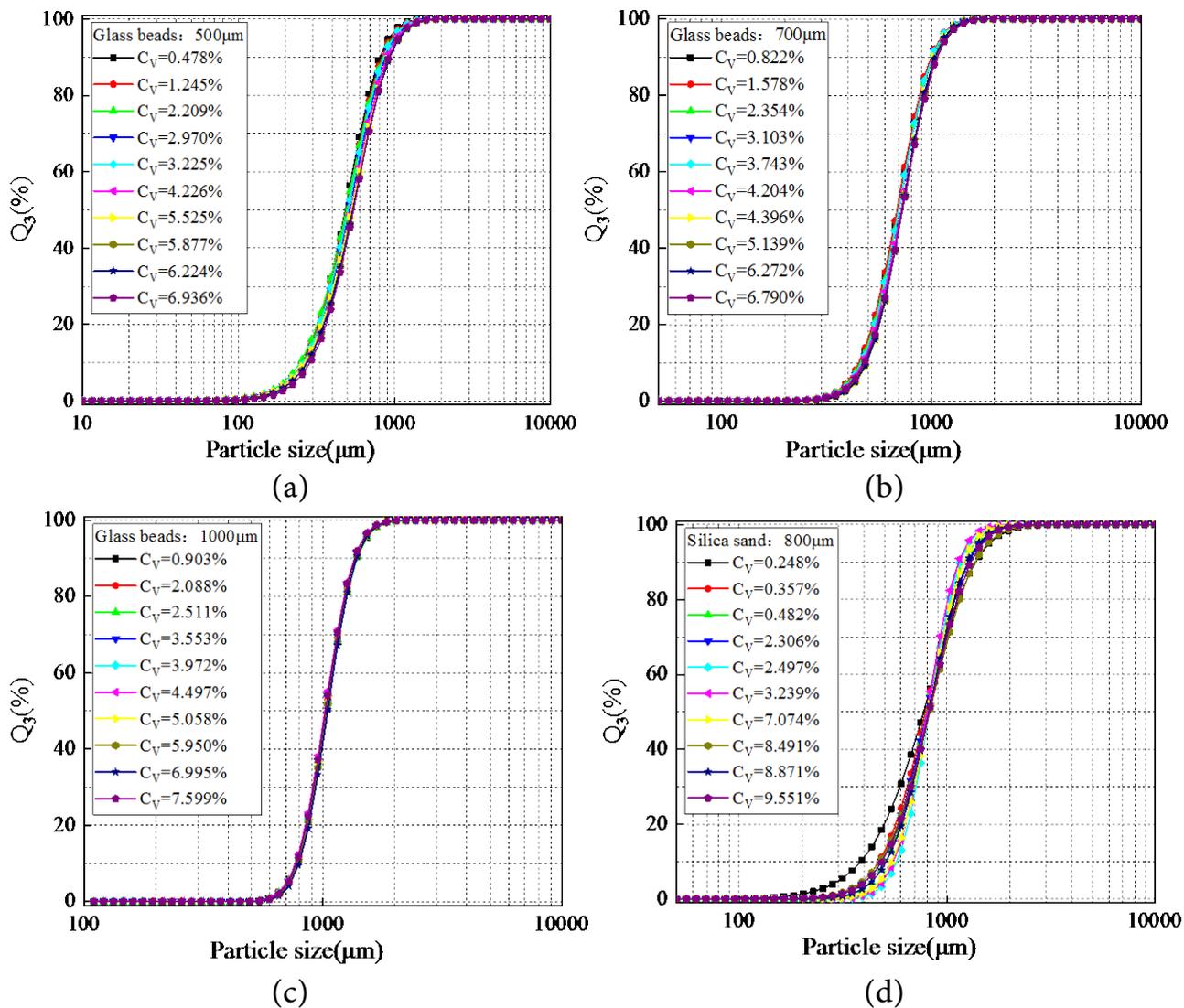


Figure 3. Cumulative distribution of spherical glass beads and non-spherical silica sand particles under different concentrations.

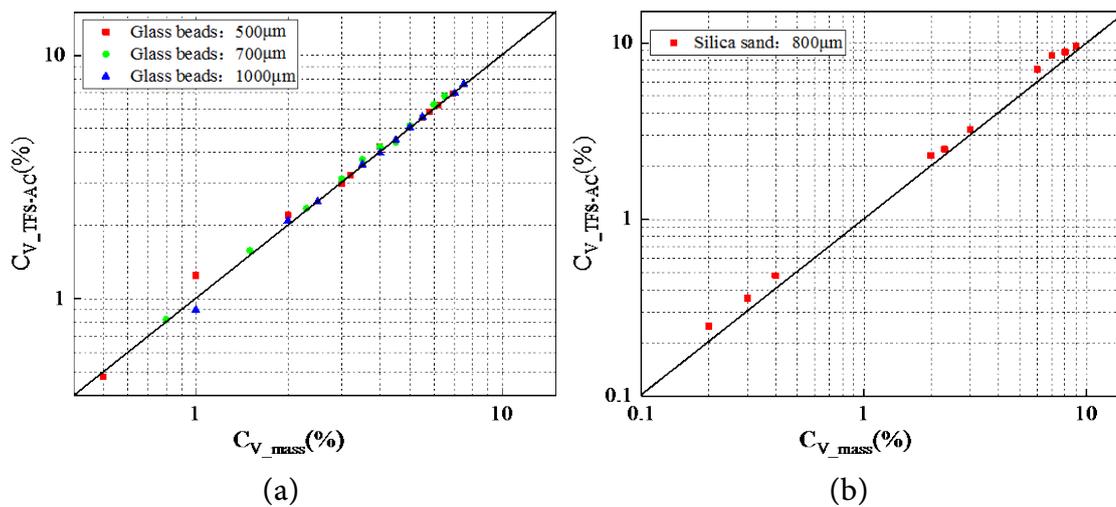


Figure 4. Particle volume concentration measured.

4. Further Discussion

Particulate two-phase flow widely exists in energy, industry, environment and other fields. Especially the determination of particle parameters in coal yard thermal power generation, due to the poor environmental conditions in the coal yard, the instruments used to measure the coal diameter are limited. In the process of coal feeding into the hall furnace, the accurate grasp of the effective size range of coal particles can improve the combustion efficiency, and the control of speed and concentration can ensure the sustainability of the combustion process.

Particle size distribution and concentration can be obtained simultaneously by taking the particle velocity as the known value and inverse calculating the transmittance spectrum with an appropriate inversion algorithm. That is to say, as long as the particle is in the flow state, we can use this technology for real-time and on-line measurement of particle size distribution, volume concentration and particle velocity. Therefore, in the next work, we will develop this technology so that it can be used to measure particle velocity, particle size and concentration in two-phase flow.

5. Conclusions

This paper introduces a simple transmittance fluctuation correlation spectrum measuring device for simultaneous measurement of particle size distribution, particle concentration and particle velocity. The particle velocity is obtained by using the transmittance cross-correlation spectrum of two parallel beams, and the particle size distribution and concentration are obtained by using the transmittance autocorrelation spectrum of a single beam.

In the actual test, the glass beads and silica sand particles dispersed in water are driven by the circulating dispersion device, their transmittance signals are measured and their transmittance correlation spectrum is obtained. The particle size distribution, concentration and velocity are obtained by inversion calculation. Most importantly, the particle size distribution and concentration measurements are agreed with what we know, and the consistency and repeatability of the multiple measurements are high from the experimental results, so the method is expected to be developed for multi-parameter measurements of particles in two-phase flow fields, especially in the energy and power fields, this technology will bring certain potential and application value to promote the development of clean energy.

Conflicts of Interest

The author declares no conflicts of interest.

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