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Postprint: Experimental Study on Measurement of Coal-fired Particulate Matter Concentration Using Laser Total Scattering Method

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Abstract

This study conducted mass concentration measurement experiments on coal-fired fly ash particles of different properties and concentrations using a laser total scattering method particulate matter concentration detection system. The results demonstrate that the combined total scattering method particulate matter concentration detection system and inversion calculation method can accurately determine the mass concentration of standard particles with an error of approximately 7%. For coal-fired fly ash particles, the calculated results can reflect variations in particle concentration within the gas stream; however, the calculated values exceed the true values by approximately 19.3% to 27.2%. Furthermore, the calculation deviation for fly ash from the pre-stage electric field of the precipitator is greater than that for fly ash from the fourth-stage electric field. Further theoretical calculations indicate that as particle size increases, the scattering light distribution gradually concentrates in the forward direction (i.e., the 0° direction), causing the photoelectric detector to collect partial forward-scattered light while simultaneously collecting transmitted light, which results in inversion calculated values exceeding true values. Moreover, the pre-stage electric field fly ash contains a higher proportion of large-sized, non-spherical particles with a broader particle size distribution range, deviating from the assumptions of the inversion algorithm and consequently increasing the calculation deviation.

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Full Text

Experimental Study on Mass Concentration Measurements of Coal-Derived Particulate Matter via Light Extinction Method

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Abstract

This study investigates mass concentration measurements of coal-derived fly ash particles using a laser light extinction method. Experiments were conducted on a self-designed light-extinction-based particle concentration measuring system using fly ash particles of varying properties and concentrations. Results demonstrate that the combined system and inversion method accurately determine mass concentrations of standard spherical SiO powders with deviations of approximately 7%. For real fly ash particles, the inversion results reflect concentration variations in the gas stream but are 19.3%-27.2% higher than actual values, with greater deviations observed for ash collected from upstream electrostatic precipitator (ESP) fields compared to downstream fields. Theoretical calculations reveal that as particle size increases, the scattering light distribution progressively concentrates in the forward direction (0°), causing the photodetector to collect both transmitted light and portions of forward-scattered light, which leads to overestimation. Furthermore, fly ash from upstream ESP fields contains more large, non-spherical particles with broader size distributions, deviating from the inversion algorithm' s assumptions and resulting in larger measurement deviations.

Keywords: light extinction method; fly ash; particulate matter; mass concentration; optical measurement

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1. Introduction

As emission concentrations of particulate matter from coal-fired power plants continue to decrease, the importance and urgency of achieving accurate mass concentration measurements have become increasingly prominent. Accurate online detection is essential not only for determining compliance with emission standards but also for enabling feedback control of precipitators to ensure efficient and economical operation. The laser light extinction method has attracted widespread attention as an online measurement technique that offers convenience, low equipment requirements, high accuracy, rapid response, and good repeatability.

The measurement principle of the light extinction method is based on the attenuation of transmitted light intensity when a beam of parallel monochromatic light irradiates particles. The degree of attenuation is used to invert and calculate particle concentration. Previous studies have demonstrated various applications of this technique. Kourti et al. analyzed the feasibility of measuring polydisperse particles and achieved size measurements for particles below 2–3 µm. Paphael et al. applied the method for online measurement of solids concentration and mean particle size during polymerization. Wang and Cai performed optical measurements of droplets in steam turbines. Marioth et al. used three-wavelength extinction technology to measure particle and droplet sizes in supercritical CO flows, noting its suitability for supercritical fluid processes. Kocifaj et al. analyzed size inversion calculations for irregularly shaped particles. Qin and Cai developed a light fluctuation spectroscopy method based on extinction principles combined with fluctuation and spectral analysis for online measurement of pulverized coal concentration and size distribution. Zhao et al. established a method for online soot concentration measurement that is independent of particle size distribution and mean diameter, achieving good experimental results. Lou et al. and Yin et al. applied extinction theory to oil mist droplet size distribution measurements. Chen and Lai conducted real-time atmospheric particulate monitoring studies. Cui et al. analyzed the influence of particle size distribution on mass concentration measurements, showing that deviations increase with higher proportions of particles having dimensionless size factors (D/) greater than 30. Wang et al. proposed theoretical and experimental methods for synchronous multi-angle scattering detection for smoke and dust emission measurements.

Compared to other dust detection applications, fly ash from power station boilers exhibits variable shapes, broad size ranges, and complex compositions. However, research on online measurement of coal-derived fly ash using the light extinction method remains limited. Therefore, investigating the accuracy of this method for coal-derived particulate matter and understanding how the unique physical and chemical properties of fly ash affect measurements holds significant theoretical and practical value.

This study employs real fly ash particles collected from an operating coal-fired power plant to conduct mass concentration measurement experiments on a self-designed laser light extinction system. Concentrations are inverted from incident and transmitted light intensity variations based on extinction theory. Simultaneously, an Electrical Low-Pressure Impactor (ELPI) performs online concentration measurements for comparison, enabling analysis of measurement accuracy and the influence of fly ash properties including particle size, size distribution characteristics, and shape.

1.2 Experimental System and Method

Experiments were conducted on a self-designed laser light extinction particle concentration detection system. As shown in [Figure 3: see original paper], the system comprises two main components: an optical path system and a gas path system.

The optical path system includes a laser source (LBX-633), variable aperture, focusing lens, and photodetector (ET-2030). The laser source generates stable monochromatic light at 632.5±0.5 nm (red). The laser beam enters the detection chamber to irradiate the particle-laden gas stream (air). The photodetector receives transmitted light and converts it into analog signals, which are digitized through a multi-channel AD acquisition system and input to a computer for calculation. The extinction level, -ln(I/I), is determined from incident (I) and transmitted (I) light intensities. The detection chamber has an optical path length of 1 m, with high-transmittance optical windows at both ends equipped with high-pressure air purge systems to prevent particle deposition and interference.

The gas path system consists of compressed air, an aerosol generator (TSI 3400A), detection chamber (organic glass, 100×30×30 cm), ELPI, and vacuum pump. The aerosol generator produces particle-laden streams with varying concentrations (20–300 mg/m³) of either SiO standard particles or ESP field fly ash. During experiments, particle samples and compressed air generate the desired particle-laden flow, which passes through the detection chamber for optical measurement. The exhaust stream then enters the ELPI for collection and measurement of number and mass concentrations. The ELPI classifies particles into 13 stages based on aerodynamic diameter and calculates size distribution and concentration information through particle charging and discharging processes. This study evaluates light extinction measurement accuracy by comparing optical inversion results with ELPI measurements. Each operating condition was tested three times, with average values used for analysis.

1.3 Particle Concentration Inversion Based on Extinction Theory

When a light beam passes through a uniformly particle-laden gas medium, the relationship between transmitted and incident light intensity follows the Lambert-Beer law:

$$I = I_0 \exp(\tau L) \tag{1}$$

where I and I are incident and transmitted light intensities, L is the optical path length, and   is the turbidity of the particle-laden medium.

Assuming spherical particles and incoherent single scattering, the total turbidity of a particle system can be calculated from individual particle extinction coefficients:

$$\tau = \int_a^b N(D) K_{\text{ext}}(D) \frac{\pi D^2}{4} dD \tag{2}$$

where a and b are the lower and upper size limits, N(D) is the number size distribution function, and K is the particle extinction coefficient. The extinction coefficient depends on wavelength , relative complex refractive index m, and particle diameter D.

Based on the equivalent extinction coefficient principle, the average extinction coefficient K and Sauter mean diameter D(3,2) for polydisperse systems are defined as:

$$K_m = \frac{\int_a^b N(D) K_{\text{ext}}(D) D^2 dD}{\int_a^b N(D) D^2 dD} \tag{3}$$

$$D(3,2) = \frac{\int_a^b N(D) D^3 dD}{\int_a^b N(D) D^2 dD} \tag{4}$$

Combining equations (1)-(4) yields the inversion formulas for volume concentration C and mass concentration C :

$$C_v = \frac{\pi}{6} \int_a^b N(D) D^3 dD \tag{5}$$

$$C_m = \rho_p C_v = \frac{\rho_p \tau L}{K_m} \frac{D(3,2)}{3} \tag{6}$$

where is particle density. With known , m, and D(3,2), the average extinction coefficient K can be obtained from Mie scattering theory, enabling volume and mass concentration inversion from measured extinction.

2.1 Experimental System Reliability Verification

[Figure 4: see original paper] shows the relationship between inverted and actual mass concentrations for SiO standard particles. The results demonstrate excellent linear correlation (R^2 = 0.9984) between concentrations calculated from light extinction and actual values. The inverted values are approximately 1.07 times the actual values, corresponding to only ~7% error. This confirms that for standard spherical particles, the inversion method accurately reflects true concentrations.

2.2 Fly Ash Particle Concentration Measurements

[Figure 5: see original paper] illustrates the relationship between extinction level and particle concentration for ESP field fly ash. Positive correlations are observed for all fields, with R^2 values of 0.9962, 0.9975, 0.9978, and 0.9983 from the first to fourth field, respectively. These results confirm that coherent multiple scattering is absent, satisfying the fundamental assumption of extinction theory. Notably, transmitted light signals vary significantly among different ESP fields, indicating distinct effects on light extinction measurements.

[Figure 6: see original paper] presents the relationship between inverted and actual concentrations for each fly ash sample. While inverted values reflect concentration variations, all are higher than actual values. The deviation between calculated and actual values is defined as measurement deviation. [Figure 7: see original paper] shows the relationship between measurement deviation and particle size across ESP fields. As Sauter mean diameter decreases from 4.22 µm (first field) to 3.35 µm, 2.53 µm, and 1.85 µm (fourth field), the measurement deviation decreases from 27.2% to 23.6%, 23.2%, and 19.3%, respectively. Meanwhile, the correlation coefficient increases from 0.9962 to 0.9975, 0.9978, and 0.9983. Thus, the light extinction method demonstrates higher accuracy for smaller fly ash particles.

2.3 Analysis of Fly Ash Characteristics' Influence

During measurement, incident light scattering occurs simultaneously with transmission. The angular distribution of scattered light correlates with particle size. [Figure 8: see original paper] shows Mie scattering calculations for spherical particles of 0.021 µm, 0.211 µm, 0.633 µm, and 2.111 µm (dimensionless size factors D/ of 0.1, 1, 3, and 10). As the dimensionless size factor increases, scattering intensity grows and concentrates in the forward direction (0°). For small particles (D = 0.021 µm), backward (180°) and forward scattering intensities are comparable. Further calculations reveal that for 6.334 µm particles (dimensionless size factor of 30), forward scattering intensity within ±5° reaches the same order of magnitude as transmitted light. Since concentration inversion relies on the I/I ratio, excessive forward scattering causes the photodetector to collect both transmitted and forward-scattered light, resulting in overestimation.

Discrepancies between real fly ash characteristics and theoretical assumptions also contribute to measurement deviations. First, particle size affects inversion accuracy. This study employs average extinction coefficients and Sauter mean diameter to simplify calculations, with introduced deviations increasing with particle size. Upstream ESP fields contain more large particles, causing more significant deviations, which explains the observed trend: first field > second field > third field > fourth field. Second, the inversion algorithm assumes spherical particles, whereas real fly ash contains numerous irregular shapes and agglomerates, particularly in the first ESP field. These irregular particles further increase measurement deviations.

3. Conclusion

This study investigated mass concentration measurements of coal-derived fly ash particles using a laser light extinction system. The combined self-designed measurement system and inversion method accurately determined standard SiO particle concentrations with errors below 10%. For real fly ash, the method reflected concentration variations but consistently overestimated values by 19.3%-27.2%, with greater deviations for upstream ESP field ash. Theoretical analysis indicates that as particle size increases, forward-scattered light concentration causes photodetectors to collect scattered light along with transmitted light, leading to overestimation. Upstream ESP field ash contains more large, non-spherical particles with broader size distributions, deviating from algorithm assumptions and increasing measurement deviations.

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