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Techniques for measuring particle size distribution of particulate matter emitted from animal feeding operations

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HIGHLIGHTS

► Particle size distributions of PM samples were analyzed by four analyzers.
► Significant differences in PSD measurements were observed.
► Laser diffraction analyzers provided greater and broader PSDs than ESZ analyzer.
► Measured $PM_{2.5}$ mass fractions differed from the lognormal fitting $PM_{2.5}$ fractions.

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ABSTRACT

While various techniques for measuring particle size distributions (PSD) of particulate matter (PM) exist, there is no a single agreed upon standard or reference method for PM with different characteristics. This study investigated differences in the PSD measurements by four PSD analyzers: LS13 320 multi-wave length laser diffraction particle size analyzer, LS230 laser diffraction particle size analyzer, LA-300 laser scattering particle size analyzer, and Coulter Counter Multisizer3 (CCM3). Simultaneously collected total suspended particulate (TSP) samples in a commercial egg production house were analyzed by the four analyzers for PSDs. In addition, four types of testing powders (limestone, starch, No.3 micro aluminum, and No.5 micro aluminum) were also analyzed by these four PSD analyzers. The results suggest when comparing measured mass median diameters (MMDs) and geometric standard deviations (GSD) of the PSDs, the laser diffraction method (LS13 320, LS230 and LA-300) provided larger MMDs and broader distributions (GSDs) than the electrical sensing zone method (CCM3) for all samples. When comparing mass fractions of PM_{10} and $PM_{2.5}$ between the measured values and the lognormal fitting values derived from the measured MMDs and GSDs, lognormal fitting method produced reasonably accurate PM_{10} mass fraction estimations (within 5%), but it failed to produce accurate $PM_{2.5}$ mass fraction estimations. The measured $PM_{2.5}$ mass fractions significantly differed from the lognormal fitting $PM_{2.5}$ fractions and the mean differences reached as high as 95%. It is strongly recommended that when reporting a PSD of certain PM samples, in addition to MMD and GSD, the mass fractions of PM_{10} and $PM_{2.5}$ should also be reported.

1. Introduction

As a criteria pollutant, particulate matter (PM) has been a research topic for numerous studies in the context of air pollution. The studies of health impacts, emission estimation of PM, and development of new control technologies require knowledge of PM characteristics. Among these PM characteristics, the particle size distribution (PSD) is perhaps the most important physical parameter governing particle behavior. Various methods and techniques are available for conducting PSD analyses. Advantages and disadvantages associated with each method exist. Unfortunately, there is no single agreed upon method to determine the PSD of PM emitted from difference sources.

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In the literature, the commonly used techniques for PSD measurements can be classified into five categories based upon the principals applied in particle size measurements (Hinds, 1999): (1) aerodynamic method, including aerodynamic particle sizer (APS) and various cascade impactors; (2) optical method, including various optical particle counters, light scattering and laser diffraction particle size analyzers; (3) electrical sensing zone method, i.e. Coulter Counter; (4) electrical mobility and condensation method, e.g. differential mobility analyzer (DMA) plus condensation nuclei counter (CNC); (5) electron microscopy.

The APS measures the aerodynamic equivalent diameter (AED) of individual particles using the time-of-flight principle (Hinds, 1999; Mitchell and Nagel, 1999; Peters and Leith, 2003). It has a particle size measurement range of 0.5–20 μm. The cascade impactor method uses the principle of inertia to separate PM into different particle size ranges based upon different cut-off sizes at different impaction stages connected in series (Hinds, 1999). The impactor method provides onsite PSD measurement of airborne particles, but the PSD classification of this method can only include a small number of size classes. The inertial removal may cause inter-stage loss due to sharp bends in the inter-stage flow path.

The optical particle counters (OPCs) are used most frequently for measuring number concentrations corresponding to different size classes. While they can provide real-time concentrations and size measurements of airborne particles, they are not intended for use on larger particles or in hostile environments with high levels of PM and gaseous pollutants (Parker et al., 2009).

In light scattering particle size analyzers, for particles larger than the light wavelength, Mie scattering theory is applied to determine the angular distribution of scattered lights by particles suspended in a solvent. This angular distribution of the scattered lights is a very sensitive indicator of PSD (Hinds, 1999). In this method, knowledge of the refractive index of the particle and the solvent is required to solve Mie equations for determination of the scattered light angular distribution. It was reported (Xu and Guida, 2003) that the light scattering method may provide more reliable PSD measurements on account of ease of use and broad size ranges, from sub-micrometers to millimeters. On the other hand, the light scattering methods are typically limited to measuring particles greater than 0.3 μm due to reduced detection efficiency with smaller particle size and errors caused by particle shape and refractive index variations. In particle size measurements of airborne particles, the light scattering analyzers measure PSDs from PM samples taken using gravimetric collection techniques. Thus, the light scattering analyzers don't provide real-time PSD measurements. In this method, PM samples need to be extracted from filter media into a solvent for PSD analysis. Consequently, this method is only suitable for insoluble particles. All the optical analyzers provide PSD measurements in equivalent spherical diameter (ESD), not AED. Information of particle shape and density is needed to convert ESD to AED.

The electrical sensing zone (ESZ) method is also known as the Coulter Counter method (Xu and Guida, 2003; Lines et al., 1996). In a Coulter Counter, the particles suspended in an electrolyte solution are forced to pass through a small aperture where an electric field is applied. The solution's conductance changes as the particles pass through the aperture. The change in conductance is a function of particle size. When particles pass through the aperture, the particles' individual volumes are directly measured. This method measures a single particle's volume and provides high resolution and reproducibility for individual particle size assessment in ESD (Lines et al., 1996). However, particles that can be analyzed are restricted to those that can be dispersed in an electrolyte solution and still retain their original integrity. Like the light scattering particle size analyzers, the Coulter Counter also analyze PSDs of airborne particles from samples taken using gravimetric collection techniques. Thus, this method does not provide real-time measurements of PSDs either.

The electrical mobility depends on the electric mobility of the particles for PSD measurement and it can only work well for particles with good mobility. The electron microscopy method is capable of providing both particle size and morphology information. However, this method could not provide sufficient statistical representation of particle measurements to derive a PSD for a PM sample. It is not appropriate for continuous or long term PSD analysis.

Due to lack of a standardized method for PSD measurements in different applications, efforts have been made to compare PSD results measured by some aforementioned methods. When both cascade impactor and laser diffraction particle size analyzer (one type of light scattering analyzers) were used to evaluate PSDs of particles generated by nebulizers (Ziegler and Wachtel, 2005; Smyth and Hickey, 2003), the results of PSDs measured by both of these two techniques correlated with each other very well. In comparison of the light scattering method and the ESZ method, Xu and Guida (2003) reported that the laser diffraction particle size analyzer provided much larger mean sizes and broader distributions for irregular particles when compared with the Coulter Counter. Similar finding was also reported by Jerez et al. (2011) in a study of PSDs in a swine building. When compared the ESZ with other two methods, McClure (2009) found that the Coulter Counter (ESZ method) compared well to APS, whereas Xu and Guida (2003) discovered that the ESZ produced compatible results with dynamic image analysis, which are much less affected by particle shape (Xu and Guida, 2003). In general, particle size results of non-spherical particles measured by different instruments are often less consistent when compared with each other (Xu and Guida, 2003).

The objectives of this reported study were to (1) investigate differences of PSDs measured by different particle size analyzers using either laser diffraction or ESZ techniques for PM from animal feeding operations with large mass median diameters (MMDs) and geometric standard deviations (GSDs); (2) compare mass fractions of PM_{10} and $PM_{2.5}$ between the measured values and the lognormal fitting values derived from the measured MMDs and GSDs. For future relevant studies, it is recommended that limitations of PSD measurements by a given method should be recognized and measured PM_{10} and $PM_{2.5}$ mass fraction should be simultaneously reported when reporting a MMD and a GSD for a PSD measurement.

2. Material and methods

2.1. Particle size analyzers

The particle size analyzers for the study include (1) a LS13 320 multi-wave length laser diffraction particle size analyzer (Beckman Coulter Inc., Miami, FL) owned by the Research Group at North Carolina State University (NCSU); (2) a LA300 laser scattering particle size analyzer (Horiba Instruments Inc., Irvine, CA) owned by the Research Group at University of Illinois at Urbana-Champaign (UIUC); (3) a Coulter Counter Multisizer3, CCM3 (Beckman Coulter Inc., Miami, FL) owned by the Center for Agricultural Air Quality Engineering and Science at Texas A&M University (TAMU); (4) a Coulter Counter Multisizer3, CCM3 (Beckman Coulter Inc., Miami, FL) and a LS230 laser diffraction particle size analyzer (Beckman Coulter Inc., Miami, FL) owned by the research group at USDA-ARS Cotton Production and Processing Research Unit in Lubbock, TX, hereby also known as USDA.