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Upon correlating diameters measured by optical particle counters and aerodynamic particle sizers

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ABSTRACT

Converting optical diameter measured by an optical particle counter (OPC) to aerodynamic diameter measured by an aerodynamic particle sizer (APS) is of interest because the OPC is more affordable and portable. In this study, optical diameter was compared with volume equivalent diameter derived from aerodynamic diameter using monodisperse oleic acid and sodium chloride test aerosols generated by a Vibrating Orifice Aerosol Generator (VOAG). While prior studies assumed optical diameter to be equal to volume equivalent diameter, experimental results showed the assumption to be valid only if the aerosol has the same optical properties as standard polystyrene (PSL) particles. For oleic acid aerosol, the optical diameter was less than the derived volume equivalent diameter because its refractive index ($m=1.46$) is less than of PSL ($m=1.60$). While the refractive index of sodium chloride ($m=1.54$) is close to that of PSL, a much larger optical diameter of sodium chloride than its volume equivalent diameter was observed due to its irregular crystallography. Regression equations derived from the calibration were verified by testing with a validated respirable sampler. With known refractive index and shape factor, these equations can convert optical diameter directly to aerodynamic diameter with a residual bias less than 1 μm.

1. Introduction

The Aerodynamic Particle Sizer (APS) is a commonly used real-time instrument due to its rapid, precise, and accurate measurement of aerodynamic particle size distribution, which is determined by quantifying the time-of-flight of particles traveling through a laser velocimeter (Baron, 1986). While several problems in APS measurement have been reported, including error sizing in high Reynolds number, size shifting for liquid aerosol, and low aspiration efficiency (Baron, Deye, Martinez, Jones, & Bennett, 2008; Rader, Brockmann, Ceman, & Lucero, 1990; Volckens & Peters, 2005), new models have resolved these issues.

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The APS is advantageous in aerodynamic size distribution measurement, but it is less affordable to some users. The Optical Particle Counter (OPC), which has also been widely used in aerosol research, air pollution studies, and cleanroom monitoring, is an alternative aerosol sizing instruments because of its low cost, ability for real-time measurement, and portability (Kulkarni, Baron, & Willeke, 2011). Particle sizing using the OPC is based on the principle of single particle elastic light scattering following the Mie theory (Heyder & Gebhart, 1979). As the particle is illuminated by the incident radiation, a detector quantifies the intensity of the scattered light in an angular range, the signal of which is converted to equivalent optical diameter.

While convenient, the non-monotonic size dependence of the scattered light intensity, as well as the changing response with varying refractive index of different materials and shape factor of the particles of interest limit the sizing accuracy of an OPC (Szymanski, Nagy, & Czitrovszky, 2009). A theoretical scattering light response by Mie theory is available, but OPCs are generally calibrated by solid, spherical, and non-absorptive polystyrene latex (PSL) particles as reference to obtain the relationship between the response and reference particle size (Liebhaber & Willeke, 1993). However, particles in practical systems are usually non-spherical with various refractive indices depending on the particle materials, resulting in erroneous sizing (Sabbagh-Kupelwieser, Maisser, & Szymanski, 2011). The situation gets worse when testing aerosol is absorptive. Liu, Marple, Whitby, and Barsic (1974) measured coal dust samples with absorptive property ($m=1.54-0.5i$) by an OPC and microscopic technique in parallel and found that particle size determined by the OPC is significantly smaller than the geometric size by the microscopic technique. This is because coal dust absorbs part of the light to yield a weaker light scattering response, resulting in an underestimate of the particle size.

A monotonic increase of the light intensity with an increasing particle size yields an ideal measurement. In reality, multi-valued responses may occur that make OPC's particle sizing uncertain (Szymanski et al., 2009). A wide-angle scattering geometry can alleviate the situation because this design allows a more monotonic response curve, although it is at the expense of wider particle sizing channels (Szymanski et al., 2009). Note the abovementioned situation is for non-absorptive particles. Particles with absorptive properties have a response curve that is monotonically smoother.

In spite of the abovementioned limitation of OPCs, many studies make efforts to link optical diameter to aerodynamic diameter (Binnig, Meyer, & Kasper, 2007; Friehmelt & Heidenreich, 1999; Hinds & Kraske, 1986; Marple & Rubow, 1976). This is because aerodynamic diameter is more relevant for studies focusing on inhalation and health effects of particulate matter. Thus, the OPC has been calibrated aerodynamically through theoretical and experimental approaches. Hinds and Kraske (1986) performed a theoretical calibration by comparing the instrument-output particle size with the true size calculated according to the Mie theory. Nevertheless, this method is limited to spheres. Such a calibration for irregular shape particles requires enormous computational effort and it is impossible for particles with an unknown refractive index. Marple and Rubow (1976) designed an impactor for calibrating the OPC aerodynamically. This experimental method gives an accurate conversion from optical diameter to aerodynamic diameter, but the specific impactor is required for the calibration. Binnig et al. (2007) used a commercial $PM_{2.5}$ cyclone to calibrate $PM_{2.5}$ measured by an OPC, but calibration was done only for particles around 2.5 μm. Friehmelt and Heidenreich (1999) calibrated an OPC with an APS directly using monodisperse PSL and glycerin particles from 0.5 to 5 μm. The results of light scattering pulse height vs the volume equivalent diameter are useful for that specific OPC, but this pulse height vs diameter is not intuitive to users; what would benefit users is the relationship between optical and aerodynamic diameters that allows direct reference.

The objective of this study was to establish the relationship between the diameters measured by the OPC and the APS for liquid and solid particles. The relationship between the optical diameter and the volume equivalent diameter was also investigated. Finally, a commercial parallel impactor following the respirable convention aerodynamically was applied to verify the calibration curve.

2. Method

2.1. Experimental setup

Figure 1 illustrates a schematic diagram of the experimental setup. Aerosol was introduced into a cylindrical test chamber made of stainless steel from the top with filtered air supplied by a compressed air cylinder. The chamber dimension was 41 cm in diameter and 71 cm in height. The corresponding air velocity through the chamber was approximately 3.8 mm/s, which satisfied calm air conditions (Vincent, 2007). A honeycomb airflow straightener was installed close to the top of the chamber, and tests showed size distributions across the cross-section were nearly identical with the coefficient of variation in particle number concentration being $<3\%$. An OPC and an APS in parallel collected test aerosols through tubing from the chamber.

Mini Laser Aerosol Spectrometer (Mini-Las) 11-R (Grimm Technologies, Inc., Douglasville, GA, USA) is an OPC with time resolution of 6 seconds and size range from 0.25 to 32 μm in 31 channels. Running at 1.2 lpm, Mini-Las 11-R uses light sources with a wavelength of 660 nm and measures the scattering light at 90°. Note that 11-R offers the size distribution in terms of optical diameter which is defined as the diameter of a particle having the same response in an instrument that optically detects PSL particles by their interaction with light (Kulkarni et al., 2011). On the other hand, TSI APS model 3321 (TSI, Inc., Shoreview MN, USA) provides size distributions from 0.5 to 20 μm in 52 channels in terms of aerodynamic