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A method of simultaneously measuring particle shape parameter and aerodynamic size

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HIGHLIGHTS

- Measure aerosol particle shape parameter and aerodynamic size simultaneously.
- Preliminarily illustrate capability of discriminating nonspherical particle shapes.
- Shape parameters of ambient aerosols show lognormal probability distribution.

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ABSTRACT

For the purpose of classification of airborne particles, this paper describes an experimental apparatus for simultaneously measuring shape characteristics and aerodynamic size at single particle level. The shape of a particle is indicated through near forward scattering light collected by 3 PMTs placed at 120-degree offset azimuthal angles and the aerodynamic diameter is obtained by time-of-flight that a particle takes to traverse double laser beams. Laboratory experiments are performed on sampled aerosol particles in spherical, cuboid and elongated shape, and preliminary results indicate that the experimental apparatus has a good capability of discriminating between spherical and irregular particles. A variance factor of scattered light related to shape of ambient airborne particles under different conditions are also presented, which can be modeled using lognormal probability density distribution. Combined with aerodynamic size information, these results suggest potential uses in environmental aerosol monitoring for characterizing constituents of particles.

1. Introduction

The optical properties of atmospheric aerosol are determined by chemical composition, concentration, size, shape, and internal structure of liquid and solid particles suspended in air. Optical scattering techniques are widely used as a means of classifying particles on the basis of shape and size. The size and shape of airborne particles determinate their behavior in the air, including generation and vanishing, transportation and sedimentation, and may help in tracing their source or evaluating the extent of pollution. Depending on the aerosol type, one can identify among the particles different minerals, sulfates, nitrates, biological particles such as bacteria and pollen, organic particles, soot, sea salt, etc. For example, most sulfates, inorganic compounds and ammonium exist in the air as fine particles less than 2.5 μm diameter; many bacteria are rod-shaped and at diameter 0.2–8 μm; sea-salt aerosol sizes from approximately 0.1 to 1 μm and the shape depends on the humidity, cubic particles are found at low humidity due to the cubic structure of sodium chloride (Kokhanovsky, 2008).

Elastic light scattering by small particles is much stronger than that of inelastic light scattering, such as fluorescence or Raman scattering, and makes it possible to develop angularly resolved measurement techniques. Angularly resolved (scattering intensity at different polar and azimuthal angles) or spatial scattering light contains abundant information of particles, especially useful for accessing particle shape. However, angularly resolved scattering intensity distribution is related to many other parameters, such as size, refractive index, orientation and position in the light illumination field, and makes it difficult to extract all of these physical characteristics. Even for the simplest spherical particles, it is not an easy work to acquire complex refractive index and size.

William D. Dick (Dick et al., 1998) used dual amplitude weighted nephelometer (DAWN) multi-angle light scattering instrument to

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determine spherical and nonspherical fractions of laboratory-produced and atmospheric aerosols classified at mobility diameters of 0.2–0.8 μm (size parameters of 1.3–5.1). DAWN shape data revealed an overall strong correlation of nonspherical fractions to soil dust content and 'less hygroscopic' fractions.

Stephen Holler introduced a technique for recording high-resolution Two-dimensional Angular Optical Scattering (TAOS) from single airborne microparticles (Holler et al., 1998). Light scattering pattern of ethanol (EtOH) microdroplets, dry clusters of *Bacillus subtilis* (BG) spores, and dry clusters of polystyrene latex (PSL) spheres were shown in this paper. Kevin B. Aptowicz. et al. developed a similar TAOS system that could detect light scattering profiles simultaneously from two laser source (Aptowicz et al., 2004). With the aid of numerical simulations on basis of Mie theory, they can clearly distinguish between droplets of pure H_2O and droplets that contain a considerable amount of D_2O by comparing the angular scattering patterns. Because the high angular resolution scattering profile is extremely complicated, it is limited to slow data acquisition rates and offline analysis.

Paul H. Kaye. et al. presented an overview of the historical development of the theoretical models and experimental techniques underpinning angularly resolved light scattering (Kaye et al., 2007). They concluded that 'even for the simplest case of homogeneous spherical particles, it is still a challenge to extract the complex index of refraction and the particle size from the measured data. And the situation is exacerbated for non-spherical particles and cluster of particles. Depending on research interests or practical application, carefully designed optical systems to detect angularly resolved elastic light scattering from airborne particles can provide useful information of particle size and shape, e.g. Waveband Integrated Bioaerosol Sensor (WIBS) (Healy et al., 2012a) and Aerosol Size and Shape Analyser (ASAS) (Shelton et al., 2004) can detect biological agent in real-time using particle size and shape information combined with fluorescence characterization.

For a rapid single particle detection system, low angular resolution optical system is preferable. Paul H. Kaye developed a real-time monitoring system for airborne particle shape and size analysis (Kaye et al., 1996). An ellipsoidal reflector was used to collect scattering light throughout a range of polar angles from approximately 28° to 141°, and three miniature photomultiplier tube (PMT) detectors were arranged symmetrically about the laser beam axis to measure azimuthal scattering variations. The instrument is capable of analysing data from up to 10,000 particles per second in the size range of 1 μm–10 μm and allowing spheroidal particles having Feret ratios as low as 1.08:1 to be discriminated from perfect spheres. Later on, with the aim of discriminating biological aerosols, P. H. Kaye et al. developed a prototype laboratory light-scattering instrument (Kaye et al., 2000). This instrument integrates two approaches to airborne particle characterization: spatial light-scattering analysis and intrinsic fluorescence measurement. Light scattered by the particle in the forward direction (between angles of 4° and 30°) is imaged onto a 31-pixel hybrid photodiode detector to assess particle size and shape. Preliminary results suggested that this multi-parameter measurement approach can provide an effective means of classifying different particle types with data acquisition rate around 5000 particles/s.

For some particular purpose, shape and size measurements may be integrated with other light scattering techniques. A typical application is for biological aerosol detection as of an applicable instrument named "Waveband Integrated Bioaerosol Sensor (WIBS)" (Foot et al., 2008; Gabey et al., 2010; Healy et al., 2012b; Kaye et al., 2005). Currently, this instrument measures particle shape and optical size by placing a quadrant photomultiplier detector in the forward scattering polar angle range of 6–25° and azimuthal angles at 90-degree offset. Assessment of the WIBS-4 using individual samples of pollen and fungal spore material were performed in laboratory (Healy et al., 2012a), and it was particularly noted that the asymmetry factor of particle might prove invaluable when discrimination between certain individual fungal spores/smuts or pollen is required.

Aerodynamic size may help to classify airborne particles, e.g. Hairston et al. (1997) designed an instrument for real-time detection of bioaerosols using simultaneous measurement of particle aerodynamic size and intrinsic fluorescence.

On the purpose of rapid accessing size and shape characteristics of airborne particles, the authors designed an experimental setup capable of simultaneously measuring aerodynamic diameter and shape parameter at single particle level, which can be named Aerosol Particle Sizer and Shape Analyser (hereinafter referred to as APSSA for short). Here we describe the measurement principles and show preliminary results from prepared aerosol samples. The authors emphasize that the primary objective of this paper is to introduce a new technology that is still in developing with preliminary results illustrating the capability of distinguishing between spherical and non-spherical particles.

2. Principles of apparatus

The experimental apparatus (APSSA) comprises six parts: an aerosol stream and sheath flow inlet, aerodynamic sizing optical assembly, near forward light scattering optical assembly, an enclosed laser investigation chamber, amplifying electronics and data display/storage device and vacuum pumping equipment. A simplified schematic diagram (only inlet and optical assemblies are included) of the apparatus is shown in Fig. 1.

Particle laden air is drawn into the laser investigation chamber through a home designed aerodynamic lens tube (Lee et al., 2003) with sheath flow to accelerate and focus the particles. The aerodynamic lens tube has seven collimating orifices with descending diameters from top to the bottom. Each orifice focuses successively smaller diameter particles along the center line. At the exit nozzle, particles over a wide size have been constrained and emerge as a narrow particle beam. The diameters of the orifices are designed focusing particles with aerodynamic diameter from 1 μm to 7 μm. Sampling flow rate is usually 1 L/min and sheath flow 4 L/min. One purpose of using aerodynamic lens tube here is for reducing particle loss which may happen in thin tube sampling inlet (Armendariz and Leith, 2002; Peters and Leith, 2003). The centerline airflow velocity near the nozzle is estimated to be 150 m/s. The accelerated and focused particles are illuminated by two partially overlapping laser beams (single 650 nm diode laser beam with an Yttrium Orthovanadate (YVO4) (Wikipedia, 2016b) birefringence plate to separate ordinary and extraordinary light vertically to ~100 μm). An ellipsoidal mirror, placed at 45° forward to the laser beam axis, focuses the elastic scattering light onto an avalanche photodiode (APD) to generate a double crested shape signal, and the peak-to-peak time-of-flight is proportional to the aerodynamic diameter (Holm et al., 1997).

Less than 1 mm below the 650 nm sizing beam, a blue continuous diode laser beam of 405 nm wavelength illuminates the sized particle to generate another elastic scattering light. The forward scattered light at polar angles between 6° and 18° is collimated by a plane-convex lens (lens 6) with a beam dump at the center to block the incident laser. Another plane-convex lens (lens 7, identical to Lens 6) is placed to refocus it to pass through an aperture for decreasing stray light, as if the light scattered from a particle is emitted from the center of the aperture. Three miniature photomultiplier tube (PMT, 10 mm diameter cathode) receive the diverged light at 120° offset azimuthal angles via 3 positive lens (Lens 1, Lens 2, Lens 3) respectively. The output of the four detectors