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Dynamic Aerosol In-Situ Imager (DAISI)

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Abstract: Transverse confocal imaging with pulsed laser illumination enables real-time multi-parameter characterization of individual aerosol particles Independent values for size, shape, dynamics, and cross-section enable enhanced PM speciation.

OCIS codes: (010.1100) atmospheric and oceanic optics; (110.2945) illumination design; (010.1120) air pollution monitoring.

1. Introduction

Air quality and contamination are attracting attention and concern throughout the U.S. and around the world. The environmental sciences increasingly recognize the importance of particulate matter (PM) on air quality. A variety of optical sensors are available for real-time counting and approximate sizing of aerosols [1]. But for effective PM mitigation, we need methods for identifying the composition and source of aerosol particles, not just approximate size. Cumulative sample collection methods are currently used for quantitative and qualitative characterization of aerosol pollution [2]. Particles are gathered on a filter or in an impactor for at least 24 hours, then analyzed in a laboratory for total weight, composition, or microscopic characterization. Drawbacks to aerosol testing by cumulative sampling include cost, delay, and sample instability (e.g. dehydration and physical deformation).

This sensor study is motivated by a desire to provide multi-parameter characterization (including shape and size) of individual aerosol particles in real time. Multi-parameter characterization enables speciation of aerosols to confirm the presence of multiple pollution components, to facilitate identification of dominant pollution sources, and to unambiguously detect specific problematic aerosols (e.g. asbestos).

2. DAISI Concept

Dynamic Aerosol In-Situ Imaging (DAISI) is an optical technology for capturing spatially resolved images of aerosol particles suspended in the air. Multiple images of each particle are analyzed to characterize physical size, shape, scattering cross-section, and flow velocity. The DAISI imagery evaluates each particle in a continuous air flow. Particles as small as 1 μm diameter can be spatially resolved while smaller particles can be characterized with respect to effective size and dynamics. Thus DAISI provides detailed characterization of inhalable aerosols in the regulated PM2.5 and PM10 classes.

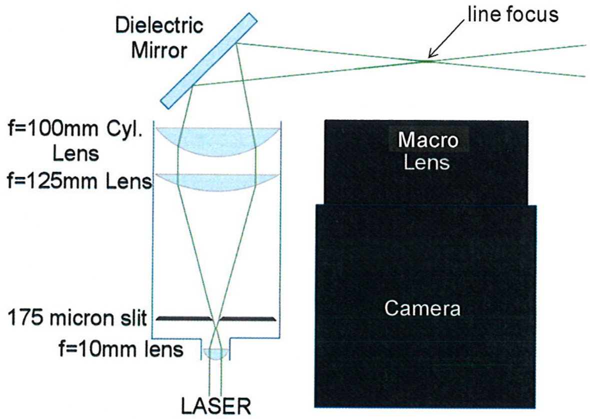

Figure 1. Conceptual drawing of the DAISI system.

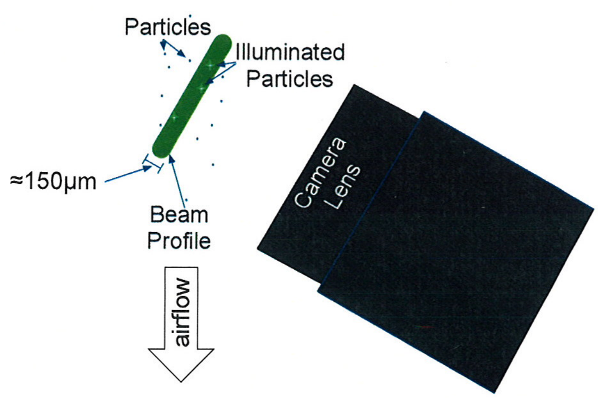

Figure 2. Aerosol sampling by the DAISI system

A DAISI system for aerosol characterization includes an illuminator, digital camera, and macro imaging lens as illustrated in Figure 1. The system also includes a plenum that provides a continuous laminar flow of sample air through the illuminated and imaged volume as shown in Figure 2. The air flow is tilted with respect to both the camera optical axis and the object plane of the imager. Thus sample particles continuously flow through the illuminated region at the object plane.

Consider an object plane with dimensions W_x and W_y imaged by the DAISI camera. The pulsed laser illumination beam is directed in the +y direction and illuminates a sheet of width W_z that is centered on the object plane. The air sample flows with velocity v_a tilted at an angle θ from the camera axis (in the x-z plane). The illumination laser pulses at a rate f_L and the camera frame rate f_C is very much slower, with an imaging duty cycle close to 100%. The laser pulse rate has a lower limit

$$f_L >> v_a \cdot \cos\theta / W_z \tag{1}$$

assuring that each particle in the flow creates a multiple-exposure track (c.f. Figure 3). An upper limit

$$f_L < v_a \cdot \sin\theta / d_{\max} \tag{2}$$

assures that individual particle images do not overlap for a maximum particle diameter, d_{max}. The laser pulse duration (typically a few ns) is short enough to eliminate all image smear. Just as in laser velocimetry, the x and y velocity components of individual particles are readily derived from the spacings between consecutive particle images.

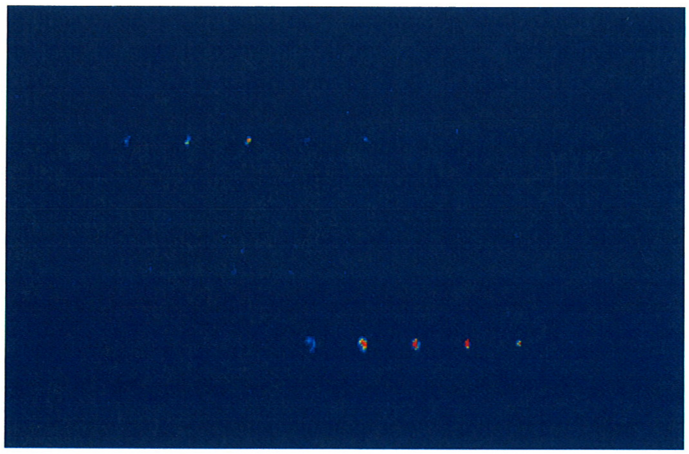

Figure 3. A section of a DAISI image including two aerosol particle tracks.

Over the size range of suspended aerosol particles the materials of which they are comprised are essentially transparent. The complete volume of a particle is illuminated by the side-incident laser beam. Therefore, the profile of a particle image corresponds directly to the physical profile of the particle. The integrated image signal is proportional to the 90° scattering cross-section of the particle. The intensity pattern of the particle image depends on the complex details of scattering (in the Mie regime) and therefore is sensitive to particle size and shape.

3. Transverse Confocal Imaging

We refer to the DAISI optical system as a "transverse confocal imager" because the volume into which the illuminator is focused is coincident with the depth of field of the camera. In conventional confocal imaging the imager and illuminator are focused along a common axis at a single point [3], providing the primary advantages of increased spatial resolution and rejection of interference from out-of-focus structures. By comparison, transverse confocal imaging does not enhance resolution, but it provides even stronger rejection of out-of-focus object features. Transverse confocal imaging also permits simultaneous imaging of the entire object plane, whereas conventional confocal imaging requires 2D scanning.

For a diffraction-limited camera with f-number N_C illuminated at wavelength λ, the object-space diameter of the point-spread-function (Airy disk) is

$$d_A = 1.22 \cdot \lambda \cdot N_C \tag{3}$$

and the spatial resolution is $\Delta res = d_A/2$. The depth of field

$$DoF = 4 \cdot \lambda \cdot N_C^2 \tag{4}$$

is the thickness of the volume centered on the object plane over which the Strehl ratio exceeds 0.8. Combining equations 3 and 4, the depth of field can also be described in terms of the optical resolution

$$DoF = 10.7 \cdot \Delta res^2 / \lambda . \tag{5}$$

Within the DoF, the spatial resolution is >90% of maximum.

In a transverse confocal imaging system, the illumination beam is collimated with respect to its x-profile (and wider than W_x). Anamorphic optics focus the z-profile of the illumination beam at the camera optical axis. Equations 3 and 4 can also be used to describe this illumination profile; they lead to the constraint

$$W_z > 0.305 \cdot \sqrt{W_y \cdot \lambda}\ . \qquad (6)$$

Equating W_z with DoF, we obtain the limit for spatial resolution of a transverse confocal imaging system,

$$\Delta res > 0.17 \cdot W_y^{1/4} \cdot \lambda^{3/4}\ . \qquad (7)$$

As a suggestive example, a system that images an 8mm-wide sample flow at a wavelength of 0.532μm can achieve a spatial resolution of 1.0μm while completely rejecting interference from out-of-focus particles. Such a system requires an f:3 camera (with suitable working distance) and an f:60 illumination beam with a width of 20μm. A DAISI system with such optics could resolve both PM2.5 and PM10 particles. However, the number of images in each particle track would be limited.

4. Prototype DAISI System

A laboratory prototype DAISI sensor is shown in Figure 4. On the left is a plenum that supports laminar flow of sample air through the object plane at θ=60°. Four windows surrounding the sample region provide for the camera view, the illumination beam input, and stray light control.

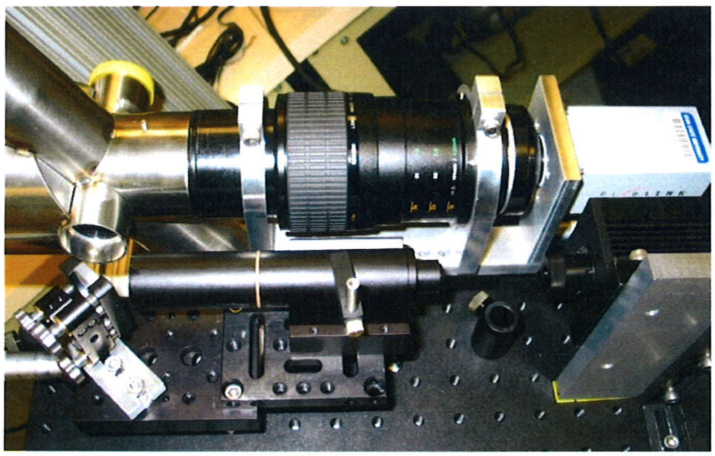

Figure 4. Laboratory prototype DAISI sensor.

Imaging is performed by a Pixelink PL-B781U camera (3000 x 2208 monochome focal plane, 3.5μm pitch, 10 bit readout, and 4Hz frame rate) with a Canon model MP-E macro-zoom lens at a setting of 3.5x (N_C=8), so that each pixel corresponds to 1μm in object space and the object plane size is 3.0 x 2.2mm (W_x by W_y).

Illumination is provided by a CNI laser model MPL-H-532, a frequency-doubled (λ=0.532μm) passively Q-switched Nd:YAG pulsed at 3 kHz. At the laser wavelength, the camera imaging resolution is Δres ~ 3μm and the digital image oversamples the scene by a factor of 3x.

The laser beam is shaped using the optics shown in Figure 1. The laser beam is expanded to a diameter of 3.3mm, then focused across the object plane by a cylindrical lens. The width of the illumination beam is limited by an aperture that is reimaged (at 0.8x magnification) to W_z = 140μm. This arrangement increases the uniformity of illumination in the z-direction, taking advantage of the fact that this prototype sensor does not approach the limits of resolution or field of view for transverse confocal imaging.

A miniature fan at the base of the plenum draws sample air down the plenum at v_a ~ 0.2 m/s. At this speed, the sensor captures 4-5 images of each particle that crosses the object plane (see Figure 3).

5. References

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