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Nozzles for Focusing Aerosol Particles

**by Yong-Le Pan, John Bowersett, Steven C. Hill,
Ronald G. Pinnick, and Richard K. Chang**

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Yong-Le Pan, John Bowersett, Steven C. Hill, and Ronald G. Pinnick
Computational and Information Sciences Directorate, ARL

Richard K. Chang
Center for Laser Diagnostics and Depart of Applied Physics
Yale University, New Haven, CT 06520

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14. ABSTRACT

We report on the design, fabrication, and testing of nozzles that we have used for single-particle sampling measurements of laser-induced fluorescence and two-dimensional angular optical scattering. Single-piece nozzles and a two-piece nozzle with a sheath flow are described.

15. SUBJECT TERMS

Aerodynamic focusing nozzle, sheath nozzle, atmospheric particles, bioaerosols

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We acknowledge support from the Defense Advanced Research Projects Agency (DARPA) Spectral Sensing of Bioaerosols (SSBA); DARPA Semiconductor Ultraviolet Optical Sources (SUVOS); the Defense Threat Reduction Agency (DTRA) Rapid Aerosol Agent Detection (RAAD); DTRA Basic Science; the Air Force Research Laboratory (AFRL); the Department of Homeland Security (DHS) Enhanced Bioaerosol Agent Detection (EBAD); and the Department of Energy (DOE).

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1. Introduction

A nozzle is typically used to control the flow of a fluid exiting some region (e.g., a pipe) and moving into another fluid. In aerosol science and its applications, nozzles are often used to generate particles (as in a nebulizer where the nozzle helps control the flow of a liquid into a gas), or, as in the applications discussed here, to control the motion of the particles in the flowing gas. An aerosol is a suspension of particles in a gas. The particles may be solid, liquid, or a mixture of both. "Aerosol" is often used to refer to the particles in the suspension. Ambient aerosol particles commonly have sizes ranging from a few nanometers to a few hundred micrometers. They can be composed of a wide variety of materials. For these applications, the particles, because of their inertia, can take different trajectories depending upon their size, shape, density, and velocity, and upon the density and viscosity of the gas.

A nozzle may be used to aerodynamically focus aerosol particles so that particles in a size range can be concentrated in air (*1–6*), or used to separate and/or measure particles of different sizes based on their inertial properties (*7–10*). Also, the nozzle may be used to increase the speed of particles so that they can be impacted upon a surface (*9–12*). Furthermore, for the application emphasized here, the nozzles may be used to focus particles into a relatively small-diameter jet (*13–19*) so that the particles can be analyzed using mass spectrometry (*8*), laser-induced fluorescence (*20–29*), light scattering (*30–34*), or laser induced breakdown spectroscopy (*35*).

For the applications in which we are most interested, collimating particles from ambient air, the jet of air moves into a region where the pressure is close to atmospheric pressure, and so there are significant interactions between the rapidly flowing jet and the gas already in the chamber. As a point of interest, for mass spectrometry applications (*8*) the particles are typically drawn into the region of high vacuum, the interactions between the jet of gas and the gas in the chamber are negligible, and the trajectories of particles are simpler. Also, in order to achieve high sample rates for the particles, we use high particle velocities (e.g., 10 m/s), and so we avoid the aerodynamic lens technologies (*17, 18, 35*) that work well at low gas velocities (~0.5 L/min).

Here we report our development of several nozzles designed to aerodynamically focus aerosol particles into a small-diameter jet, so that individual particles can be illuminated by a laser beam and their light scattering and/or laser-induced fluorescence (LIF) spectra can be measured well. We also mention an additional nozzle that can aerodynamically puff selected particles out of the air stream so that they can be sorted and collected (*25*).

The design specifications for the aerodynamic focusing nozzles depend upon the application. For our applications in single-particle LIF and elastic scattering measurements (*20–34*), we want the particles to be focused into as narrow a stream as possible (as small as 20 µm diameter would be excellent), and for the particles to remain collimated for a distance of a few millimeters.

Also, we want particles having different sizes and shapes to flow at the same speed and the same trajectory in the particle stream as it moves away from the nozzle. To help the particles flow in a collimated stream, we used an eduction tube a short distance (e.g., about 1 cm) below the nozzle.

In general, nozzles can be divided into single-piece nozzles, double-sheath nozzles, and multiple-stage nozzles (aerodynamic lenses). In this report, we briefly present the development of two different single-piece aerodynamically focusing nozzles, and then one nozzle that has a sheath flow.

2. First-generation Single-piece Nozzle

The first of our aerodynamic focusing nozzles was designed and machined by Yong-Le Pan in 1998. It was a single-piece nozzle that looks similar to a 30° cone (figure 1). Originally, plastic glass was used to make the nozzle, but it did not work well, possibly because of static charges. The first nozzle that worked well was machined from aluminum. Subsequently, several versions of this nozzle were remachined by the Yale Gibbs machine shop and used in various laboratories. This nozzle produces a laminar aerosol flow with an aerosol jet diameter of a few hundred micron at a flow rate of 0.6 to 2.1 L/min. Individual aerosol particles (1 to 10 μm size) within the jet move at about 10 m/s when the flow is nominally 1 L/min. These nozzles have been used for Single Particle Fluorescence Spectrometer (SPFS) and Two-Dimensional Angular Optical Scattering (TAOS) measurements and have been used with a variety of bioaerosol simulants and interferent aerosol particles (*15–18*, *25–26*).

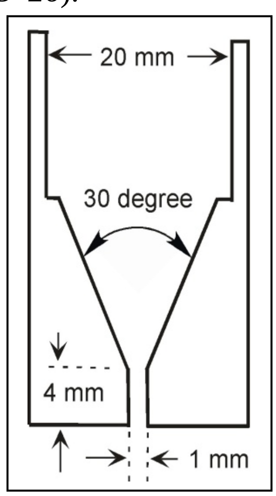

Figure 1. The design of the first-generation aerodynamic focusing nozzle for aerosol particles used for SPFS and TAOS instrument prototypes. The first nozzle that worked well was machined from aluminum.

3. Second-generation Nozzle

The primary reason we designed and built the second-generation nozzle was that we wanted to measure TAOS over very large angles using an elliptical mirror (*27*). In this setup, the laser and particle interrogation region (located at the mirror focal point) is located well below (more than 1 in) the nozzle exit. At this distance, the aerosol stream is no longer well focused. We modified the nozzle assembly so that it could be inserted into the relatively small (0.40 in) opening of the mirror and close to the mirror focal point (figure 2). This second-generation nozzle was designed and machined around 2003. Because this nozzle had much smaller dimensions and required more complicated internal curves, it was too difficult to make using elementary machining techniques. Eventually, it was fabricated by John Bowersett at the U.S. Army Research Laboratory (ARL) by electrical discharge machining (EDM). This second-generation nozzle functions similarly to the first-generation nozzle but with a better focusing capability. It has been used for a variety of SPFS and TAOS prototypes in various laboratories and field tests. One of the SPFS-puffer systems was operated 24 hours per day, 7 days per week in the San Francisco International Airport, CA, for several months by Sandia National Laboratories (SNL) (*19–21*, *27*).

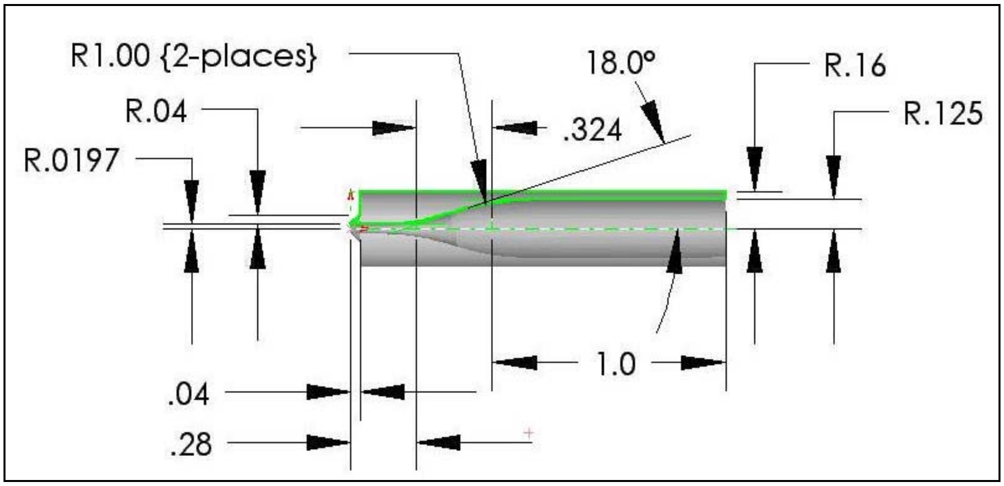

Figure 2. The design of the second-generation nozzle for aerodynamically focusing 1–10 µm diameter aerosol particles into an aerosol jet. Some nozzles were fabricated in aluminum and some in steel. It has been used for SPFS and TAOS measurement technologies both in the laboratory and various test fields.

4. Third-generation Nozzle—With Sheath Flow

Although the second-generation nozzle functions well and performed successfully in various applications, it had shortcomings. We found that particles of different size move at slightly different speeds within the aerosol jet. This is a problem because particles of different sizes arrive at the sampling region (where they are illuminated by the ultraviolet [UV] laser and where their fluorescence and/or TAOS are measured) at different times. Further, the aerosol stream did not remain well-collimated very far from the tip of the nozzle, limiting the region over which particles could be interrogated reliably with pulsed laser sources. So we decided to develop a new third-generation nozzle assembly with a sheath flow. Sheath nozzles have been employed previously in aerosol counting instruments such as the Particle Measuring Systems models, ASASP-X and LAS-X, and in the TSI Aerosol Particle Sizer Spectrometer. The inner nozzle of our assembly has similar design to the second-generation nozzle, but with a separate outer nozzle for a clean-air sheath flow (figure 3). This nozzle can produce a tightly focused aerosol jet of particles having relatively uniform speed over distances of more than 5 mm.

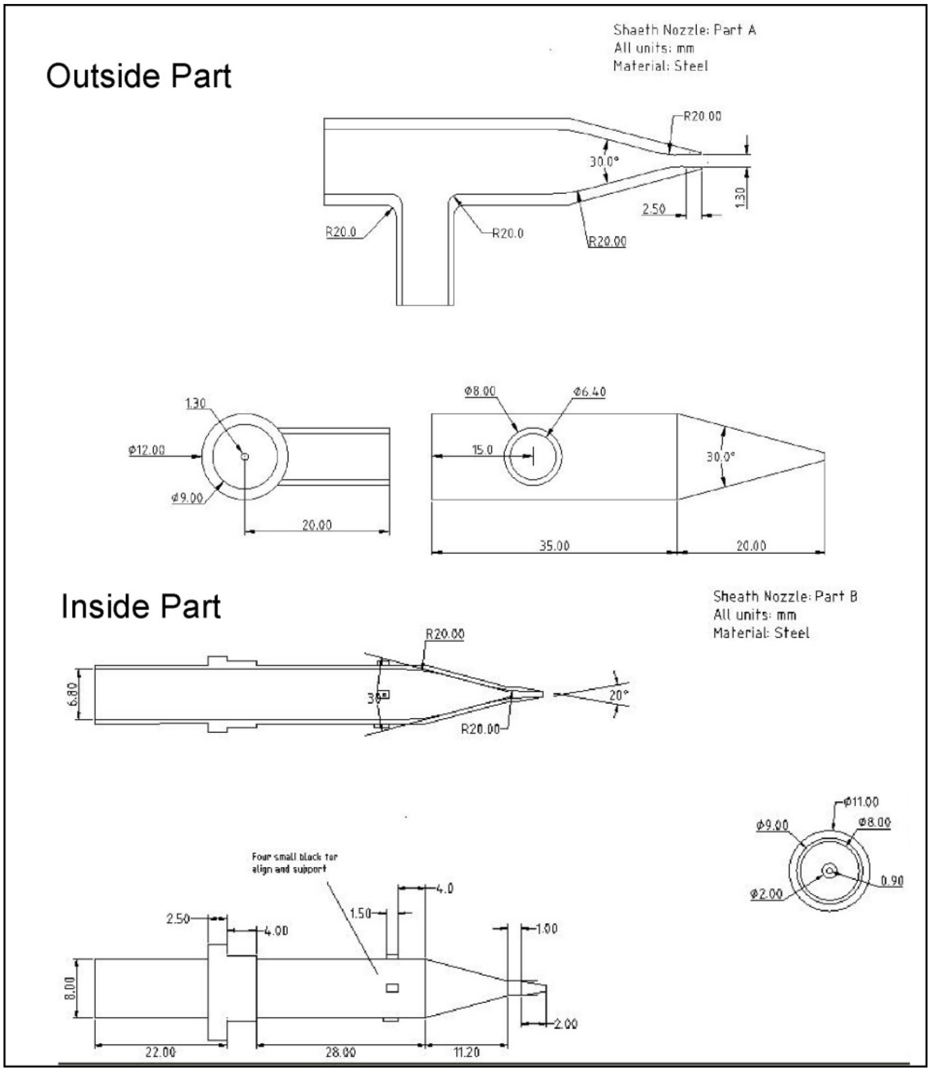

Figure 3. Design of the third-generation nozzle assembly for aerodynamic focusing of 1–10 µm diameter particles into an aerosol jet. The outer nozzle of the assembly provides for a clean-air sheath resulting in a tightly focused of particles having nearly uniform speed and similar trajectories over a distance of about 5 mm. The nozzles are made from stainless steel.

This nozzle provides for a well-defined interrogation region and also prevents the contamination of optics by preventing sampled aerosol from circulating in the optical cell.

The nozzle was EDM-machined by John Bowertsett of the ARL machine shop in 2006. The machining process posed a particular challenge, because the inner surfaces needed to be joined smoothly, with no abrupt changes in curvature, and the exit hole needed to be small (0.9-mm diameter). The external portions of the nozzles were machined in a more conventional manner using computer numerical control (CNC) lathes and milling machines running programs written by computer aided machining (CAM) software. The close tolerance of concentricity of the two nozzles was achieved by placing a perforated ring at the end of the inner nozzle. This ring formed a close sliding fit to the outer nozzle. Fabrication of the nozzle with the desired shape was accomplished using EDM technology. First, a copper tungsten electrode was turned on a CNC lathe. The geometry of the electrode matched that of the inner surface to be machined. Next, the electrode was precisely aligned over the nozzle and the EDM process initiated. Roughing and finishing electrodes were used to produce the desired finish on the inside surface. A high degree of precision is accomplished using this method.

The nozzle assembly was tested before it was used in the TAOS and SPFS prototype detection systems. Figure 4 shows the test setup and some test results. A pulsed 532-nm laser sheet was focused by a cylindrical lens to illuminate the aerosol stream that was formed by the nozzle within a small airtight chamber. The scattering image from a 300-μm diameter fiber was used for size calibration. Test titanium oxide (TiO_2) particles with mean sizes of 2, 4.3, 7.2, and 9.6 μm were used. The aerosol sample rates were 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, and 1.5 L/min (through the inner nozzle), with or without a matched sheath flow through the outer nozzle. The photos reveal that this nozzle assembly has the best focusing capability around 1.0 L/min (through the inner nozzle) and can focus the aerosol particles into a stream less than 300-μm diameter and keep the stream collimated for a distance longer than 5 mm for particles larger than 3-μm diameter. The focusing is less tight for the smaller particles. This third-generation nozzle has been used for the recent SPFS and TAOS prototypes, particularly for the sampling aerosol particles directly from atmosphere and the dual-wavelength excitation UV-LIF experiments (*22–24*, *28–29*).

The third-generation nozzle was slightly modified in 2008 for installation into a new SPFS-puffer system. There were no changes at the nozzle tips of the sheath nozzle combination, but the nozzle assembly is modified for easier machining and connection to the chamber (figure 5).

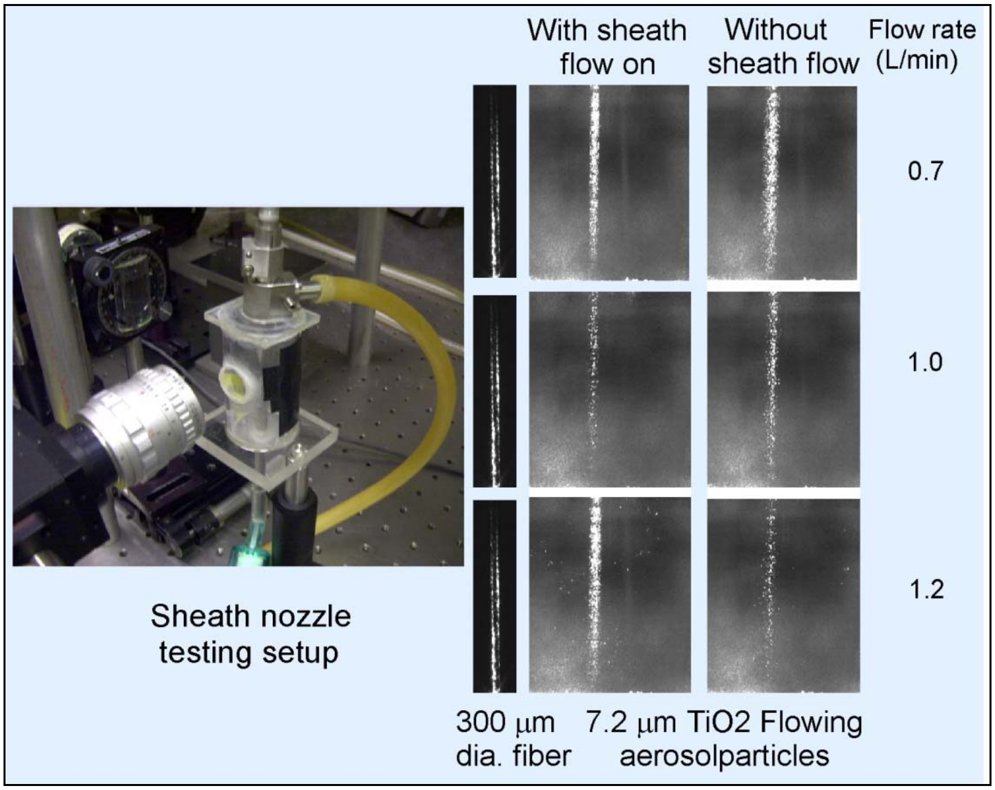

Figure 4. (Left) Testing setup for the third-generation sheath nozzle, and (right) the scattering images of flowing aerosol particles at different flow rates with and without the sheath flow.

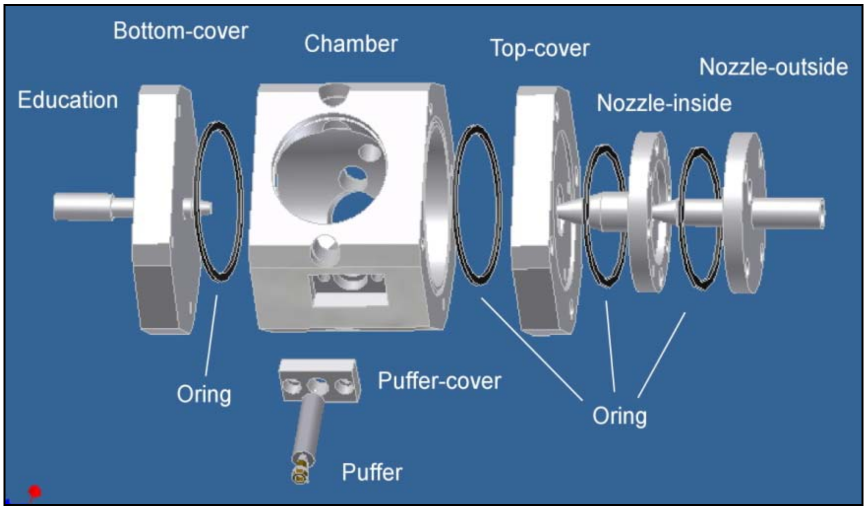

Figure 5. The latest version of the third-generation nozzle connects to the "top cover" of a SPFS-puffer system.

5. Use of these Nozzles in Army, DoD, DTRA, DARPA, DOE, and DHS Programs

These nozzles have been used for bioaerosol detection and characterization in our SPFS (*15–24*) and TAOS technologies (*25–29*). The nozzles have found application in various programs carried out by the ARL/Yale research team, such as the Defense Threat Reduction Agency (DTRA) Rapid Aerosol Agent Detection (RAAD) program, the DTRA Basic Science Atmospheric Organic Carbon Aerosol Study, the Air Force Research Laboratory (AFRL) Scattering Pattern Measurements program, the U.S. Army Medical Institute for Infectious Disease BL-3 Detector Development program, the Department of Homeland Security (DHS) Enhanced Biological Agents Detection (EBAD) and Particle Penetration programs, the Defense Advanced Research Projects Agency (DARPA) Spectral Sensor for Biological Agents (SSBA) program, the DARPA Semiconductor UV Optical Source (SUVOS) program, and the Department of Energy (DOE) Selection of Hazardous Particles program.

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List of Symbols, Abbreviations, and Acronyms

AFRL	Air Force Research Laboratory
ARL	U.S. Army Research Laboratory
CAM	computer aided machining
CNC	computer numerical control
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOE	Department of Energy
DTRA	Defense Threat Reduction Agency
EBAD	Enhanced Bioaerosol Agent Detection
EDM	electrical discharge machining
LIF	laser-induced fluorescence
RAAD	Rapid Aerosol Agent Detection
SNL	Sandia National Laboratories
SPFS	Single Particle Fluorescence Spectrometer
SSBA	Spectral Sensing of Bioaerosols
SUVOS	Semiconductor UV Optical Sources
TAOS	Two-Dimensional Angular Optical Scattering
UV	ultraviolet

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