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Dynamic Evaluation of Aerosol Sampling Inlets

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■ A wind tunnel has been designed and built that incorporates a new method for determining sampling efficiencies. The inlet under study is integrated into a modified optical single-particle counter that records the aerosol concentration penetrated through the inlet. The penetrated aerosol concentration is thus measured dynamically and quickly for various particle sizes, sampling velocities, wind velocities, and sampling angles. All measurements are related to the sampled aerosol concentration at isokinetic conditions, for which the aerosol depositions on the inner wall are also determined, so that the aerosol concentration upstream of the inlet is known for all sampling conditions. The method is illustrated through results obtained with a thin-walled sampling tube.

Introduction

This study describes and illustrates a new method for determining the sampling efficiency of aerosol sampling inlets. Most theoretical and experimental studies have focused on the aspiration efficiency (*1–17*), which only considers sampling from the air environment to the face of the inlet. Studies considering the entire inlet have primarily evaluated specific inlet designs (*18–29*). In the traditional technique for evaluating entire inlets, tagged test aerosol are sampled through the inlet onto a filter. The aerosol deposits in the inlet and on the filter are then determined by fluorometric or radiometric techniques. Such determinations are very time consuming, which therefore limits the degree of evaluation generally performed on a specific inlet.

In the technique presented here, the entire inlet is integrated into an optical single-particle counter that has been modified to accept a total flow of up to 75 L/min. The aerosol concentration sampled by low- or medium-volume inlets can thus be determined dynamically for various particle sizes, sampling velocities, wind velocities, and sampling angles. By a counting of each individual particle penetrated through the inlet, the sampling time can be kept short, and the degree of data scatter appears to be lower than presented in most publications.

Sampling Strategy

Belyaev and Levin (*5, 6*) have shown that the sampling efficiency of an entire inlet may be characterized by the product of three distinct efficiencies. Utilizing different symbols, we define the overall sampling efficiency of an inlet, E_s, as

$$E_s = E_a E_r E_t \quad (1)$$

where E_a is the aspiration efficiency, E_r is the entry efficiency, and E_t is the transmission efficiency.

The aspiration efficiency, E_a, is the ratio of the particle concentration at the face of the inlet to the particle concentration in the undisturbed environment. It is a function of the aerodynamic, inertial, and gravitational forces acting on the particle. The entry efficiency, E_r, is the ratio of the particle concentration passing the inlet face to the particle concentration incident to that face. It is a function of the shape of the inlet's front edge from which particles may rebound and be aspirated into the inlet. Particle rebound from the front edge of the inlet vs. adhesion to that edge is generally not considered in the trajectory calculations for the aspiration efficiency. The transmission efficiency, E_t, is the ratio of the particle concentration exiting from the inlet to the particle concentration just past the inlet face. It accounts for the particle losses to the inside wall by impaction, gravitational settling, and turbulent or laminar diffusion.

In order to describe the measurement method used, we further subscript the efficiencies by sampling angle, θ, relative to the wind direction, and by velocity ratio, R, defined as the ratio of wind velocity outside the sampler, u_o, to the average air velocity in the inlet, u_i:

$$E_{s,R,\theta} = E_{a,R,\theta} E_{r,R,\theta} E_{t,R,\theta} \quad (2)$$

The true particle concentration in the wind tunnel is determined by sampling isokinetically with a thin-walled inlet for which the aspiration efficiency, $E_{a,1,o}$, and the entry efficiency $E_{r,1,o}$, may be assumed equal to 100% so that

$$E_{s,1,o} = E_{t,1,o} \quad (3)$$

The transmission efficiency, $E_{t,1,o}$, is found by counting the particles penetrated through the inlet and dividing this number by the same number plus the particles lost to the inner measured of the inlet as measured by a wash-off technique.

Once the overall sampling efficiency is known for isokinetic flow, the particle count rate for all other kinetic conditions and tube orientations, $N_{s,R,\theta}$, is related to the particle count rate at isokinetic condition, $N_{s,1,o}$. We can thus define a relative sampling efficiency, $E_{rel,R,\theta}$, as the ratio of sampled particle concentration to that at isokinetic flow:

$$E_{rel,R,\theta} = (N_{s,R,\theta}/N_{s,1,o})R \quad (4)$$

In the calculation of the sampled particle concentration, the count rate is divided by the inlet velocity. Thus, the ratio of count rates is multiplied by velocity ratio R. The total sampling efficiency of the inlet is the product of eq 3 and 4:

$$E_{s,R,\theta} = E_{rel,R,\theta} E_{t,1,o} \quad (5)$$

In our technique the particle penetration is dynamically registered by the counter at all angles and velocity ratios of interest for all pertinent particle sizes. If the inlet is thin-walled, it is periodically operated isokinetically to give a reference count. If the inlet under study is thick-walled—for which the product of aspiration and entry efficiency may not be 100%—or if the inlet is of complex design, the reference count is determined by a separate thin-walled inlet.

Experimental Design

We designed a special wind tunnel for sampling efficiency studies (*30*). The schematic representation of Figure 1 displays the essential elements. Laboratory air is drawn through four HEPA filters into the mixing

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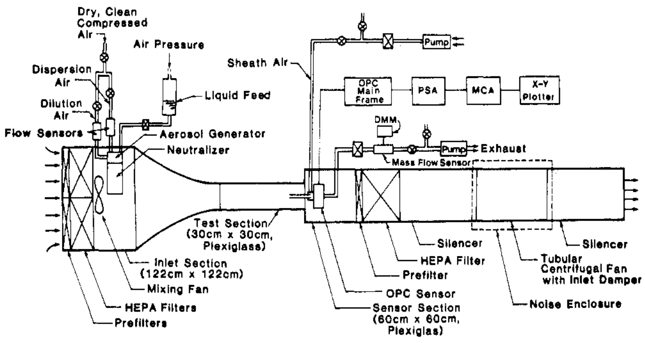

Figure 1. Wind tunnel for sampling efficiency studies: OPC = optical particle counter; PSA = Pulse-shaping Amplifier; MCA = multichannel analyzer; DMM = digital multimeter.

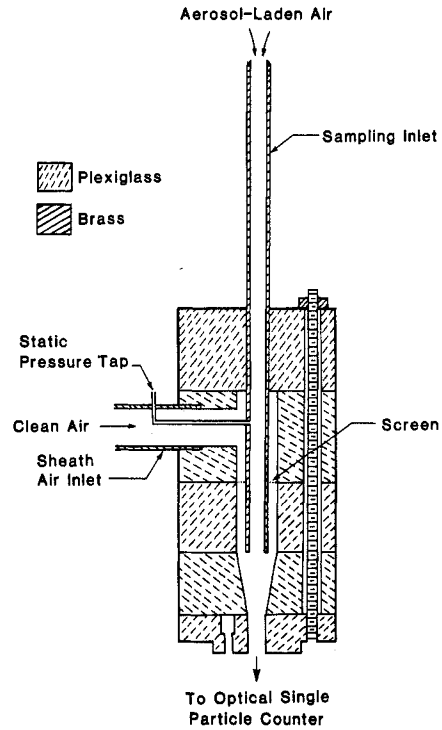

Figure 2. Sampling inlet under study integrated into entry section of the optical single-particle counter.

chamber of the wind tunnel (*31*). The air is accelerated through a tapered section which results in a constant-velocity profile throughout most of the 30 cm × 30 cm test section, as measured by a thermal anemometer probe.

Test aerosols are injected into the mixing chamber through an aerosol generator whose design is based on the vibrating-orifice principle (*32*). In our design the krypton-85 charge-neutralizer section is fixed, and the vibrating-orifice section is removable as a small unit. Our liquid feed system (*30*) uses air pressure (*33*) instead of a syringe. The aerosol is distributed in the mixing chamber by a large disc fan as used for window exhausting in homes. This results in well-mixed aerosol concentrations in the core of the test section. Conventional mixing baffles were found to eliminate too many particles above 20 μm in diameter. The turbulence level in the wind tunnel can be varied from 3% to 8% by adjustments in the speed of the mixing fan. Turbulence variations in this range did not significantly affect our test-inlet's performance. Wedding et al. report similar findings on a different inlet design (*27*).

The inlet under study samples from the aerosol flow in the test section of the wind tunnel. In order to sample dynamically, the inlet is integrated into the sensor of a modified optical single-particle counter (Model 245/242, Royco Instruments Inc., Menlo Park, CA). As seen in Figure 2, the sampling inlet is surrounded by clean sheath air so that the aerosol leaves the inlet in or near the centerline of a converging circular channel without particle losses to the wall. Upon leaving the entry section, the aerosol passes through the view volume of the sensor. The sensor thus registers all particles penetrated through the inlet. Studies with the circular inlet found the particle count to be independent of the volumetric sheath air flow rate when that rate was 4–40 times the volumetric aerosol flow rate. Such changes in sheath air to aerosol flow rate facilitate the dynamic study of sampling efficiency for different velocity ratios, R, without geometric modification of the sensor's entry section. Different-sized inlets are studied by exchanging portions of the sensor's entry section.

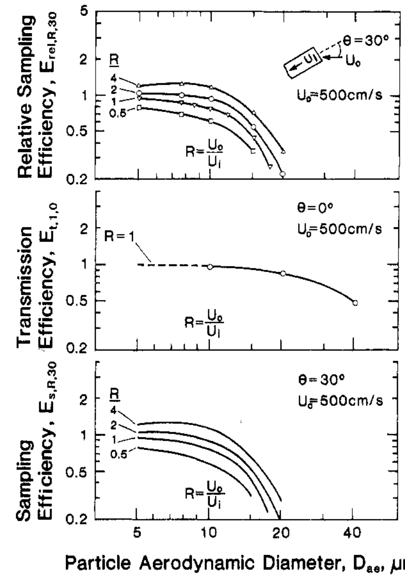

Figure 3. Sampling efficiency at θ = 30° and wind velocity of 500 cm/s: thin-wall inlet tube, i.d. = 0.565 cm, o.d. = 0.635 cm ($^1/_4$ in.), L = 20 cm.

The aerosol flow rate is calibrated and measured during testing by noting the pressure difference between the static pressure tap indicated in Figure 2 and the upstream static pressure in the test section. Most measurements are made with the face of the inlet protruding about 15 cm into the 30 cm × 30 cm test section and with the sensor secured in a 60 cm × 60 cm downstream section. The air flow deflects around the body of the sensor and does not affect the flow pattern at the face of the inlet as verified by thermal anemometer measurements for the 250–1000 cm/s flow velocity range studied (*30*). The angle of the inlet can be varied from parallel (θ = 0°) to perpendicular (θ = 90°) to the wind tunnel flow. When sampling at or near 90° to the flow, the sensor is located external to the test section.

The optics of the particle sensor are defocused (*30*) in order to accommodate flow rates up to 75 L/min through the sensor. The monodisperse particles penetrated through the inlet are thus distributed over several channels when recorded by a multichannel analyzer. The sheath air flow is supplied by an air mover, and the combined flow is withdrawn from the sensor by a pump outside the wind tunnel.

Downstream of the sensor section the aerosols are removed by in-line filters. The air mover for the wind tunnel is in line with two duct silencers which reduce the aerodynamic flow noise. The air mover is also surrounded by a ventilated enclosure, which reduces the noise radiated by the body of the fan.

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Results and Discussion

Figure 3 exemplifies our method by showing measured sampling efficiencies for a thin-walled tube operated at 30° downward from the flow direction. Oleic acid particles from 5 to 40 μm in diameter were used as test aerosols. The relative sampling efficiency of the inlet for various velocity ratios and $\theta = 30°$ is shown in the upper graph. The transmission efficiency for isokinetic flow is shown in the middle graph. The overall sampling efficiency is the product of the two efficiencies and is shown in the lower graph.

The low degree of data scatter, exemplified in Figure 3 and noted in all our experiments to date (*30*), as well as the large body of data that one can obtain for a specific inlet in relatively short time, will hopefully facilitate the development of analytical models for the prediction of the overall sampling efficiency. Such a model should include aspiration of particles to the face of the inlet, bounce of particles from the edge of the inlet into or away from the inlet, impaction onto the inner wall of the inlet just past the inlet face, gravitational settling in the inlet, and turbulent or laminar deposition inside the inlet.

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Retention of Boron by Coal Ash

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■ Adsorption of boron by the hydrous oxides of aluminum, iron, and silicon appears to be the major process that controls the net release of boron from fly ash when the ash is leached at loading rates of greater than 25 g of ash/L. Coprecipitation of borate species with the hydrous oxides also contributes to the retention.

The amount of coal ash obtained from the combustion of a selected but representative group of United States coals ranges from 4% to 22% (*1*). The major components of the ash include the alkali and alkaline earth oxides, main-group oxides of aluminum and silicon, and iron oxide (*1*, *2*). The trace components are many (*1*, *3*), with some of the elements being enriched (*3*). In general, the highest concentrations of trace and toxic species are found to be associated with the smallest particles (*3*, *4*).

One of the trace components in coal ash of special concern is boron. The amount of boron found in coal ash varies from 5 to 200 mg/kg, depending upon the mine site (*5*). Of the total boron present in the coal as much as 71% may be lost to the atmosphere upon combustion (*6*), and of that found in the ash a sizable fraction (>50%) is readily

