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Development and Laboratory Performance Evaluation of a Personal Multipollutant Sampler for Simultaneous Measurements of Particulate and Gaseous Pollutants

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A personal multipollutant sampler has been developed. This sampler can be used for measuring exposures to particulate matter and criteria gases. The system uses a single personal sampling pump that operates at a flow rate of 5.2 l/min. The basic unit consists of two impaction-based samplers for $PM_{2.5}$ and PM_{10} attached to a single elutriator. Two mini $PM_{2.5}$ samplers are also attached to the elutriator for organic carbon (OC), elemental carbon (EC), sulfate, and nitrate measurements. For the collection of nitrate and sulfate, the minisampler includes a miniaturized honeycomb glass denuder that is placed upstream of the filter to remove nitric acid and sulfur dioxide and to minimize artifacts. Two passive samplers can also be attached to the elutriator for measurements of gaseous copollutants such as O_3, SO_2, and NO_2.

The performance of the multipollutant sampler was examined through a series of laboratory chamber tests. The results showed a good agreement between the multipollutant sampler and the reference methods. The overall sampler performance demonstrates its suitability for personal exposure assessment studies.

INTRODUCTION

Epidemiological studies have shown significant associations between particulate matter and increased mortality and morbidity. Recent results from various studies have indicated that the respirable fraction of particulate matter (PM_{10} and $PM_{2.5}$) is responsible for observed adverse health effects (Schwartz and Dockery 1992; Pope et al. 1993; Dockery et al. 1993; Dockery and Pope 1994). Results from these epidemiological studies have been difficult to interpret due to findings from cross-sectional exposure studies that showed that outdoor particulate concentrations are a poor indicator of personal exposures to particles (Clayton et al. 1993; Bahadori 1998).

Human exposures to particulate matter are predominantly influenced by three factors: ambient particle concentrations, contributions from various indoor sources, and human activity patterns. Recent findings from exposure studies indicate that personal exposures and ambient $PM_{2.5}$ concentrations are more closely associated, especially for certain individuals (Rojas-Bracho et al. 2000; Sarnat et al. 2000). However, two fundamental questions about the relationship between personal $PM_{2.5}$ exposures and ambient concentrations still exist. First, it is unclear whether the personal-ambient concentration relationships differ for specific fine particle components, such as EC, OC, trace elements, sulfate, and nitrate; and second, it is possible that health effects attributed to $PM_{2.5}$ may be synergistically linked to the effects from gaseous copollutants, such as ozone, sulfur dioxide, and nitrogen dioxide.

Using an integrated monitoring system to directly measure personal exposures to both particulate matter and gaseous copollutants will minimize the errors associated with indirect assessment methods and dramatically improve our understanding of personal exposure to these air pollutants. Such a system, though, has to be sufficiently compact, lightweight, and quiet to avoid interfering with normal personal activities.

Various personal monitoring systems have been developed (John and Reischel 1980; Marple et al. 1995; Koutrakis et al. 1989) to measure particle mass and a few inorganic ions. In this paper, we present the development and the laboratory evaluation of an integrated multipollutant personal sampler (MPS). This system has the capability of simultaneously measuring particulate mass ($PM_{2.5}$ and PM_{10}), elemental and organic carbon (EC/OC), sulfate, nitrate, and gaseous copollutants such as ozone, sulfur dioxide, and nitrogen dioxide. The development of this MPS is part of our ongoing effort to improve personal and microenvironmental aerosol sampling technologies. These new devices will enable us to improve our understanding of factors affecting human exposure to particulate and gaseous air

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pollutants. This system will be used extensively in our field studies in various locations in the U.S.

DESIGN CONSIDERATIONS ON INERTIAL IMPACTORS

Impactors have been used successfully for particle collection and classification (De la Mora et al. 1990; Marple et al. 1987; Marple et al. 1991). The basic mechanism for inertial deposition of particles is the specific motion of aerosol particles in the impaction zone or stagnation point. In this region, the streamlines change abruptly. Particles larger than the impactor's cutsize will impact onto the plate, while smaller particles will remain in the streamlines and will not be collected.

According to the impaction theory, the Stoke's number, Stk, is the governing parameter for impaction and is defined as follows:

$$\mathrm{Stk} = \frac{\rho_p d_p^2 U C_c}{9\,\mu W}, \qquad [1]$$

where μ is the dynamic viscosity of the air (g/cm s), d_p is the diameter of the particle (μm), ρ_p is the particle density (g/cm^3), W is the nozzle diameter, U is the jet velocity (cm/s), and C_c is the Cunningham slip correction factor. The slip correction factor is given by the following equation (Hinds 1982):

$$C_c = 1 + \frac{2}{Pd_p}[6.32 + 2.01\exp(-0.1095\,Pd_p)], \qquad [2]$$

where P is the absolute atmospheric pressure (cm Hg) upstream of the nozzle.

Various guidelines for the critical design parameters were obtained from the numerical analysis of the Navier–Stokes fluid flow equations (Marple 1970; Marple and Liu 1974). It has been shown that for round nozzle impactors, the aerodynamic diameter of particles collected with 50% efficiency (d_{50} = cutpoint or separation point) corresponds to a $\sqrt{\mathrm{Stk}_{50}}$ of 0.5. Therefore theoretical d_{50} particle diameter can be calculated using Equation (1) for any desired flow rate and nozzle diameter.

There are three major areas of concern associated with the design of an impactor: particle bounce from the collection surface, overloading of collected particles on the impaction substrate, and interstage losses (collection of particles on surfaces other than the impaction plate). One approach frequently used for minimizing particle bounce is the application of a sticky substance such as oil or grease on the impaction plate. The use of oil as a coating medium requires the use of a porous substrate to retain the oil. Porous metal disks (Reischl and John 1978), porous glass frits (Koutrakis et al. 1989), and 10 μm Teflon membrane filters have been used in various impactors. Also, the substrate has to perform well under various loading conditions. Once a monolayer of particles is collected on the surface, incoming particles may bounce after impacting onto already collected particles. Therefore the substrate must have a large enough capacity to maintain high collection efficiency, even under heavy loading conditions. Other factors such as the grease coating thickness (Pak et al. 1992; Reischl and John 1978), particle hardness (Hinds et al. 1999), and shape can also affect bouncing behavior.

Another important design parameter that also significantly affects the overall impactor performance is the S/W ratio, where S is the distance between the nozzle exit and the impaction plate and W is the nozzle diameter. According to the numerical analysis of conventional impactors by Marple et al. (1993), the S/W ratio should be >1 for round nozzles and 1.5 for rectangular impactors, while the Reynolds dimensionless number, Re, should be below 3000. Reynolds numbers over this limit would result in a highly turbulent flow and increase particle loss. Theoretical analysis and experimental results have also shown that the efficiency curve will be sharpest for Re values between 500 and 3000. The nozzle throat length, L, to nozzle diameter ratio (L/W) is also considered to be a critical design parameter and affects the impactor collection efficiency. Moreover, the nozzle throat length, L, should be long enough to allow a full development of the flow with the jet velocity to approach a parabolic profile at the nozzle exit. However, excessive particle losses can be induced if the throat length is too long. In this paper, the effect of the critical design parameters of the personal particle samplers such as S/W, Re, and L/W as well as the impaction substrate method was experimentally investigated.

METHODS

Description of the System

The integrated MPS and its various components are shown on Figure 1. The basic unit consists of $PM_{2.5}$ and PM_{10} impaction based samplers that remove particles larger than 2.5 μm and 10 μm, respectively. The samplers are attached to a single elutriator to minimize entrainment of fibers and other airborne material associated with personal activities. Two mini $PM_{2.5}$ impactors are also attached to the basic unit. One is used for sampling OC and EC, the other for sampling sulfate and nitrate. The sulfate/nitrate sampler contains a mini glass honeycomb denuder that is used to remove nitric acid and sulfur dioxide from the sampled air. The system uses a single personal sampling pump that operates at a flow rate of 5.2 l min^{-1} (Model AFC 400S, BGI Inc., Waltham, MA). Two passive diffusion samplers are also attached to the side of the elutriator for the measurement of gaseous copollutants such as O_3, SO_2, and NO_2.

$PM_{2.5}$(SPM2.5) and PM_{10} (SPM10) Personal Samplers for Mass Sampling

Figure 2 illustrates the main components of the $SPM_{2.5}$ and SPM_{10} impactors. Both personal samplers consist of the following three components: (1) the acceleration nozzle (2); the impaction substrate; and (3) the filter holder. The filter holder component is the same for both samplers. All three components are made of aluminum. The critical sampler design parameters are shown in Table 1. The impaction substrate section consists of

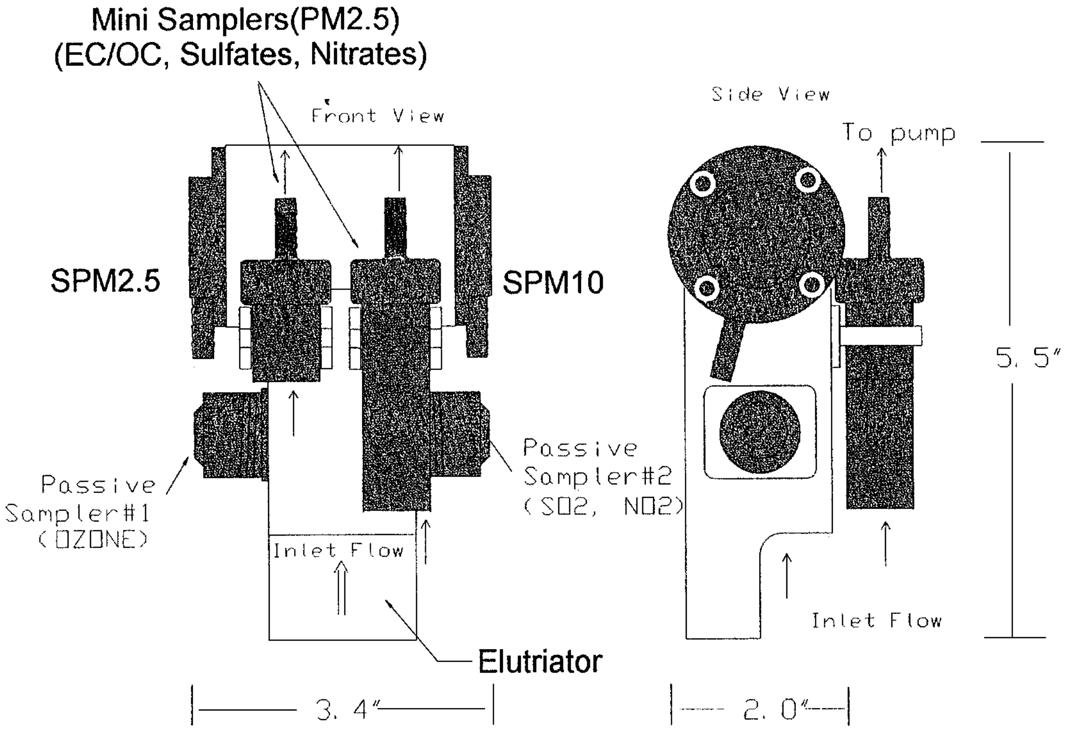


Figure 1. Personal environmental monitoring system.

a hollow aluminum disk with a height of 0.16 cm and a diameter of 0.95 cm for $PM_{2.5}$ and a diameter 1.9 cm for PM_{10}. Both samplers can operate at two different air flow sampling rates, 4 and 1.8 l min^{-1}. This design feature provides flexibility to either reduce the sampling time to <24 h or minimize pump capacity.

Two types of impaction substrates were investigated: oiled porous metal disk and grease. A porous metal disk was inserted tightly in the hollow aluminum disk and was impregnated with mineral oil to minimize particle bounce. Metal disks of various pore sizes were tested. A greased surface was also tested as

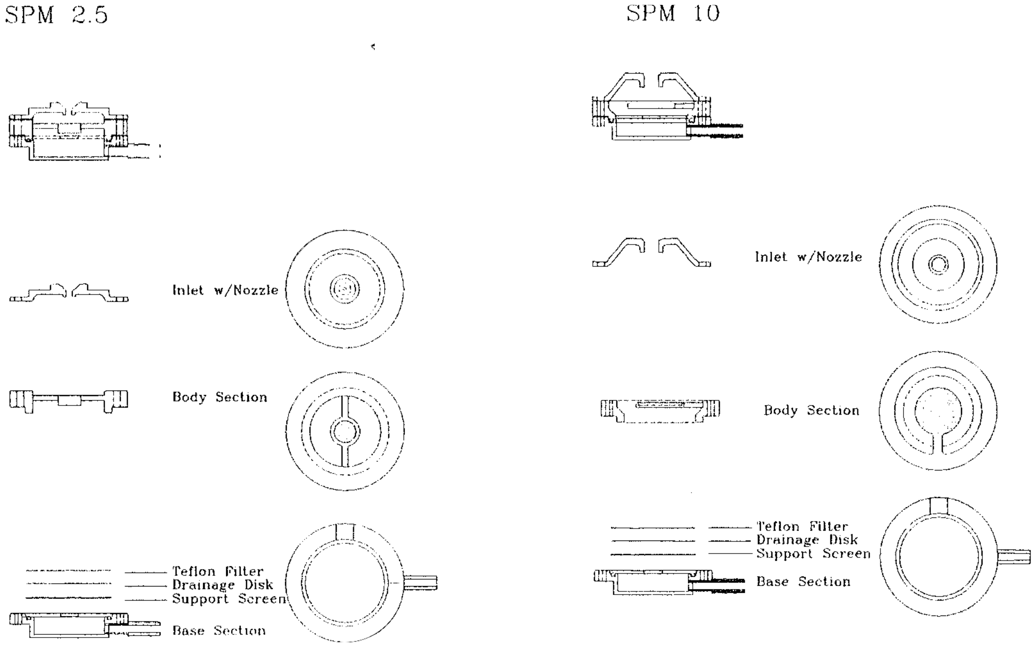


Figure 2. Personal samplers—$SPM_{2.5}$ and SPM_{10}.

Table 1
$SPM_{2.5}$ and SPM_{10} design characteristics

Flow (l/min)	Nozzle diameter D (cm)	Jet velocity (cm/s)	Re	S/W	L/W	$\sqrt{Stk_{50}}$	Sampler pressure drop (KPa)
$SPM_{2.5}$							
4	0.243	1430	2325	1.56	1.00	0.49	1.1
1.8	0.188	1081	1352	1.36	1.00	0.48	1.2
SPM_{10}							
4	0.60	236	942	1.2	0.91	0.48	1.3
1.8	0.48	169	535	1.3	0.90	0.47	1.3

($\rho_p = 1.1$ g/cm^3, $\mu = 1.810 \times 10^{-4}$ g/cm.s, $P_{atm} = 76$ cm Hg). Where S is the distance between the acceleration nozzle exit and the impaction substrate block (m); L is the throat length of the acceleration nozzle (m); Stk_{50} is the Stokes dimensionless number for a particle having a 50% probability of impacting; W is the characteristic dimension of the impactor that is the nozzle diameter or nozzle half width for round and rectangular nozzles, respectively (m); U is the average velocity of the jet (cm/s); and Re is the Reynolds dimensionless number.

an impaction substrate. This was performed by filling up the cavity of the hollow aluminum disk with silicone grease. The grease surface was then smoothed to minimize turbulence in the impaction zone. The smoothness of the impaction surface was found to be important for the impactor's performance.

The third component of the sampler is the filter holder, which holds a standard 37 mm Teflon filter. All three impactor components are held in place using four centering bolts. Leak tests indicated excellent sealing. The pressure drop across the sampler, including the 2 μm pore PTFE Teflon filter, is within the acceptable pump limits (see Table 1). Finally, sensitivity is adequate for a 24 h sampling period with a 5.7 and 2.6 μg/m^3 estimated limit of detection for the flow rates of 1.8 and 41 min^{-1}, respectively.

Minisampler for EC/OC Measurements (EC/OC)

The EC/OC sampler is shown in Figure 3. It consists of a conventional inertial impactor, which removes particles larger than 2.5 μm at a flow rate of 0.8 l min^{-1}. Downstream of the impactor is a filter pack that contains a 15 mm quartz filter. The two impaction substrate methods were also investigated: oiled metal disks of various pore sizes and a greased surface. Table 2 shows the sampler design parameters.

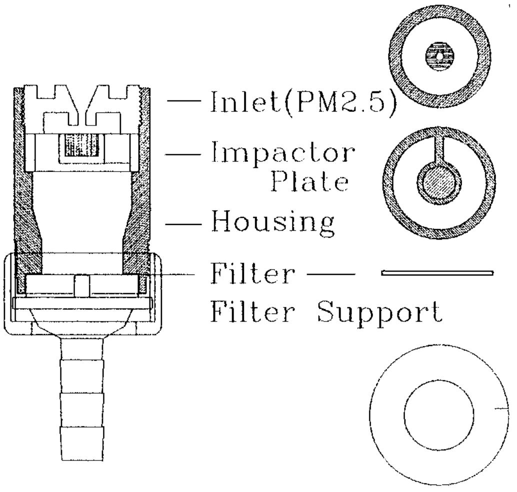


Figure 3. Minisampler for EC/OC measurements.

Quartz filters can be analyzed using a Thermo/Optical Reflectance (TOR) method to determine concentrations (Chow et al. 1992). Estimated limits of detection for this method for a 24 h sampling period are 1.6 and 0.37 μg/m^3 for OC and EC, respectively. The flow rate per unit filter area is also 71 cm^3 mm^{-2} min^{-1} for the minisampler, while the value for the FRM sampler is 110 cm^3 mm^{-2} min^{-1}. Therefore sensitivity is adequate for a 24 h sampling period and is comparable with that of the FRM.

Minisampler for Sulfate and Nitrate Measurements (MSD)

An accurate measurement of personal exposure to labile species such as ammonium nitrate or other semivolatile compounds is a challenging task. Volatilization of ammonium nitrate collected on Teflon filters over a long sampling period is well known and has been observed in several studies (Koutrakis et al. 1992). In order to prevent vaporization of the volatile ammonium nitrate, a sodium carbonate coated glass fiber filter is used. Because acidic gases such as nitric and nitrous acids can react with the coated filter and introduce positive artifacts in the nitrate measurement, it is necessary to use a diffusion denuder to remove these acidic gases.

Table 2
Minisamplers MSC and MSD—design characteristics

Flow (l/min)	Nozzle diameter D (cm)	Jet velocity (cm/s)	Re	S/W	L/W	$\sqrt{Stk_{50}}$
0.8	0.14	869	808	1.36	0.95	0.50

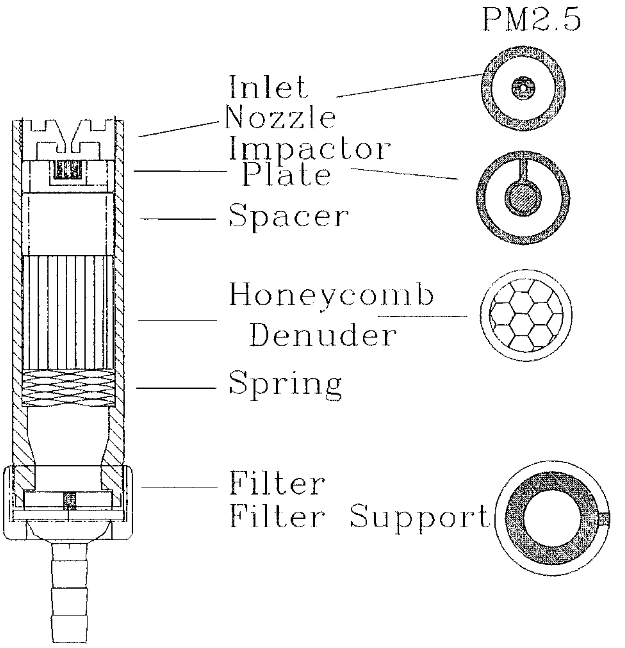


Figure 4. Minisampler for Sulfates and Nitrates (MSD).

The various components of the sampler are shown in Figure 4. The first stage of this sampler is a conventional inertial impactor that removes particles larger than 2.5 μm at a flow of 0.8 l min^{-1}. This component is identical to that of the EC/OC minisampler. A miniaturized all glass honeycomb diffusion denuder is placed downstream of the impactor. This denuder is coated with sodium carbonate/glycerol to remove nitric acid, nitrous acid, and sulfur dioxide gases. This denuder was previously developed in our lab and has been evaluated for efficiency and capacity over a 24 h sampling period (Koutrakis et al. 1989). Particles are collected downstream of the denuder on a 15 mm glass fiber filter, which is also coated with sodium carbonate/glycerol. Table 2 shows the critical design parameters for the minisampler.

Nitrate and sulfate collected on the filter can be measured by ion chromatography of aqueous extracts. Estimated limit of detection of this method for a 24 h sampling period are 0.257 and 0.240 μg/m^3 for sulfate and nitrate, respectively. Sensitivity is adequate for a 24 h sampling period and is comparable to that of the Federal Reference Method. Preliminary field intercomparison data for sulfates and nitrates show good agreement with the reference methods (Results from our field studies will be published after completion.).

Passive Samplers for SO_2, NO_2, and O_3

Two passive samplers are attached diametrically on the side of the elutriator for the measurement of gaseous copollutants. The samplers sample the air through the elutriator. In order to minimize losses of these reactive gases, the aluminum elutriator is coated with PFA Teflon. The first passive diffusion sampler is used to collect ozone. This sampler is based on a method previously developed and validated in our laboratory (Koutrakis et al. 1993) and uses a nitrite coated glass fiber filter to collect ozone.

The second passive sampler is used for simultaneous measurement of gaseous sulfur dioxide and nitrogen dioxide (Ogawa & Company, USA 1998). This sampler uses a triethanolamine coated cellulose filter to collect these gases.

Previous studies have shown that the collection rate of passive samplers depends on the wind speed (Liu et al. 1995). In our system, air flows through the elutriator with constant face velocity across the passive samplers; therefore the sampler collection rate remains constant. Estimated limits of detection (LODs) for a 24 h sampling period are 6 ppb for Ozone, 8 ppb for NO_2, and 5 ppb for SO_2.

Experimental Characterization of Samplers

The experimental setup that was used for the characterization of personal samplers is shown in Figure 5. The sampler's collection efficiency was examined as a function of several design parameters, such as Re, S/W, L/W, and substrate method. Particle concentrations were continuously monitored upstream and downstream of the test sampler.

Polydisperse particles were generated by nebulizing an aqueous suspension of 2–20 μm hollow glass spheres (density: 1.1 g/cm^3; Polysciences, Inc., Warrington, PA) with a Retec Model X-70/N nebulizer using filtered air at 7 psi. The aerosol was mixed with filtered room air. The test air mixture of polydisperse glass spheres then passed into the top end of a vertical cylindrical duct (35.0 cm [*L*] × 7.6 cm [*ID*]) made of anodized aluminum. Additional filtered room air was also added at the top of the duct. Turbulence was induced near the top of the duct, using a rectangular plate, to assure uniform concentration throughout the duct. The sampler was connected at the bottom of the duct. Alternate measurements were performed upstream and downstream of the sampler. An isokinetic probe placed inside the duct was used for the upstream measurements. In each experiment, the concentration and size distribution of particles were measured for 10 min upstream, 10 min downstream, and 10 min again upstream. The aerodynamic particle sizer (APS; Model 3320, TSI Inc., St. Paul, MN) was used to measure particles in the size range of 0.5 to 10 μm. At the start of each working day the APS calibration was checked at five particle diameters (0.99, 2.13, 2.90, 4.56, and 9.14 μm) using polysterene microspheres (Polysciences, Inc, Warrington, PA) to ensure the instrument's calibration.

For each particle size, the sampler's collection efficiency was determined as follows:

$$\text{Collection Efficiency} = \frac{C_{up} - C_{dn}}{C_{up}}, \qquad [3]$$

where C_{up} and C_{dn} are the particle concentrations upstream and downstream of the impactor, respectively.

Particle loss onto the sampler nozzle and internal surfaces was determined by removing the impaction plate section of the sampler and repeating the previously described experiment.

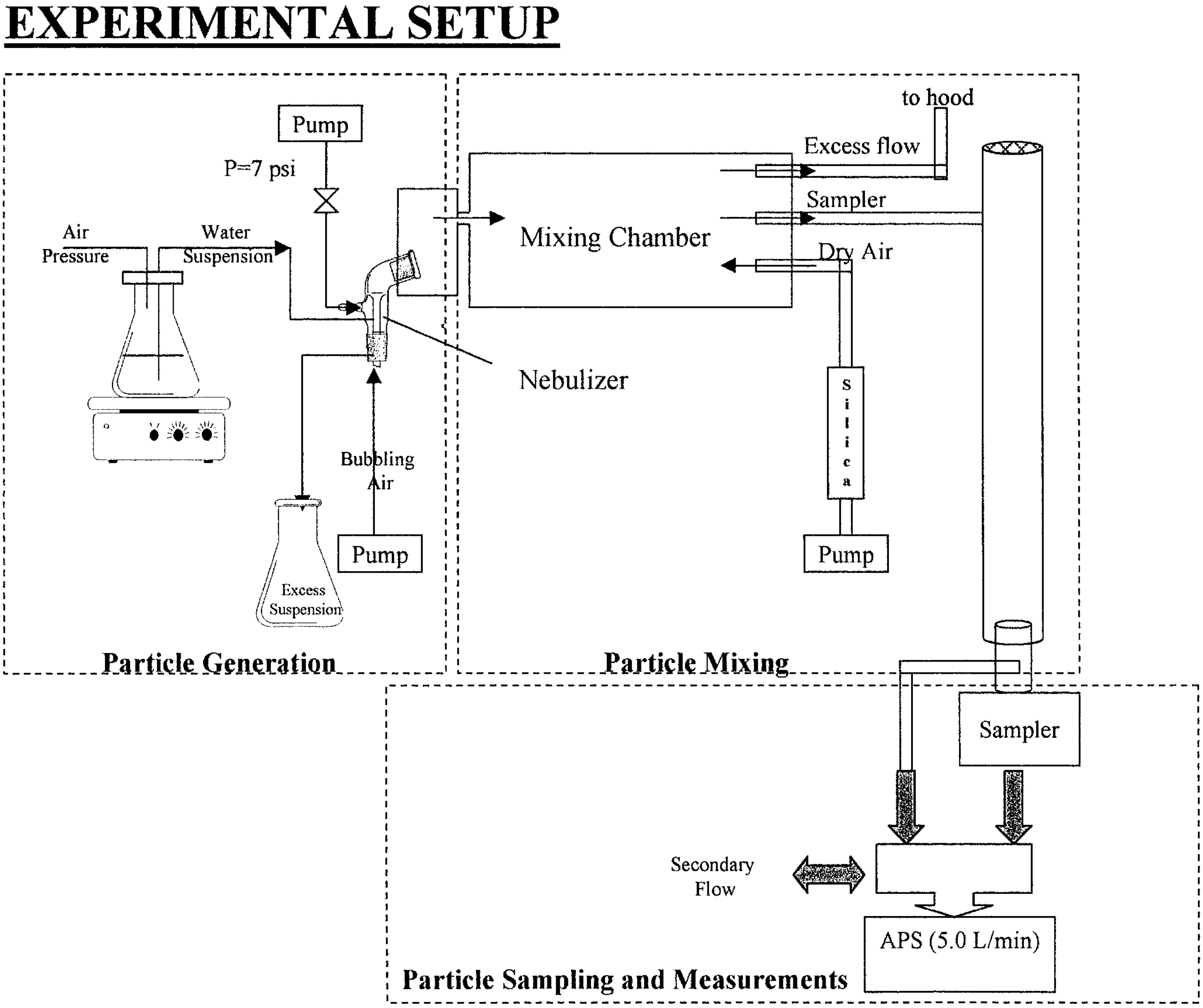


Figure 5. Experimental setup for the characterization of samplers.

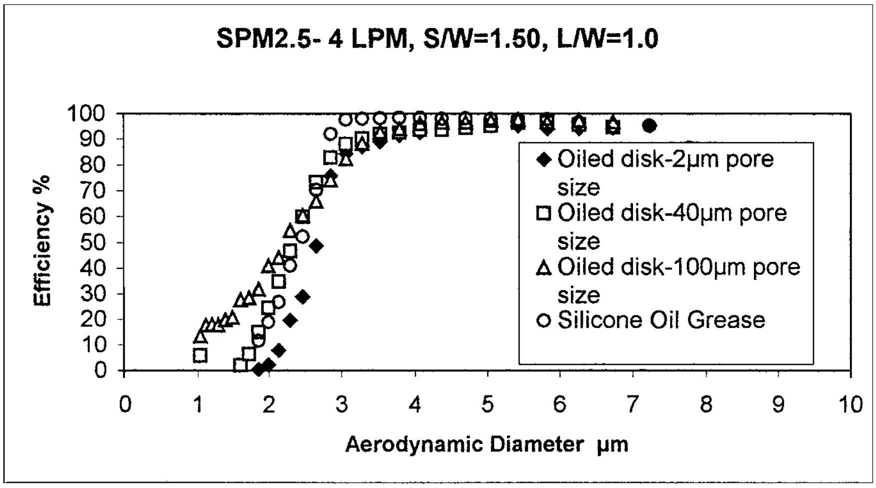
RESULTS AND DISCUSSION

Experimental Characterization of Personal Samplers $SPM_{2.5}$ and SPM_{10}

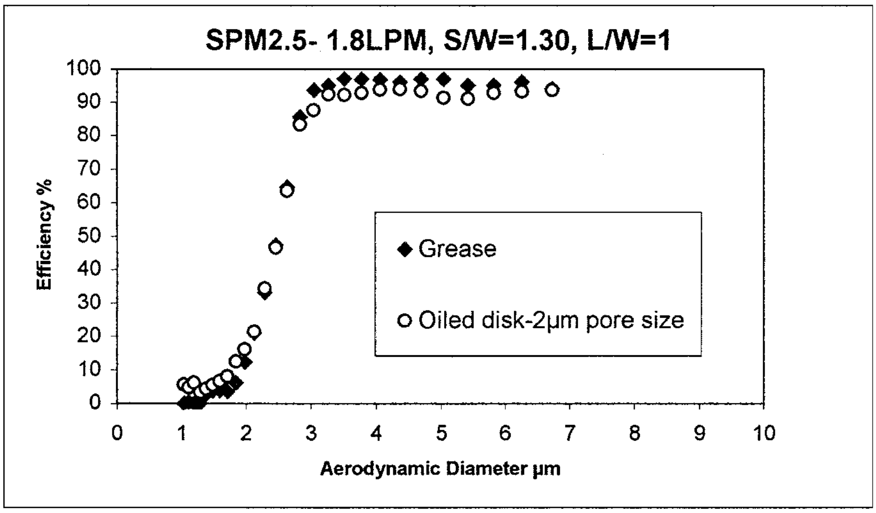
The effect of the critical design parameters such as Re, S/W, L/W, and substrate method on the performance of the sampler was investigated. Two impaction substrate methods were primarily investigated as part of our design development: oiled metal disks and greased surfaces. Disks with various pore sizes (2, 20, 40, and 100 μm) were tested. Also, several types of grease were tested.

The grease is semisolid consisting of base oil, thickener, and additives. Base oil is critical for the impactor's performance because it wicks up by capillary action through the collected particles providing a continuous wet surface for particle collection. Thickeners are used to increase the viscosity of the grease. Additives improve characteristics such as temperature range, corrosion resistance, adhesion, etc. Selecting a type of grease to be used for an impaction substrate is not an easy task. A proper grease for impaction applications has to be high in base oil, soft enough to allow particle embedding, and usable under a wide temperature range. The grease used in our samplers is a silicone base oil grease (Dow Corning 111) suitable over a wide temperature range (−40°C to 204°C).

Figures 6a and b show the $SPM_{2.5}$ sampler collection efficiency as a function of the aerodynamic diameter for various impaction substrates for both 4 and 1.8 LPM flow rates. A slight decrease in the collection efficiency for particles larger than the impactor's cutpoint was observed for oiled metal disks. Collection efficiency also decreases with pore size. Thus particle bounce for particles larger than the separation point is more pronounced for larger pore sizes. Additionally, the impactor's



a) SPM2.5 - 4 LPM nozzle



b) SPM2.5 – 1.8 LPM nozzle

Figure 6. Collection efficiency for $SPM_{2.5}$ personal sampler.

performance was found to vary slightly with the pore size. For a pore size of 100 μm, the collection efficiency curve becomes less sharp and particles smaller than the cutpoint appeared to be collected on the impaction substrate (collection efficiency on the order of 20% for particles smaller than the cutpoint). The collection of particles smaller than the cutpoint probably occurs because the oil was blown away from the large pores. As a result, the air streamlines penetrate into the substrate where the small particles were intercepted.

The greased surface impaction substrate appears to be superior to the oiled metal disk. Collection efficiencies approached almost 100% for particles larger than the cutpoint. Similar results were also reported by Demokritou et al. (2001) and Lawson (1980). The roughness of the greased surface was also found to be critical for the overall collection efficiency of the sampler. Two different surface types were investigated: a "rough" and a "smooth" surface. The rough surface is created by using an applicator to spread grease over the hollow substrate in order to create a wavy surface. A razor blade was used to "shave" the greased surface to create an extremely smooth surface. Figure 7 shows a significant difference in both cutpoint and overall collection efficiency of the $SPM_{2.5}$ sampler for the two surface types. The turbulence generated due to the surface roughness is probably responsible for particle losses of particles smaller than the cutpoint.

The thickness of the greased surface also affects the overall collection efficiency. It has been shown that bounce decreases with the coating thickness (Pak et al. 1992; Reischl and John

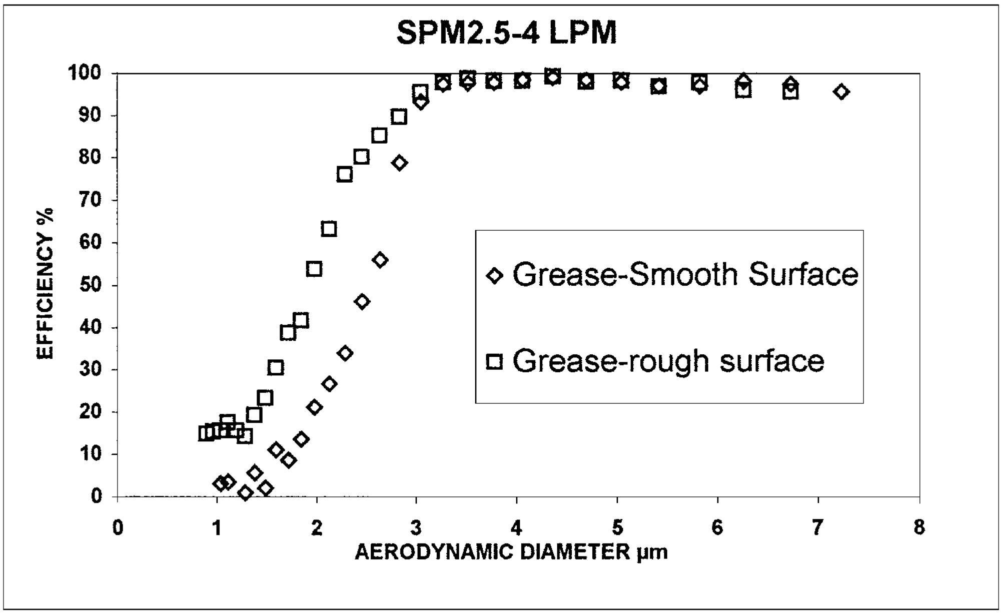


Figure 7. Collection efficiency for "rough" and "smooth" grease surfaces.

1978). A greased coating with a thickness of a few micron can rapidly become ineffective. This is because particles accumulate on the surface and incoming particles bounce off those previously deposited (Turner and Herring 1987). Using a thick and smooth grease coating (0.16 cm) as an impaction substrate was found to be very effective in eliminating particle bounce, since particles were deeply embedded into the grease and silicone oil wetted their surface.

A loading test was also conducted to evaluate the sampler performance under heavy loading conditions. For this test, the $SPM_{2.5}$ sampler was exposed to an extremely high concentration aerosol of 1,423 μg/m^3 for 5 h at a 4 LPM flow rate. This represents a total collected mass of 1.36 mg collected on the greased surface. This highly loaded greased substrate was then tested experimentally under normal loading conditions to obtain the sampler collection efficiency as a function of aerodynamic diameter. The results from these experiments showed that the overall collection efficiency and cutpoint of the sampler did not change with particle loading.

The effect of the S/W ratio on sampler performance was also experimentally investigated. Figure 8 shows the collection efficiency curve for the $SPM_{2.5}$, 1.8 LPM sampler, for various

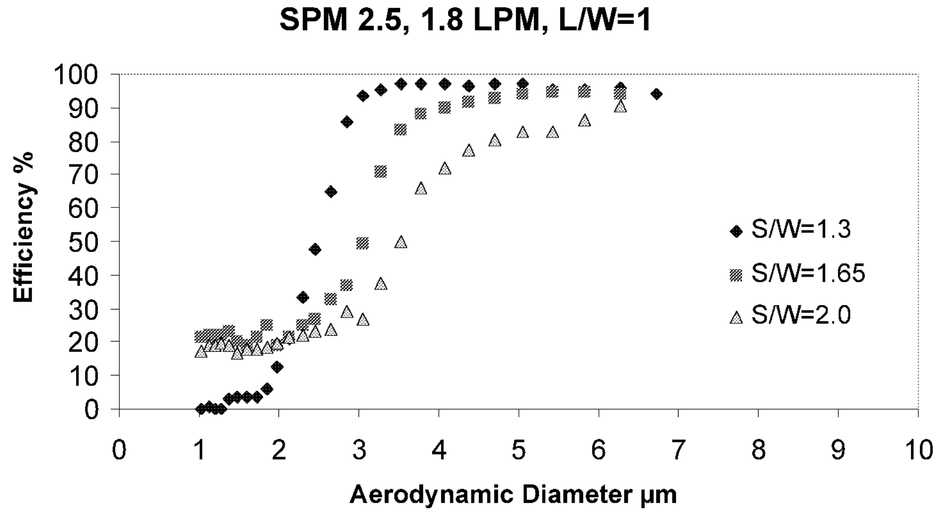
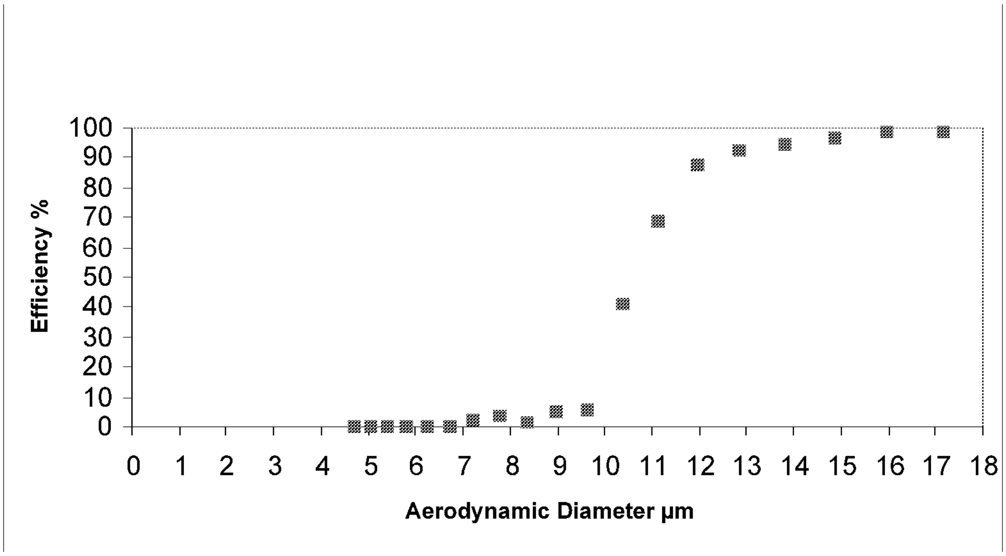
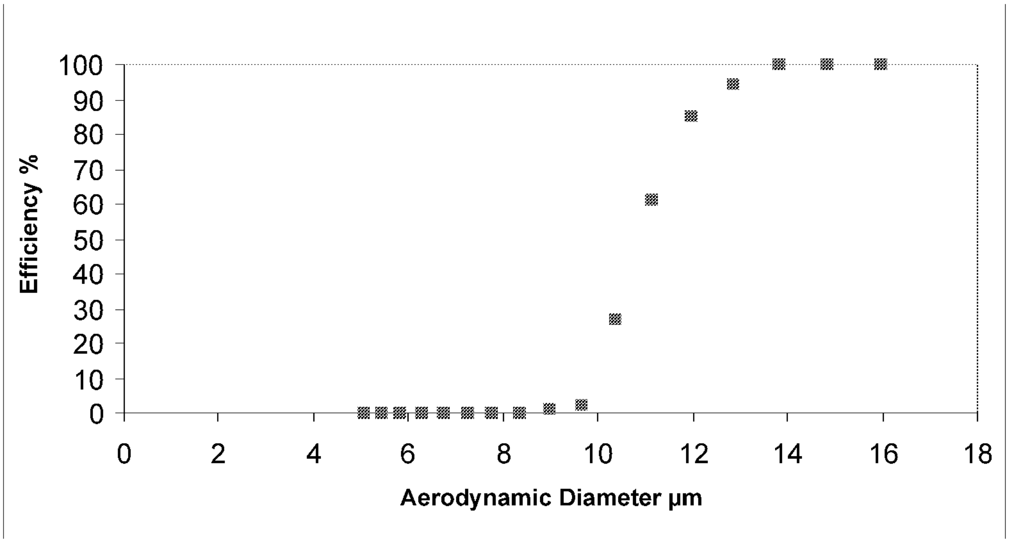


Figure 8. Collection efficiency for various S/W ratios.



a. SPM10 – 1.8 LPM nozzle



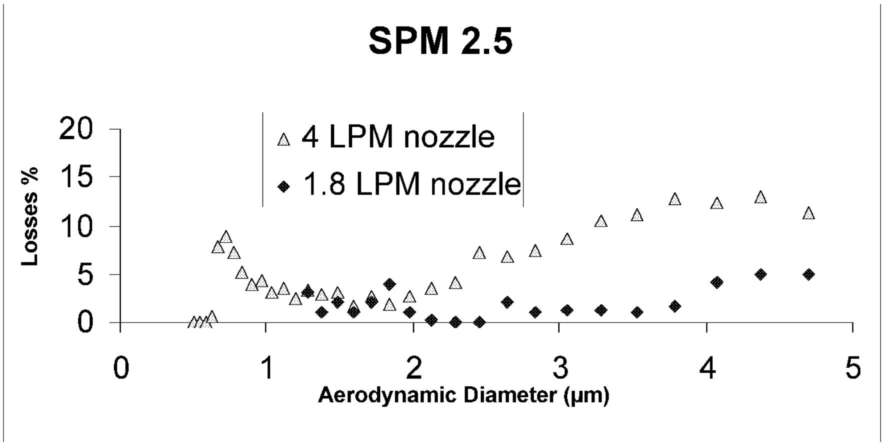
b. SPM10 – 4 LPM nozzle

Figure 9. Collection efficiency for SPM_{10} sampler.

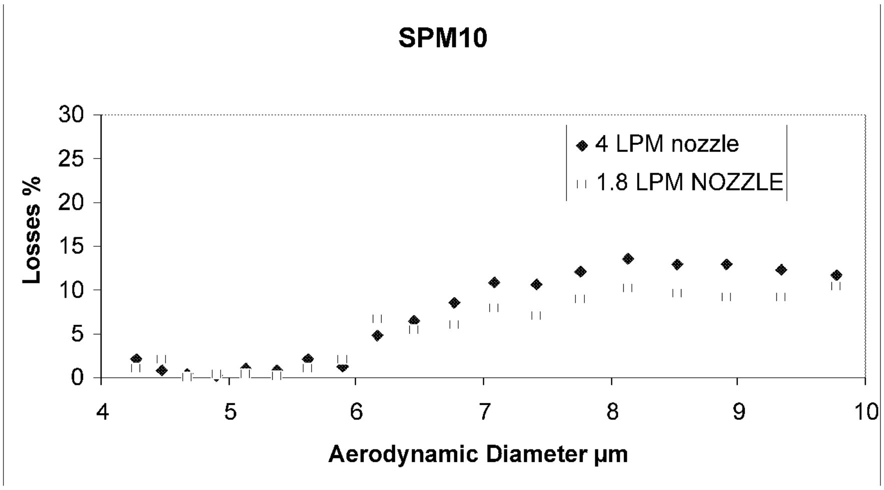
S/W ratios for the greased surface impaction substrate. As can be seen, both the collection efficiency curve and particle bounce depend on the S/W ratio. Also, it is worth mentioning that the experiments demonstrated that the effect of S/W ratio was more pronounced for the oiled metal disks as compared to the greased surface.

Figures 9a and b show the collection efficiency of the SPM_{10} sampler as a function of the aerodynamic diameter for the 4 LPM and 1.8 LPM nozzles, respectively. As can be seen, the collection efficiency curve shows very sharp characteristics for both airflow rates.

Table 3 summarizes the experimentally determined 50% cutpoint along with the geometric standard deviation (σ_g) of the developed samplers with a greased surface. The (σ_g) parameter characterizes the sharpness of the collection efficiency curve. This is the ratio of the aerodynamic particle diameter corresponding to 84% efficiency to the 50% cutoff point diameter (Marple et al. 1976). The results indicate that both $SPM_{2.5}$ and



a) Particle losses for SPM2.5 sampler.



b) Particle losses for SPM10 sampler.

Figure 10. Particle losses for $SPM_{2.5}$ and SPM_{10} sampler.

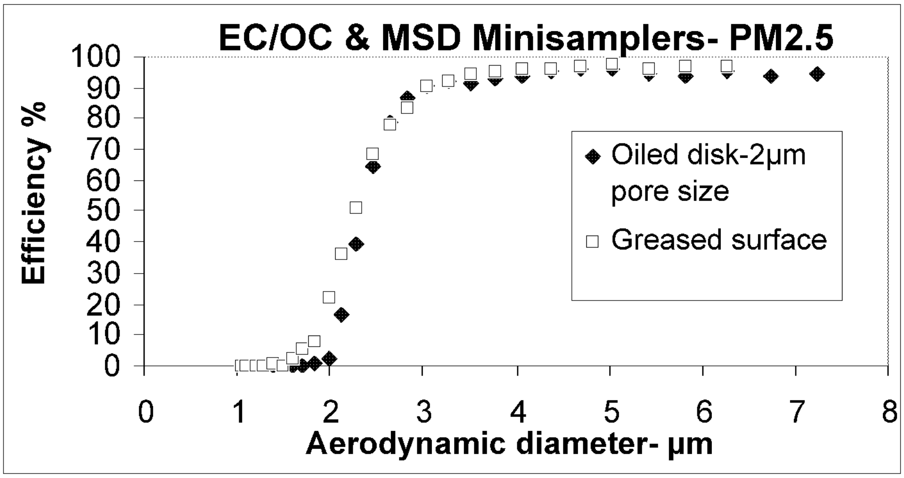


Figure 11. Collection efficiency for EC/OC and MSD minisamplers.

Table 3
$SPM_{2.5}$ and SPM_{10} personal samplers—experimental characterization data

Flow (l/min)	Cutpoint (μm)	σ_g
$PM_{2.5}$		
4	2.4 ($\pm$0.1)	1.15
1.8	2.4 ($\pm$0.1)	1.14
PM_{10}		
4	10.6 ($\pm$0.1)	1.12
1.8	10.3 ($\pm$0.1)	1.15

SPM_{10} samplers have reasonably sharp cut characteristics ($\sigma_g < 1.2$) with cutoff points close to the theoretical design values of 2.5 and 10 μm, respectively. Particle nozzle and wall losses are also within the acceptable 5–12% range, as illustrated on Figure 10.

Experimental Characterization for the Personal Minisamplers (EC/OC and MSD)

The particle collection efficiency for the minisamplers for oil coated and greased impaction substrates is shown in Figure 11. As can be seen for the greased surface, substrate collection efficiencies approach 100% for particle sizes above the impactor's cut-off size. Therefore the greased surface impaction substrate is superior to the oiled metal disk. The experimentally determined 50% cutpoint of the sampler and its geometric standard deviation are 2.4 ($\pm$ 0.1) and 1.16, respectively, for the greased surface substrate method. Particle nozzle and wall losses for particles smaller than 2.5 μm were also found to be on the order of 10%. Finally, the MSD minisampler was found to have identical collection efficiency curves with the EC/OC minisampler.

SUMMARY-CONCLUSIONS

An integrated MPS has been developed and evaluated through a series of laboratory tests. The system can be used to collect gaseous and particulate pollutants simultaneously. The system has a modular and lightweight design. The basic unit collects particles for mass/elemental analysis and has additional features for particle speciation, including simultaneous measurements of EC, OC, sulfate, and nitrate. Two passive samplers for measuring gaseous copollutants such as O_3, SO_2, and NO_2 are also included. The system operates using a single sampling pump at a total flow of 5.2 l/min.

All personal samplers show sharp cut characteristics with cutpoints very close to their theoretical values. Particle losses are also in the order of 5–12%. The overall performance of the system demonstrates its suitability for personal exposure assessment studies.

We are in the process of conducting a field intercomparison study that is expected to be completed in the next couple of months. All the preliminary field data show good agreement with the reference methods. The field intercomparison study will be reported separately after its completion. The system will be used in our field studies in various locations in the US to provide valuable information on human personal exposure to particulate matter.

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