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DEVELOPMENT OF A HIGH-VOLUME CONCENTRATED AMBIENT PARTICLES SYSTEM (CAPS) FOR HUMAN AND ANIMAL INHALATION TOXICOLOGICAL STUDIES

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A two-stage, high-volume, ambient particle concentrator was developed and characterized. This versatile system, depending on its operational parameters, can be used to fractionate and concentrate particles in three size ranges ($PM_{10-2.5}$, PM_{10-1}, $PM_{2.5-1}$). The performance of this concentrated ambient particle system (CAPS), as well as its individual virtual impaction stages, was investigated as a function of several parameters, including minor-to-total flow ratios and acceleration nozzle Reynolds number. During these laboratory tests, performance parameters such as concentration enrichment factor (CF), particle losses, collection efficiency curves, cutpoint, and pressure drop were measured. The main objective of these investigations was to optimize the ability of the system to concentrate ambient $PM_{2.5-10}$ and PM_{1-10} particles. $PM_{2.5-10}$ particles were concentrated by a factor of 70 to 150. The flow rate of the concentrated aerosol can range between 12.5 and 50 LPM (L/min). Other features of the system include relatively low-pressure drops in the major and minor flows, low particle losses, and a compact design. Performance evaluation of the system also confirmed that separation and concentration of the $PM_{2.5-10}$ particles occurred without any significant distortion of the size distribution, during the concentration process. Similar results were obtained for the PM_{1-10} size range. For this size range, concentration enrichment was 70 times, and again, no particle size distribution distortion was observed. The overall performance of this versatile system makes it suitable for inhalation toxicological studies.

Epidemiological studies have reported associations between particulate matter (PM), especially its PM10 fraction (size ≤ 10 μm), and health, even at air pollution levels below the National Ambient Air Quality Standard (NAAQS). Both respiratory and cardiovascular adverse effects have been reported, including premature mortality, respiratory and cardiovascular disease, exacerbation of asthma, decreased lung function, and increased risk of myocardial infarction (Schwartz & Dockery, 1992; Dockery et al., 1993; Dockery & Pope, 1994; Peters et al., 1997; Gamble et al., 1998).

The size of ambient particles ranges between 0.002 and 100 μm (Whitby & Svendrup, 1980). Particles typically consist of a mixture of a large number of chemical compounds, including sulfate, nitrate, ammonium ions, sea

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salt, organic and elemental carbon, metals, and biological material. Size is an important determinant of particle fate and transport in the environment. It also affects deposition in the human respiratory system. The coarse fraction of PM_{10} has a size range between 2.5 and 10 μm. These particles are typically generated mechanically by crushing or grinding processes. Coarse particles differ from fine particles (size ≤2.5 μm) not only because they are larger but also because they have different formation mechanisms, chemical composition, sources, and physical behavior. Sources of coarse particles include resuspended dust, crustal material from roads and construction, mining, and farming activities, as well as bioaerosols, such as spores and pollens. Because the composition of coarse particles differs from that of fine and ultrafine ones, it is worth investigating their effects separately.

The toxicity of coarse particles has been demonstrated in a limited number of in vitro studies (Monn & Becker, 1998; Hornberg et al., 1998). A few investigators used simulated ambient particle exposures in controlled-chamber tests or performed in vivo studies with either single-chemical-component particles or simple mixtures of a few components (Avol et al., 1988; Hackney et al., 1989; Anderson et al., 1992). Such artificial particles may not be an adequate simulation of heterogeneous particle mixtures that occur in "real-world" ambient air. For example, it has been shown that the oxidant-generating capability of real particles differs significantly from that of artificially generated ones (Lippmann, 1989).

Typical ambient coarse particle concentrations are usually too low to effectively perform laboratory inhalation toxicology studies. An effective way to increase the particle concentration is to use a virtual inertial impactor. Particles above the impactor cutoff size are separated from the majority of the gas phase and collected in the minor flow. Because particle separation occurs in a few microseconds, the concentrated particles remain in equilibrium with the existing ambient gaseous pollutants. This technique has been used successfully in our and many other labs for in vivo exposure of animals and humans to concentrated ambient fine particles (0.15 μm < aerodynamic diameter, d_P < 2.5 μm). A three-stage fine particle concentrator was developed to increase ambient fine particle concentrations by about a factor of 30 (Sioutas et al., 1995). This system has been successfully used over the last 6 yr for animal inhalation studies (Godleski et al., 1996). Recently, an ultrafine particle (d_P < 0.1 μm) concentrator was also developed in our lab for in vivo studies (Demokritou et al., 2001a). This system uses condensational growth to increase particle size to supermicrometer values. Subsequently, the grown particles are concentrated using a virtual impactor, followed by restoration to the original ambient size distribution using a thermal drying technique.

For inhalation studies, coarse particles should be concentrated with no or little distortion of their size distribution and physicochemical characteristics. In addition, a relatively high output flow rate of 30 to 50 LPM of aerosol, concentrated by a factor of 20–60, is expected to be adequate for in vivo exposure studies. This would require an input flow rate on the order of thousands of liters per minute and possibly would require the use of multistage virtual impactors.

Recently, we developed a low-flow, slit-nozzle, virtual impactor that can be used to concentrate ambient coarse particles with high efficiency (Demokritou et al., 2002d). This prototype system separates and concentrates particles with minimum losses and with insignificant distortion of the size distribution. Based on this virtual impactor technology, a two-stage, high-volume (5000 LPM) system for in vivo exposure toxicological studies was developed. The developed system is compact, with low pressure drop and high flow output, and capable of obtaining concentration enrichment factors values of over 100, with insignificant distortion of the particle size distribution and with acceptably low pressure drop. The high volume system has three configurations, for concentrating particles for the following size ranges: $PM_{10-2.5}$; PM_{10-1}, and $PM_{2.5-1}$. This article presents the development and the laboratory performance evaluation of this system.

METHODS

System Description

Figure 1 shows the main components of the Harvard University concentrated ambient particle system (HUCAPS). The system operates at an input air flow of 5000 LPM and consists of the following components: (a) a size-selective device (separator); (b) a series of two virtual impactors (concentrators); and (c) an exposure chamber. The system can be used to concentrate a variety of size fractions of atmospheric aerosols including particles with aerodynamic diameter between 2.5 and 10 µm (coarse particles, $PM_{2.5-10}$), particles with aerodynamic diameter between 1 and 2.5 µm ($PM_{1-2.5}$), and particles between 1 and 10 µm (PM_{1-10}). This was made possible by adjusting appropriately the cutpoint of the virtual impactors and the cutpoint of the size-selective inlet (separator). The main components are presented in detail, as follows.

Size-Selective Device (Separator)

This high-volume (5000 LPM) size-selective inlet is a conventional inertial impactor, which removes particles larger than a certain size from the aerosol stream before it is drawn through the concentrators. The sample air is accelerated in three jets, which are directed at the impaction substrates (Figure 2). Particles larger than a certain size (cutpoint) impact onto and are collected by the substrate. For this specific high-volume impactor, the cutpoint is adjustable and can be either 2.5 or 10 µm. When the system is used for $PM_{2.5-10}$ or PM_{1-10} inhalation exposures, the incoming particles with an aerodynamic diameter larger than 10 µm need to be removed before the smaller particles are drawn through the concentrator stages. For this operational scenario, the inlet is configured to have a cutpoint of 10 µm. For the $PM_{1-2.5}$ exposure scenario the inlet is configured to have a cutpoint of

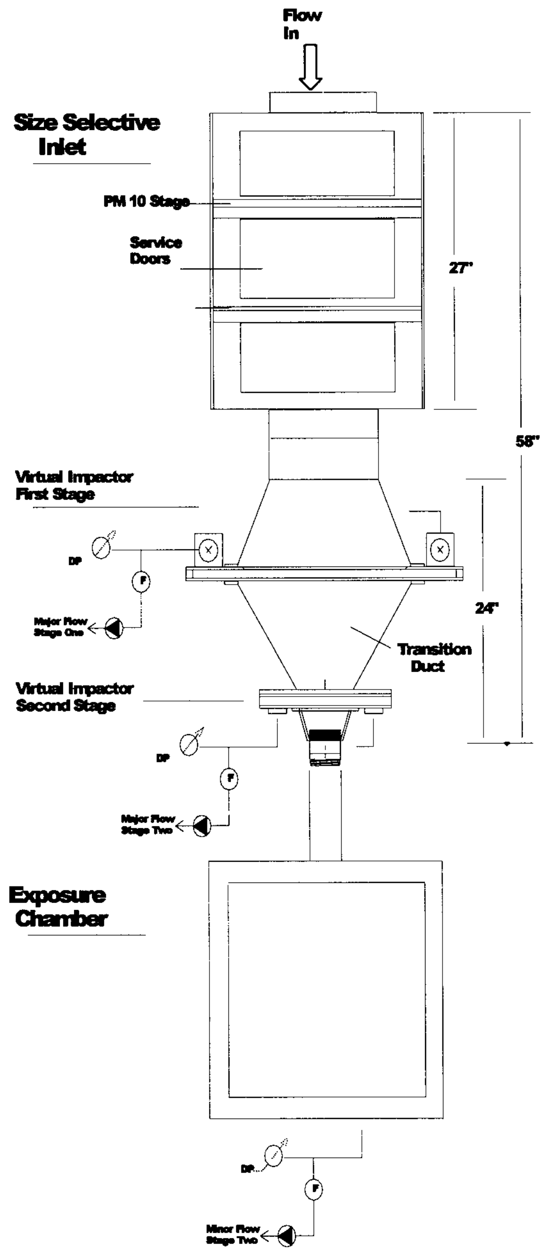


FIGURE 1. The Harvard University concentrated ambient particle system (HUCAPS).

2.5 μm (to remove particles with an aerodynamic diameter larger than 2.5 μm). Particles larger than the cutpoint are collected on a polyurethane foam (PUF) impaction substrate (which may be precleaned to remove adsorbed volatile gases), while particles smaller than the cutpoint continue to flow through the HUCAPS system. The desired cutpoint of the inlet is controlled

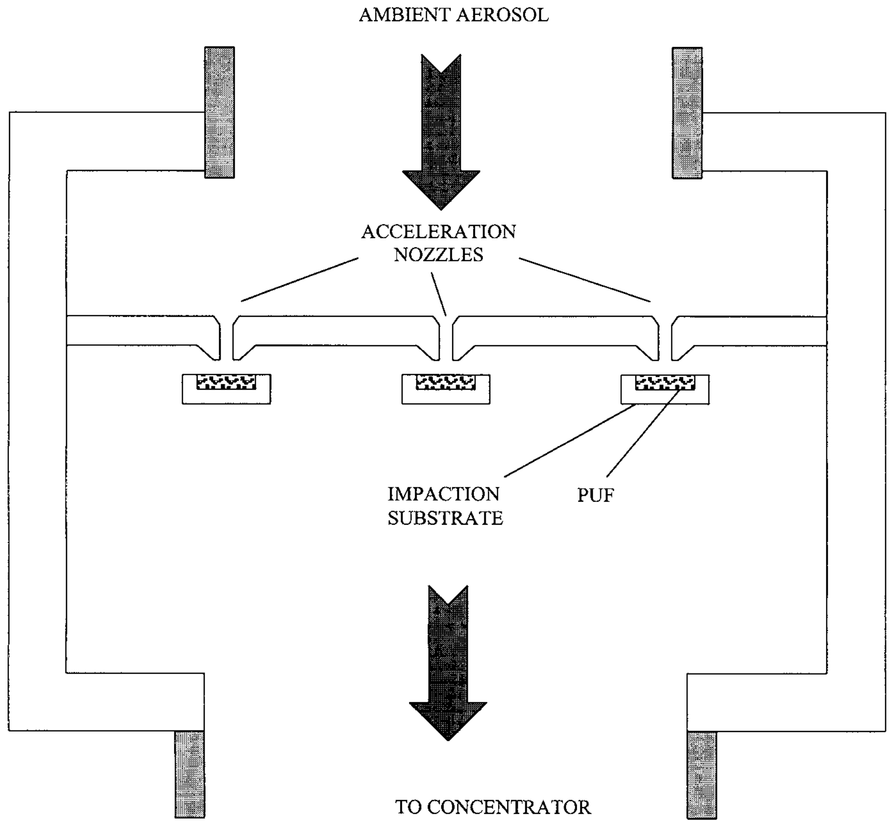


FIGURE 2. Size-selective inlet.

by using different acceleration nozzles. The major advantage of this PUF impaction substrate is its ability to collect relatively large amounts of particles (milligram to gram levels) onto relatively small substrates without using adhesives. Additionally, particle bounce and reentrainment particle losses were found to be insignificant (Kavouras & Koutrakis, 2001; Demokritou et al., 2002b, 2002c). The complete description of this high-volume conventional impactor is presented in detail elsewhere (Demokritou et al., 2002d).

Virtual Impactors

Particles smaller than the cutpoint of the separator are drawn through a series of two virtual impactors (stages I and II). A virtual impactor can be used to concentrate particles of a desired particle size range. In a virtual impactor, the inlet flow, Q_0 , is typically divided into two flow streams, with the major flow, Q_M, carrying most of the particles smaller than a distinct cutpoint, and the minor flow, Q_m, carrying most of the particles larger than the cutpoint, together with a small fraction of the smaller particles. Particles larger than the impactor cutpoint follow the relatively straight minor flow, while particles below the impactor cutpoint follow the deflected air streamlines of the major flow. As a result, particles with sizes above the impactor cutpoint are collected in the minor flow and are concentrated by a nominal factor of Q_0/Q_m, while in the minor flow, the concentrations of particles with sizes below the impactor cutpoint remain at their original values.

Problems associated with virtual impactors in general include high particle losses, especially for small particles (Sioutas et al., 1994), and relatively high pressure drop across the impactor (Marple et al., 1990). High internal particle losses may result in an actual concentration factor considerably lower than the theoretical concentration factor, which is defined as the ratio of the total flow to the minor flow, and also may result in a distortion of the particle size distribution. High pressure drop may cause significant losses of semivolatile components from ambient particles, which may be of toxicological importance (Nishioka et al., 1988; Kelly et al., 1994), and may proscribe animal exposure testing.

The design characteristics of the two new high-volume virtual impactors were based on a prototype low-flow single-jet coarse particle concentrator previously developed in our laboratory (Demokritou et al., 2002e). The new high-volume, multislit nozzle, virtual impactors consist of two main components, the acceleration and collection nozzles. Figure 3 illustrates the geometrical characteristics of both stage I and stage II virtual impactors of the HUCAPS system. It is worth pointing out that enough distance was allocated between adjacent slits to minimize any jet-to-jet interactions (Fang et al., 1991). The multislit design presented here is versatile and allows adjustment of the desired cutpoint of the virtual impactor. As presented previously (Demokritou et al., 2002e), the cutpoint is a function of acceleration nozzle Reynolds number. Thus, by blocking some of the acceleration and collection nozzles, it was possible to change the virtual impactor cutpoint. A parametric analysis was performed for each stage to evaluate the performance of the virtual impactor for various Reynolds number (Re) values. The gap between the acceleration nozzle exit and the collection nozzle entrance, *S*, is also a critical parameter for the performance of the impactor and the interstage losses (Loo & Cork, 1988; Demokritou et al., 2002e). For both stages, *S* was always set to obtain an *S*/*W* ratio value of 1.3, where *W* is the acceleration nozzle width.

Experimental Setup for the Laboratory Characterization of HUCAPS

The HUCAPS was first tested using laboratory room air. However, the concentration of coarse particles in room air was quite low, so subsequent evaluations were performed using a pocket nebulizer (Retec model X-70/N), as shown in Figure 4. A flow of nebulized aqueous suspension of hollow glass spheres (density of 1.1 g/cm^3 and nominal size distribution of 2–20 μm, Polysciences, Washington, PA) was introduced at the top of the duct. The duct was used to mix the nebulized glass spheres with room air and to evaporate the liquid water from the aerosol droplets. Also, the use of the duct made it possible to achieve complete aerosol mixing prior to entrance into

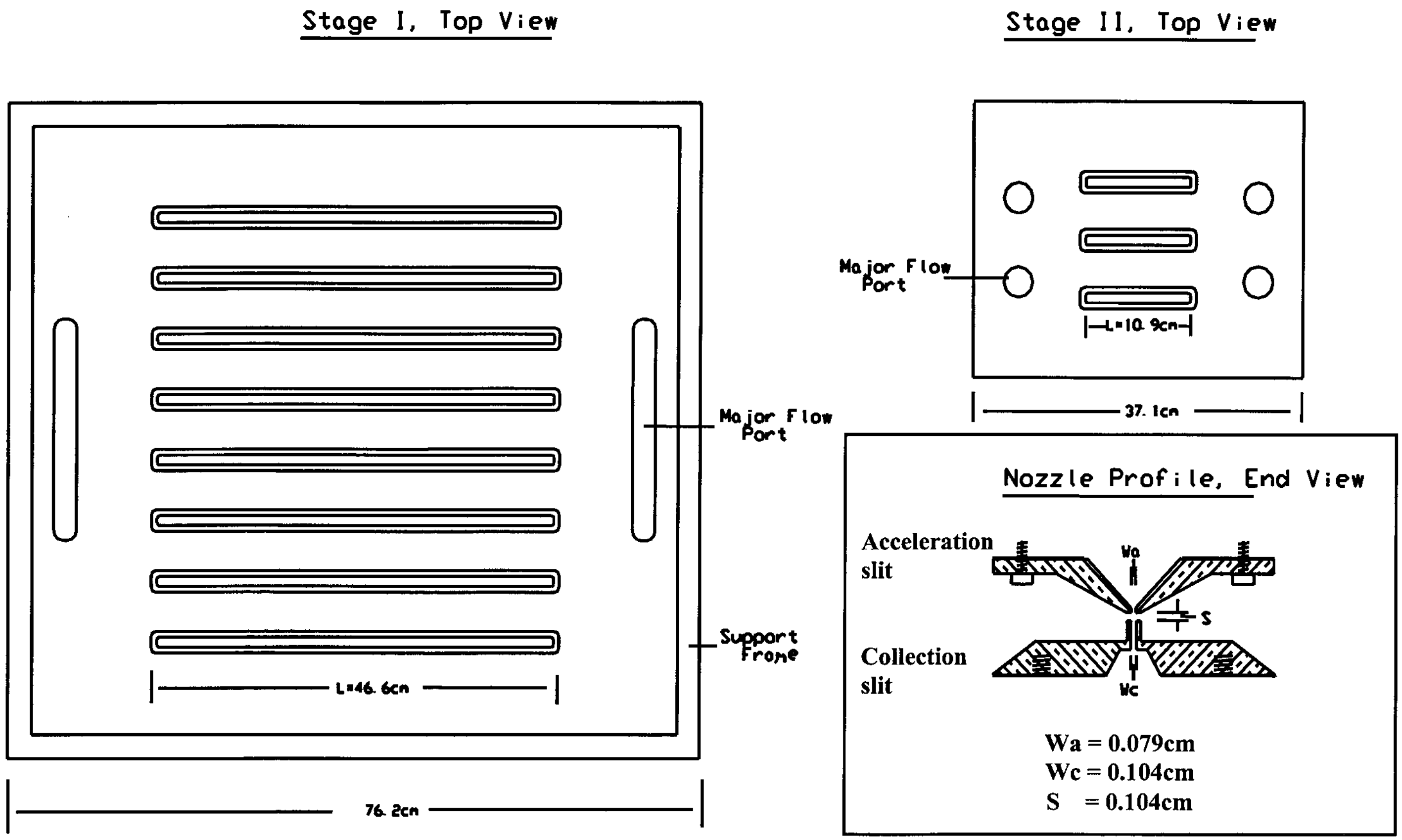


FIGURE 3. Design characteristics of virtual impactors. Wa, width of acceleration slit; Wc, width of collection slit; S, gap between the acceleration slit exit and the collection slit entrance.

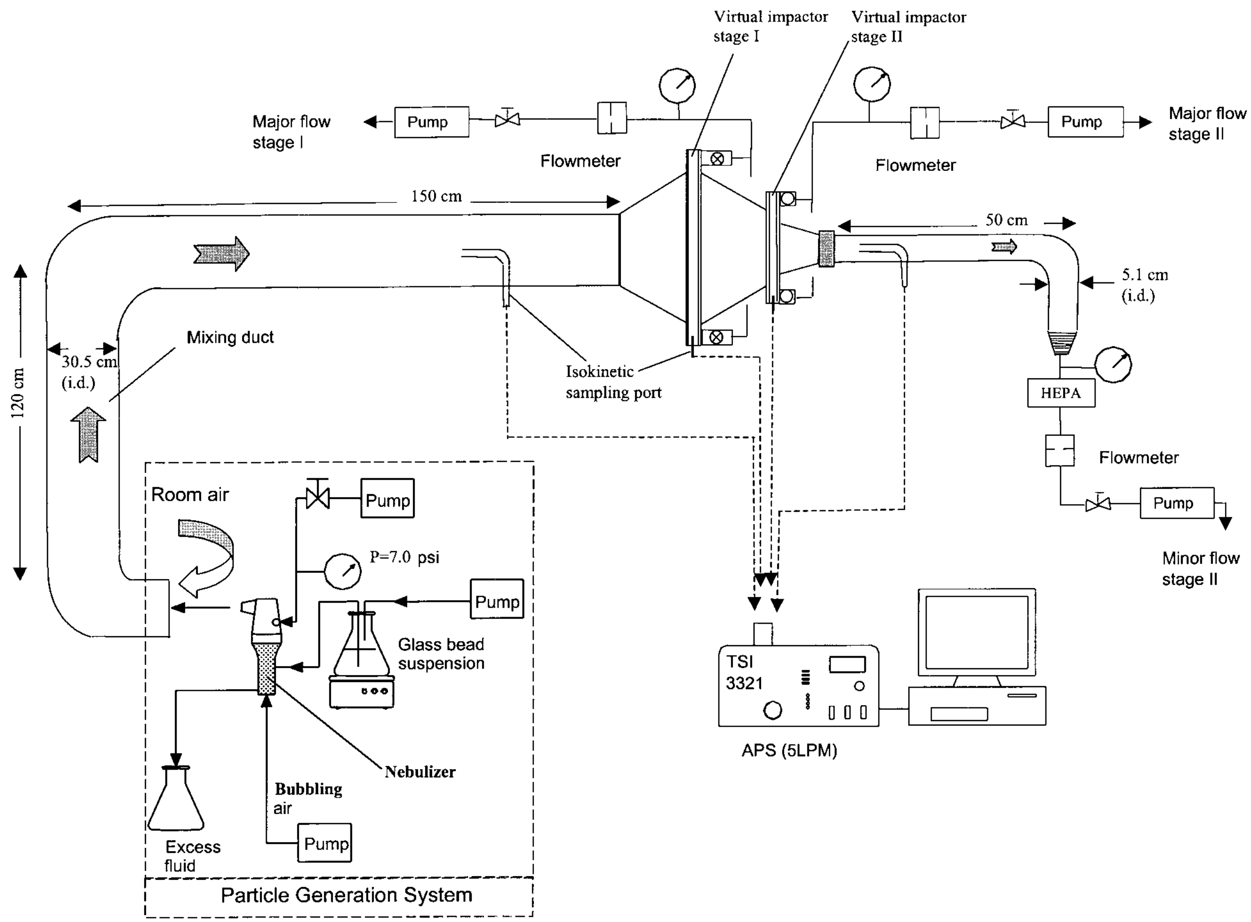


FIGURE 4. Experimental setup for the laboratory characterization of HUCAPS.

the virtual impactors. Particle number concentration and size distribution were measured upstream of the impactor, and downstream in the major and minor flows (alternating sequentially) using an aerodynamic particle sizer (APS, TSI model 3321). The sampling probes were isokinetically designed.

Each APS measurement lasted for 2 min, and the reported results are based on the average of at least 5 consecutive (alternating) tests. The relative standard deviation of the average for each particle size was less than 5%. Note that the nominal size distribution of the hollow glass spheres is based on mass per particle size. Consequently, even though there is a sharp decrease in the mass concentration for particles below 2 μm in diameter, the particle number concentration for sizes below 2 μm is measurable all the way down to the minimum size detectable by the APS (0.5 μm). Both the minor and major flows were connected to vacuum pumps (MFG Corp., Benton Harbor, MI), with flows monitored using mass flowmeters. The pressure drops in both the minor and major channels were monitored with Magnehelic vacuum gauges.

Performance Evaluation

At first, each virtual impaction stage was tested separately, for three acceleration nozzle Re values, low (~2500), medium (~5000), and high (~10,000), and for three minor-to-total flow ratios, *r* (2.5, 5, and 10%). Re values were adjusted by blocking a number of acceleration and collection nozzles while maintaining constant flow rate for each stage. Investigations were made of the effects of Reynolds number (Re) and minor-to-total flow ratio (*r*) on the performance of the virtual impactors. For each of these experiments, the cutpoint, particle losses, concentration enrichment factor, and pressure drops of both major and minor flows were measured. Furthermore, in order to take into consideration any possible particle losses in the connecting transition piece between the two stages, the two stages were assembled together and reevaluated as a whole. The experiments were conducted as follows.

For each individual stage, the particle concentration factor, collection efficiency, and interstage particle losses were determined for particles between 0.5 and 10 μm. The particle concentration factor (CF) is defined as the ratio of the particle number concentration measured in the minor flow to that in the inlet (duct) flow.

The particle classification performance, as a function of aerodynamic diameter, was calculated using the following equation:

$$\text{Collection Efficiency} = \frac{C_m Q_m}{C_m Q_m + C_M Q_M} \times 100\% \tag{1}$$

where C_m and C_M are the particle number concentrations in the minor and major flows, respectively, and Q_m and Q_M are the minor and major flows, respectively.

The internal particle losses were also determined for each particle size by comparing the sum of the number concentrations measured in the major and minor flows to those measured in the duct, as follows:

$$\text{Particle losses} = \left[1 - \frac{C_m Q_m + C_M Q_M}{C_o Q_o}\right] \times 100\% \qquad (2)$$

where C_o is the particle number concentration in the duct, upstream of the virtual impactor, and Q_0 is the total flow ($Q_m + Q_M$).

Combined Virtual Impaction Stages The overall particle concentration factor of the two combined stages was defined as the ratio of the particle number concentration measured in the minor flow of stage II to that in the duct flow upstream of stage I.

The particle classification performance of the combined stages, as a function of the aerodynamic diameter, was calculated using the following equation:

$$\text{Collection Efficiency} = \frac{C_{m2} Q_{m2}}{C_{m2} Q_{m2} + C_{M1} Q_{M1} + C_{M2} Q_{M2}} \times 100\% \qquad (3)$$

where C_{m2} and C_{M2} are the particle number concentrations in the minor and major flows of stage II, respectively, and C_{M1} is the particle number concentration in the major flow of stage I.

The sharpness (s) of the collection efficiency curve was calculated using the following equation:

$$s = \sqrt{\frac{d_{84}}{d_{16}}} \qquad (4)$$

where d_{84} and d_{16} are the sizes of particles having collection efficiencies of 84% and 16%, respectively (Hinds, 1999).

The internal particle losses of the combined stages were also determined for each particle size by comparing the sum of the number concentrations measured in the major and minor flows to those measured in the duct, as follows:

$$\text{Particle losses} = \left[1 - \frac{C_{m2} Q_{m2} + C_{M1} Q_{M1} + C_{M2} Q_{M2}}{C_o Q_o}\right] \times 100\% \qquad (5)$$

where C_o is the particle number concentration in the duct.

RESULTS AND DISCUSSION

Performance Evaluation of Individual Virtual Impactors

Table 1 summarizes the operational parameters for which the two individual virtual impaction stages were tested. Figures 5 and 6 illustrate the relation between the critical performance parameters (cutpoint, collection efficiency, particle losses, and the concentration factor [CF]), as a function of the operational parameters (minor to total flow ratio [*r*] and Re). As shown in Table 1, cutpoints between 0.9 and 2.5 μm can be obtained by varying the operational conditions of the virtual impactors (minor to total flow ratio *r*, and acceleration nozzle Re number). Pressure drops in both major and minor flows were adequately low, as is recommended for inhalation studies.

Both stages I and II were found to perform similarly as expected, since they have the same design characteristics (acceleration and collection nozzle types). Figure 5 illustrates the concentration (enrichment) factor (CF) as a function of particle aerodynamic diameter for each virtual impactor stage, for three Re values (high, medium, low). For each Re value, the CF value increases sharply at sizes close to the cutpoint and remains relatively constant once it reaches its plateau value. Also, the concentration factor de-

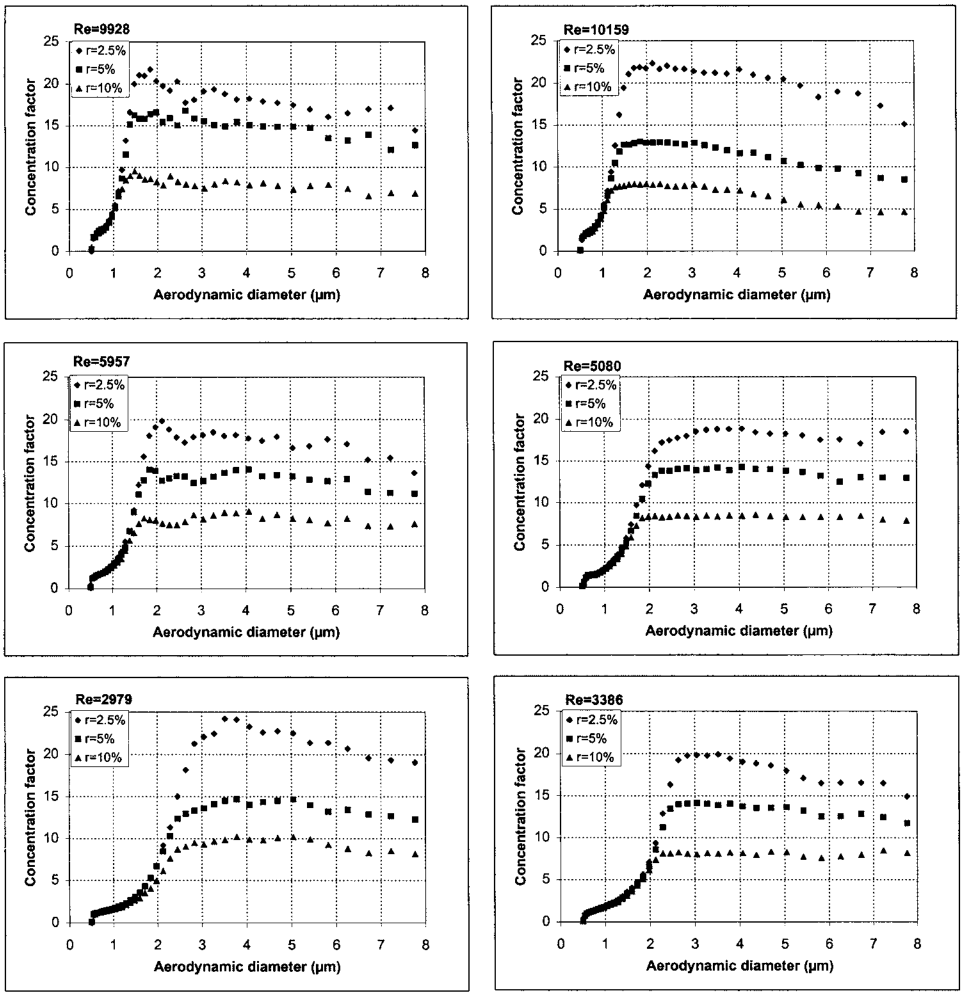
TABLE 1. Operational parameters for virtual impactors

		Pressure drop			
Length of acceleration slit[c] (cm)	Reynolds number	Minor flow (Pa)	Major flow (Pa)	r^a (%)	$d_{50}{}^b$ (m)
Stage I					
(inlet flow = 5000 LPM)					
111.8	9928	149.4	4483.8	10	0.9
111.8	9928	87.2	4608.4	5	1.1
111.8	9928	49.8	4732.9	2.5	1.4
186.3	5957	112.1	1619.2	10	1.2
186.3	5957	62.3	1793.5	5	1.5
186.3	5957	24 9	1868.3	2.5	1.8
372.5	2979	74.7	498.2	10	2.0
372.5	2979	5.0	498.2	5	2.1
372.5	2979	5.0	523.1	2.5	2.5
Stage II					
(inlet flow = 500 LPM)					
10.9	10159	74.7	4359.3	10	0.9
10.9	10159	49.8	4483.8	5	1.0
10.9	10159	24.9	4608.4	2.5	1.3
21.8	5080	62.3	1245.5	10	1.4
21.8	5080	24.9	1370.1	5	1.6
21.8	5080	12.5	1494.6	2.5	1.8
32.8	3386	24.9	523.1	10	1.7
32.8	3386	5.0	548.0	5	2.0
32 8	3386	5.0	597.8	2.5	2.3

[a]Ratio of minor to total flow.

[b]Particle size corresponding to a 50% collection efficiency.

[c]Length of acceleration slit can be changed by blocking a number of the acceleration and collection slits.



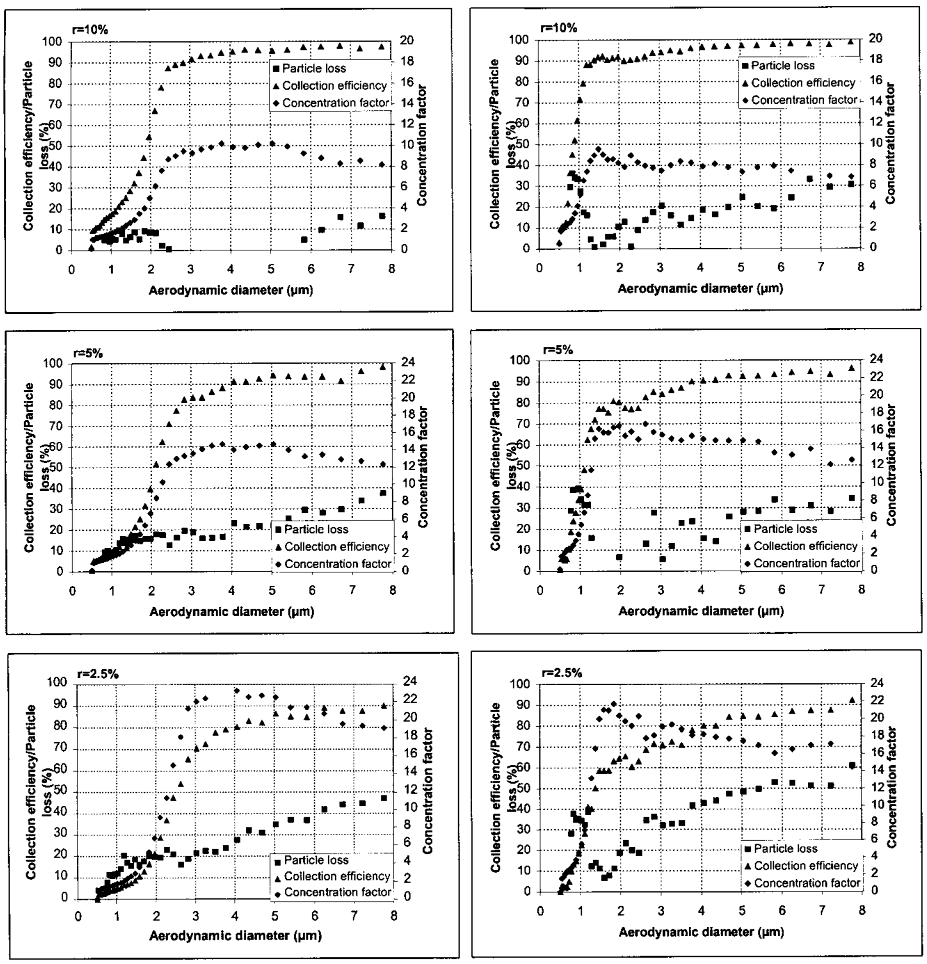
(a) STAGE I (b) STAGE II

FIGURE 5. Concentration factor (CF) as a function of aerodynamic diameter for high, medium, and low Reynolds numbers (Re) for each virtual impactor under different minor to total flow ratios (*r*).

creases with increasing *r*, while the cutpoint increases as *r* decreases. All these findings are consistent with previously reported results from theoretical and experimental studies on virtual impactors (Marple & Chien, 1980; Loo & Cork, 1988; Ding et al., 2001; Demokritou et al., 2002e).

Figure 5 also illustrates that the actual concentration factor (CF) ranges from 8 to 23 depending on the minor to total flow ratio (*r*). According to virtual impaction theory, the maximum CF value (nominal) is based on the minor to total flow ratio (r). For *r* values of 10, 5, and 2.5%, the nominal CF values are 10, 20, and 40 respectively. The observation that the actual CF for this system is very close to its nominal value is consistent with the observed minimal particle losses.

From Figure 6 (stage I), it is also clear that at a low Re (3000) the cutpoint is approximately 2.0 μm for r = 10% while for the same ratio r, the cutpoint is reduced to approximately 1.0 μm for a high Re value of 10,000. Particle losses as a function of aerodynamic diameter are also shown in Figure 6 for high (10,000) and low (3000) Re values, with r values of 10, 5, and 2.5. In general, particle losses increased with Re values, due to higher turbulence. Also, losses were higher at smaller r ratios for the same reasons that outlined earlier. Similar performance was observed for stage II.



(a) Re=2979 **(b) Re=9928**

FIGURE 6. Collection efficiency, particle losses, and concentration factor (CF) as a function of aerodynamic diameter under different minor to total flow ratios (r).

Overall Performance Evaluation of the Two-Stage Virtual Impactor System

As mentioned earlier, for inhalation studies it is usually desirable to have concentration factors (CFs) higher than 20 as well as an output flow of at least 50 LPM. A single-stage virtual impactor system similar to that characterized earlier would not be adequate to achieve such high CF values. To achieve the desired results, two virtual impactor stages were connected in series. System performance was evaluated by varying flow rates, minor to total flow ratios (*r*), for concentrating both $PM_{2.5-10}$ (coarse particles) and also for PM_{1-10}, as described in detail next.

HUCAPS as a $PM_{2.5-10}$ Particle Concentrator

These experiments focused on the system's ability to concentrate particles with an aerodynamic diameter between 2.5 and 10 μm (coarse mode: $PM_{2.5-10}$). Two minor to total flow ratios (*r*), 5 and 10%, were selected for the 2 virtual impactors, in order to achieve a lower and higher output flow rate and also a range of concentration enrichment factors.

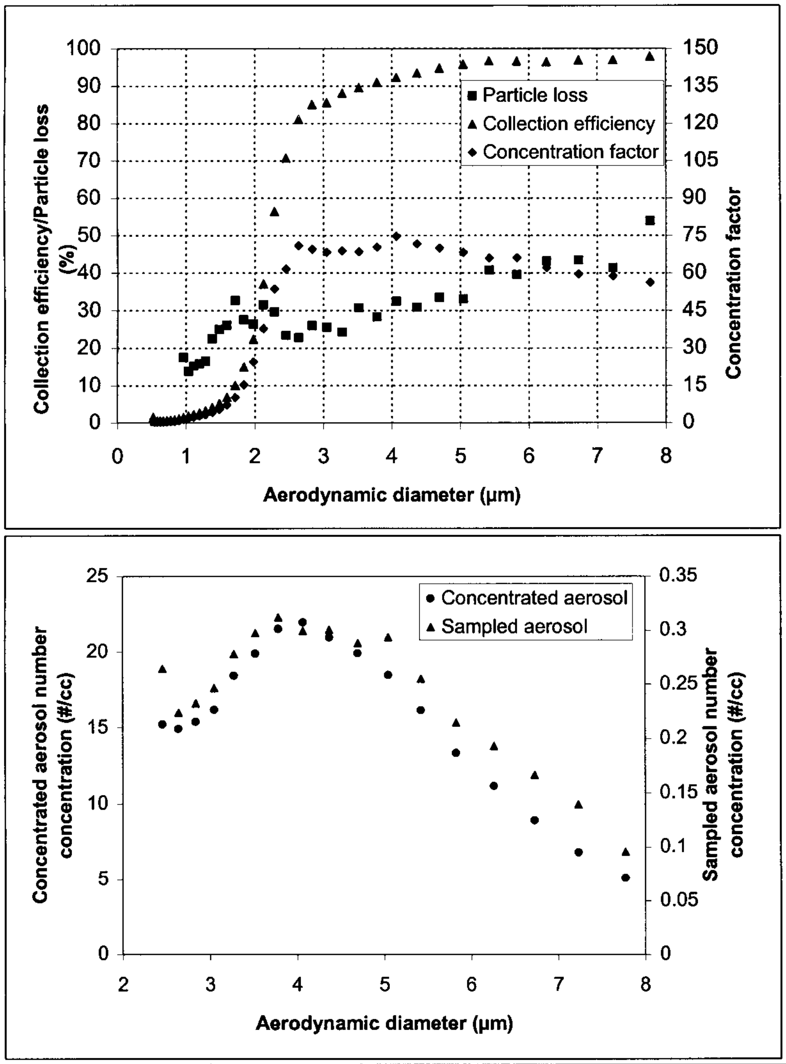
Table 2 summarizes the operational parameters of the HUCAPS. Overall pressure drop in the minor flow of the stage II virtual impactor is very low (only 104 Pa). With such a low-pressure drop, there are likely to be negligible volatilization losses of labile species such as ammonium nitrate and semi-volatile organic compounds. The cutpoint ranges from 2.2 to 2.5 μm. The average concentration factor (CF) for particles with an aerodynamic diameter between 2.5 and 10 μm (coarse particles) ranges from 70 to 150, depending on the total to minor flow ratio *r*. Total exposure chamber airflow (minor flow of stage II) can also be varied from 12.5 to 50 LPM, depending on the minor to total flow ratio.

Figure 7 shows the overall performance of the system as a function of aerodynamic diameter, including collection efficiency, concentration factor, and particle losses, with both stages operating at a minor to total flow ratio

TABLE 2. Operational parameters of HUCAPS for 2.5–10 μm particle mode (system inlet flow = 5000 LPM)

Virtual impactor stage I				Virtual impactor stage II				System pressure drop[d] (Pa)	CF_{avg}[e]	d_{50}[f] (μm)
Q_M[a] (LPM)	Q_m[b] (LPM)	Re	*r*[c] (%)	Q_M (LPM)	Q_m (LPM)	Re	*r* (%)			
4500	500	2979	10	450	50	3048	10	99.64	68	2.2
4500	500	2979	10	475	25	3048	5	80.2	137	2.5
4750	250	9928	5	237.5	12.5	2540	5	104.1	150	2.5

[a]Virtual impactor major flow.
[b]Virtual impactor minor flow.
[c]Ratio of minor to total flow.
[d]Pressure drop measured at the exit (minor flow) of virtual impactor stage II.
[e]Average concentration factor for 2.5–10 μm aerodynamic particle size range.
[f]Particle size corresponding to a 50% collection efficiency.



Aerodynamic diameter (µm)	Sampled aerosol	Concentrated aerosol
Mean	3.68	3.69
Median	3.50	3.54
Modal	3.79	4.07
Total concentration (#/cm^3)	3	203
Concentration factor = 68		

Stage I: r = 10%, Re = 2979; Stage II: r = 10%, Re = 3048

FIGURE 7. Performance of HUCAPS as a concentrator for particles with aerodynamic diameter between 2.5 and 10 µm.

r = 10%. The cutpoint of the system (d_{50}) is 2.2 μm. CF reaches its plateau value of 70 for particles larger than 2.7 μm. Sharpness of the collection efficiency curve, s, was found [using Eq. (4)] to be 1.16, which indicates excellent size classification performance of the system for the coarse particle mode. Mean, median, and modal diameters of sampled and concentrated aerosols were in good agreement (Figure 7). This indicates that there is negligible distortion of the size distribution between sampled and concentrated aerosol, as required for inhalation toxicological studies, and that all coarse particle sizes are concentrated by nearly the same factor.

HUCAPS System as a PM_{1-10} Particle Concentrator

Table 3 summarizes the operational parameters for this scenario for PM_{1-10}. The overall cutpoint of the system (d_{50}) was found to be 1.0 μm. The pressure drop in the minor flow of stage II (exposure chamber pressure drop) was found to be low (only 224 Pa). The average concentration factor (CF) for particles with an aerodynamic diameter between 1 and 10 μm (PM_{1-10}) was approximately 60.

Figure 8 shows the collection efficiency, particle losses, and concentration factor as a function of the aerodynamic diameter. CF reaches its plateau value of 65 for particles larger than 1.5 μm and remains reasonably constant for larger particle sizes. The sharpness of the collection efficiency curve was found to be 1.35, which indicates good size classification. Average particle losses were also found not to exceed 25%. Furthermore, mean, median, and modal diameters of the sampled and concentrated aerosol (minor flow of stage II) were in good agreement, indicating that there is negligible distortion of the size distribution of the concentrated aerosol.

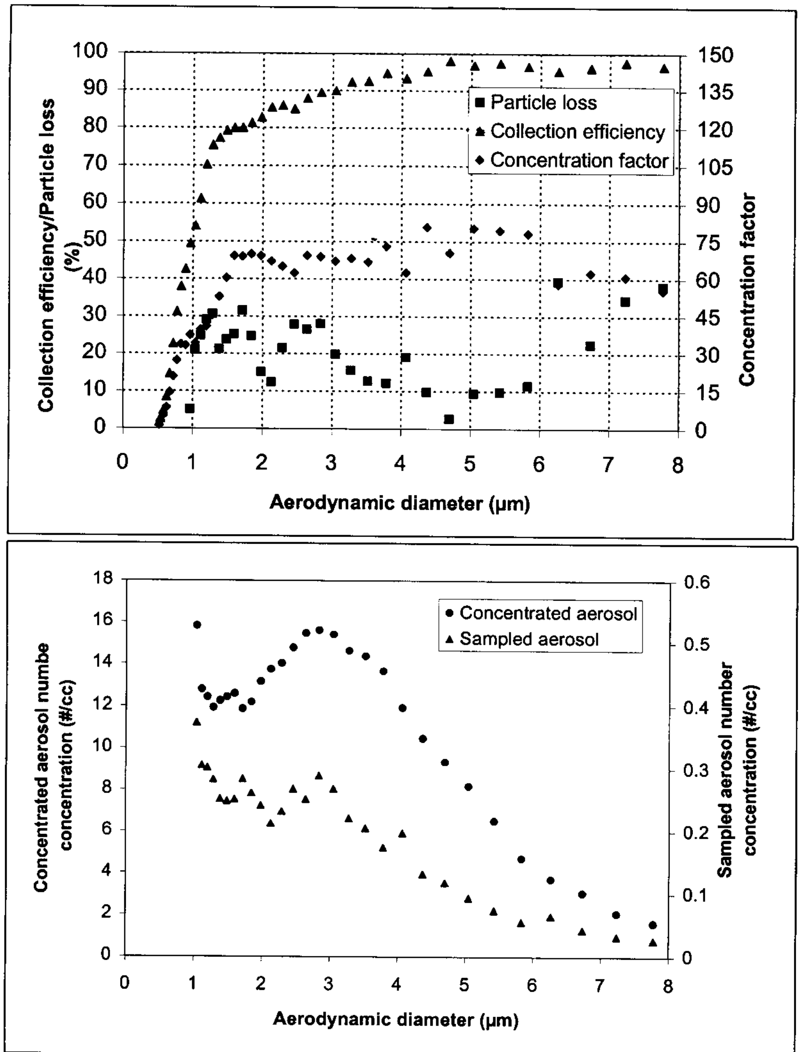
CONCLUSIONS

A two-stage, high-volume, concentrated ambient particle system (CAPS) was developed and characterized through laboratory experiments.

TABLE 3. Operational parameters of HUCAPS for 1–10 μm particle mode (system inlet flow = 5000 LPM)

Virtual impactor stage I				Virtual impactor stage II				System pressure drop[d] (Pa)	CF_{avg}[e]	d_{50}[f] (μm)
Q_M[a] (LPM)	Q_m[b] (LPM)	Re	r[c] (%)	Q_M (LPM)	Q_m (LPM)	Re	r (%)			
4500	500	9928	10	450	50	3386	10	224.2	57	1.0

[a]Virtual impactor major flow.
[b]Virtual impactor minor flow.
[c]Ratio of minor to total flow.
[d]Press drop measured at the exit (minor flow) of virtual impactor stage II.
[e]Average concentration factor for 1–10 μm aerodynamic particle size range.
[f]Particle size corresponding to a 50% collection efficiency.



Aerodynamic diameter (μm)	Sampled aerosol	Concentrated aerosol
Mean	2.28	2.50
Median	1.94	2.21
Modal	1.04	1.04
Total concentration (#/cm^3)	6	324
Concentration factor = 57		

Stage I: r = 10%, Re = 9928; Stage II: r = 10%, Re = 3386

FIGURE 8. Performance of HUCAPS as a concentrator for particles with aerodynamic diameter between 1 and 10 μm.

The performance of the CAPS system, as well as its two individual virtual impactors was investigated as a function of several parameters, including minor-to-total flow ratios and Reynolds numbers. During these tests, performance parameters such as concentration enrichment factor (CF), particle losses, collection efficiency curves, cutpoint, and pressure drop were measured.

The optimal operational configuration of the system was investigated for concentrating ambient particles in two primary size ranges, $PM_{2.5-10}$ and PM_{1-10}. Particles in the size range between 2.5 and 10 μm were concentrated by a factor of 70 to 150 times (for minor-to-total flow ratios of 10 and 5, respectively). The corresponding flow rates of the concentrated aerosol were 50 and 12.5 LPM. Other features of the system include low pressure drop in the major and minor flows, relatively low particle losses, and a compact design. Performance evaluation of this system also confirmed that separation and concentration of the $PM_{2.5-10}$ particles occurred without any significant distortion of their size distribution. Excellent separation and concentration performance was also confirmed for the PM_{1-10} operational mode. For this mode, concentration was increased by a factor of 60 without any significant distortion of its size distribution.

This versatile and highly efficient system will enable us to expose human and animal subjects to concentrated ambient particles to investigate health effects and toxicological implications. Separate experiments to evaluate the use and performance of the system using ambient aerosols will be performed in the near future, with results to be presented in a subsequent publication.

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