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Development and Evaluation of a Compact, Highly Efficient Coarse Particle Concentrator for Toxicological Studies

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A high-efficiency coarse-mode particle concentrator (CPC) has been developed and evaluated in the laboratory as well as validated in the field experiments at the University of Southern California, in Los Angeles, CA, and in Bilthoven, the Netherlands. The CPC operates with a total intake flow of 1000 LPM. The minor flow rate, containing the concentrated coarse-mode particles (2.5–10 μm), can be adjusted from 33 to 120 LPM in order to enrich ambient coarse PM concentrations by a factor of 8–30, depending on the desirable exposure level and flow rate needed. The laboratory evaluation of the virtual impactors at 3 minor flow rates (3.3, 7, and 10 LPM, respectively) indicated that extremely efficient concentration enrichment was obtained for 2.5–10 μm particles. In the field tests, the CPC operated at a minor flow rate of 33 LPM and the mass obtained was compared to the mass collected by a reference sampler, a (rotating) micro-orifice uniform deposit impactor (MOUDI), which sampled at 30 LPM. Concentration enrichment factors in the range of 26 to 30 were achieved based on particle mass, sulfate, and nitrate as well as selected trace element and metal concentrations (Al, Si, Ca, Fe, K, Mn, Cu, Zn, Ti). CPC and MOUDI concentrations were highly correlated for all species, with R^2 in the range of 0.74 to 0.89. The use of round (compared to rectangular geometry) nozzle virtual impactors in the CPC results in a high concentration efficiency, which reduces the CPC size as well as the power requirement that is required for its operation. The compact size of the CPC makes it readily transportable to desired locations for exposure to coarse-mode particles derived from different sources and thus of a varying chemical composition.

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INTRODUCTION

Abundant epidemiological literature has indicated a significant relationship between ambient particulate matter (PM) and important clinical endpoints such as respiratory symptoms (including asthma attacks), respiratory-related clinic/emergency room encounters and hospitalization, as well as cardiovascular morbidity and mortality (Dockery et al. 1989; Pope et al. 1991; Koenig et al. 1993). An average 10 μg/m^3 increase in PM_{10} is typically associated with a 1–10% increase in respiratory symptoms at PM_{10} levels near or even below 150 μg/m^3 and with lung function declines of as much as 7% during 24 h PM_{10} concentrations exceeding 150 μg/m^3 (Ostro 1993; Pope et al. 1991). Despite the growing evidence of particulate-related health effects, the paucity of information about specific biological mechanisms remains a critical missing link.

Although a few studies using artificial multicomponent fine particle aerosols (Amdur and Chen 1989; Anderson et al. 1992; Kleinman et al. 1995; Bolarin et al. 1997; Arts et al. 2000) have demonstrated mild effects in animals, they have not consistently provided support for a causal relationship between serious health effects in humans and realistic exposure levels. This discordance between the outcomes of laboratory and epidemiological studies may indicate that such artificial particles do not truly replicate the adverse effects of the complex and heterogeneous mixtures that occur in ambient air.

The recent development of fine particle concentrators based on the principle of virtual impaction (Sioutas et al. 1995a,b, 1997) or centrifugation (Gordon et al. 1999) has made it possible to perform laboratory exposures with "real-life" ambient aerosols at highly increased, yet still environmentally realistic, particle concentrations. Some preliminary results using these

technologies have been reported (Godleski et al. 1996; Clarke et al. 1999; Gavett et al. 1999; Ghio and Devlin 1999; Urch et al. 1999) suggesting physiological toxic responses to concentrated ambient particle exposures in laboratory animals and subtle responses in human volunteers. This new line of investigation will hopefully eventually lead to coherence between laboratory studies and epidemiological evidence.

The aforementioned particle concentrator technologies primarily concentrate on the accumulation mode (i.e., 0.2–2.5 μm) of atmospheric aerosols. Coarse PM may also consist of several potentially toxic components, such as resuspended PM from paved and unpaved roads, industrial materials, brake linings, tire residues, trace metals, and bioaerosols. A considerable fraction of these particles may deposit in the upper airways, and to a lesser extent in the lower airways, and may be responsible for the exacerbation of asthma. Recent data from a small number of epidemiological studies indicate that apart from—or in addition to—the fine PM fraction, health effects may also be closely associated with the coarse PM fraction and sometimes even to a larger extent (Ostro et al. 1999; Kleinman et al. 2000) than $PM_{2.5}$. In vitro studies with human monocytes (Monn and Becker 1998; Becker et al. 1996) show that cellular toxicity and inflammation may also be associated with the coarse fraction (2.5–10 μm) and its biological components. Also, in vitro data from Hornberg et al. (1998a,b) on genotoxicity of ambient fine and coarse mode PM collected from an urban area characterized by a high traffic density suggests that coarse mode PM may have comparable or even higher activity. Collectively, these studies indicated that the coarse mode PM might still contribute to a certain extent to observed health effects, especially those occurring in the higher airways like asthma.

To investigate real-world ambient coarse mode particles in experimental studies, the research presented here describes the development of a high concentration efficiency coarse particle concentrator (CPC), extended from a previously developed single-nozzle, portable coarse particle concentrator (Kim et al. 2000). The scaled-up CPC maintains the advantage of portability and compact size (80 cm × 75 cm × 45 cm) while increasing coarse particle concentrations by a factor of up to 40, and they can be readily used for human and/or animal exposure studies. Detailed comparisons between concentrated and ambient coarse aerosols based on mass, sulfate, nitrate, and selected trace elements and metals were performed. The flexibility of varying the minor-to-total flow ratio of the CPC allows for alternating the desired exposure concentration level for animal exposures as well as for higher output flow rates needed when conducting human exposures.

EXPERIMENTAL METHODS

The CPC consists of 10 single-nozzle virtual impactors (Figure 1) developed by the department of Civil Engineering of the University of Southern California. These single-nozzle virtual impactors are placed in a 2 × 5 array (Figures 2a and b).

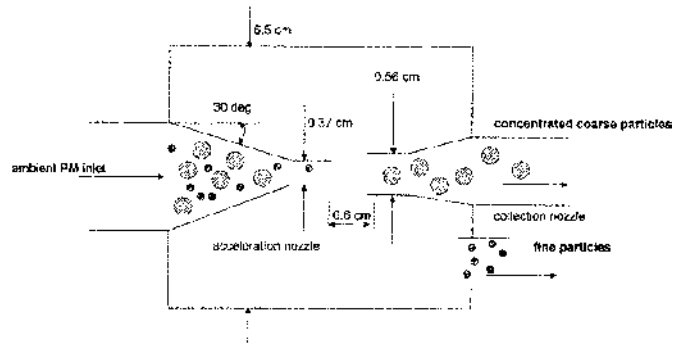


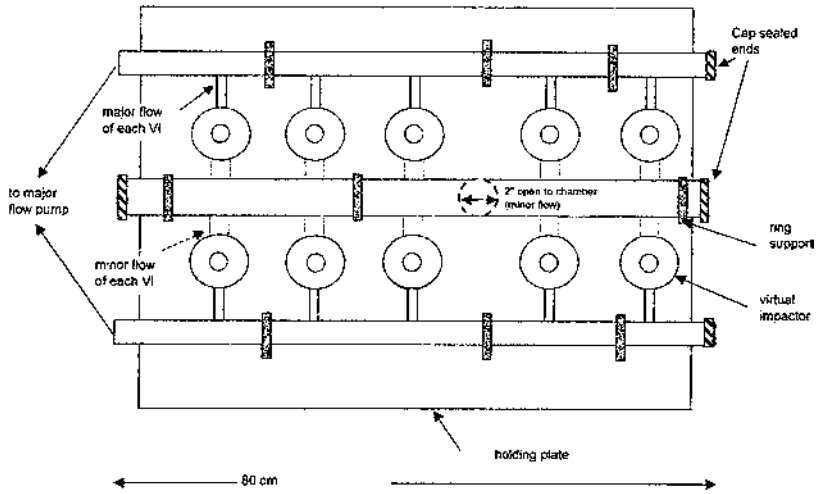
Figure 1. Schematic of the round jet impactors of the multinozzle CPC.

A 90° elbow with an inside diameter of 1.8 cm is connected to the inlet of each virtual impactor. Each virtual impactor operated at an intake flow rate of 100 LPM and therefore comprised a total intake flow rate of 1,000 LPM. The dimensions of the 90° elbow inlet were chosen to yield a theoretical 50% removal efficiency of 10 μm particles (PM_{10}) at a flow rate of 100 LPM based on the well-established impaction theory (Marple and Liu 1974). The 50% cutpoint can be estimated from the Stokes number, St, defined as (Hinds 1982)

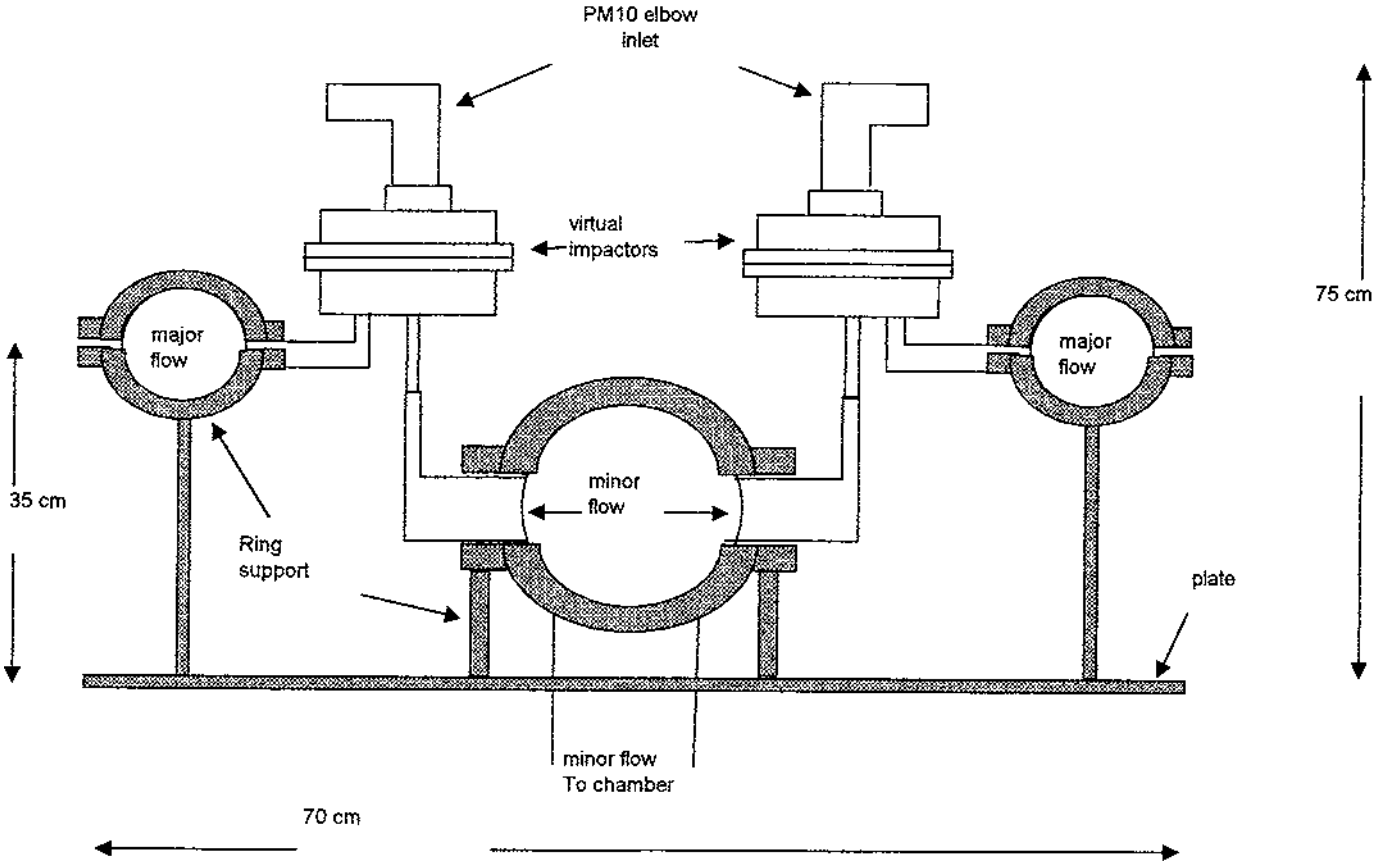
$$\mathrm{St} = \frac{\rho_p U_i d_p^2 C_c}{9\mu\, d_o}, \qquad [1]$$

where d_p, ρ_p, and C_c are the particle diameter, density, and slip correction, μ is the air viscosity (1.81×10^{-4} g/cm · s), U_i is the velocity through the 90° elbow, and d_o is the inside diameter of the elbow ($d_o = 1.8$ cm). The St corresponding to 10 μm particles is 0.24, based on the nozzle dimensions and the flow rate through each nozzle, which is close to the value typically corresponding to the 50% cutpoint of round-nozzle impactors (Marple and Liu 1974).

Particles smaller than 10 μm in aerodynamic diameter are drawn through the virtual impactor and become accelerated through a circular nozzle, which was designed to have a theoretical 50% cutpoint at about 2.0 μm for an intake flow rate of 100 LPM (Sioutas et al. 1999; Kim et al. 2000). Coarse-mode particles (2.5–10 μm) cross the deflected air streamlines and are drawn through the collection nozzle (minor flow). Particles smaller than the cutpoint of the virtual impactor are diverted through the major flow. The 10 minor flows are joined at the center of the CPC and lead to a 5 cm diameter tube, which can be connected to an animal or human exposure chamber (Figures 2a and b). The minor flow rate can vary from 3∼20% of the intake flow rate, depending on the desired exposure concentration level and/or exposure flow rate needed. Two major flow ducts, each 2.54 cm in diameter, were each connected to 5 of the virtual impactor major flows (i.e., 500 LPM) and placed on either side of the minor flow, as shown in Figures 2a and b.



(a)



(b)

Figure 2. (a) Top view of the coarse concentrator; (b) Side view of the 10 nozzle CPC.

Laboratory Characterization of the Virtual Impactors

The first series of experiments was conducted in the laboratory to investigate the relationship between the concentration enrichment as a function of particle size and minor-to-total flow ratio. This relationship was investigated for each individual virtual impactor. Briefly, monodisperse aerosols in the size range of 1 to 10 μm were generated by atomizing dilute aqueous suspensions of fluorescent polystyrene latex particles (Polysciences Inc., Warrington, PA) with a constant output nebulizer (HEART, VORTRAN Medical Technology, Inc., Sacramento, CA) at a rate

of 15 LPM. The generated particles were drawn through a 1 l bottle to remove the excess moisture and subsequently mixed with dry room air. The dry aerosol was then drawn through a tube containing 10 Po-210 neutralizers that reduce particle charges prior to entering the virtual impactor. Monodisperse particles were subsequently drawn through the 90° elbow and entered the virtual impactor. For particles in the range of 1 to 5 μm, a nephelometer (DataRAM, RAM-1, MIE, Inc., Billerica, MA) was used to first measure the mass concentration of the generated aerosols prior to entering the 90° elbow of virtual impactors. The DataRAM was subsequently connected downstream of the minor flow of the virtual impactor to measure the mass concentration of the aerosols after concentration enrichment. The measurements were repeated at least 3 times, and the average concentration enrichment was determined as a function of particle size. The contributions from background ambient concentrations before and after the enrichment were recorded and subtracted from those of the input and concentrated aerosols prior to determining the collection efficiencies at the given particle size. It should be noted that indoor air levels were on the order of 7–15 $\mu g/m^3$ and were substantially smaller than those of the generated aerosols (prior to concentration), which varied from 170 to about 500 $\mu g/m^3$. Therefore the contributions of the indoor aerosol to the overall concentrations measured upstream of and in the minor flows of the virtual impactors were considered insignificant.

Concentration enrichment for 5–9 μm particles was determined by comparing the mass collected on a glass fiber filter (2 μm pore, Gelman Science, Ann Arbor, MI) connected to the minor flow of a virtual impactor and the mass of a similar glass fiber filter in parallel to the test system to measure the concentration of the generated aerosol. The filter sampling in parallel was connected to a pump operating at 30 LPM. At the end of each run, each glass fiber filter was placed in 5 ml of ethyl acetate to extract the fluorescent dye from the collected particles. The quantities of the fluorescent dye in the extraction solutions were measured by a fluorescence detector (FD-500, GTI, Concord, MA) to determine particle concentration. Concentration enrichment for each particle size was defined as the ratio of the concentration measured in the minor flow of the virtual impactor to that of the aerosol immediately upstream of the virtual impactor inlet.

Each virtual impactor was tested at 3 different minor-to-total flow ratios. The total flow was kept constant at 100 LPM, whereas the minor flows were adjusted to 3.3, 7, and 10 LPM, resulting in ideal enrichment factors of 30, 15, and 10, respectively.

Field Evaluation of the Scaled up Coarse Particle Concentrator

Following laboratory characterization, the CPC was evaluated in collocation with a modified micro-orifice uniform deposit impactor (MOUDI, MSP Corporation, Minneapolis, MN) at 2 locations: University of Southern California, in downtown Los Angeles (13 samples in mid-August, 2000), and at the National Institute of Public Health and the Environment (RIVM, Bilthoven, the Netherlands, 6 samples in late September, 2000). The ten 90° elbow CPC inlets were arranged at 360° to ensure isokinetic sampling. In the field tests, the CPC operated at a total flow rate of 1,000 LPM and with a minor flow rate adjusted to 33 LPM. The ideal enrichment factor corresponding to this minor-to-total flow ratio would be 30. Of the 33 LPM minor flow, 11 LPM were drawn into a 4.7 cm filter (2 μm, PTFE, Gelman, Ann Arbor, MI) through an isokinetic sampling probe inserted in the 5 cm tube leading to the exposure chamber, while the remaining 22 LPM were drawn by a separate pump. The reason for using only 11 LPM through the filter was to minimize potential coarse particle losses due to the flow contraction through the filter holder inlet. The pressure drops through the minor and major flows were about 2″ H_2O and 110″ H_2O, respectively. The MOUDI was sampled at 30 LPM and modified (from its original 8 stage configuration) to include only 3 stages, collecting size-segregated particles in the aerodynamic diameter ranges of 0 to 2.5, 2.5 to 10, and 10 to 18 μm, respectively. 4.7 cm PTFE filters were used as impaction substrates in coarse PM MOUDI stages. The CPC 90° elbows and MOUDI stage 10–18 μm were coated with a thin layer of silicone grease to reduce potential particle bounce. The sampling flow rates of the MOUDI and CPC minor flows were measured before and after the sampling with calibrated flow meters (Cole-Parmer, # EW-32458-64 and #EW-32458-58, Cole-Parmer Instrument Company, Vernon Hills, IL). Additionally during sampling, the CPC minor flow filter sampler and the major flow were monitored by means of inline rotameters.

Particle mass, sulfate, and nitrate concentrations as well as concentrations of trace elements and metals were determined for both ambient and concentrated aerosols. The sampling periods varied from 3 to 12 h depending on the observed PM level. To determine particle mass concentrations, the PTFE filters of the MOUDI and minor flow were preweighed and postweighed using a Microbalance (MT 5, Mettler-Toledo Inc., Highstown, NJ; Sartorius microbalance MC-5, Sartorius AG, Goettingen, Germany) in a room with a controlled temperature of 21–24°C and relative humidity of 40–50%. Filters were weighed twice in order to increase precision. In case of a difference of more than 3 μg between consecutive weighings, the filter was weighed a third time or reweighed until 2 consecutive weighings differed by <3 μg.

Thirteen out of nineteen pairs of PTFE filter samples collected by the CPC and MOUDI were then analyzed by means of x-ray fluorescence (XRF) to determine concentrations of selected elements and metals. These samples, as well as the remaining 6 pairs (corresponding to samples collected in the Netherlands), were subsequently extracted with 0.15 ml of ethanol and 5 ml of ultrapure water. Ethanol was used in order to wet the hydrophobic Teflon filter. The samples were sonicated for 15 min and analyzed for sulfate and nitrate ions by means of ion chromatography (IC). Samples that were lower than 3 times the lower limits of detection (LOD) of either XRF or IC were excluded. Using XRF prior to IC is a procedure that is typically not recommended

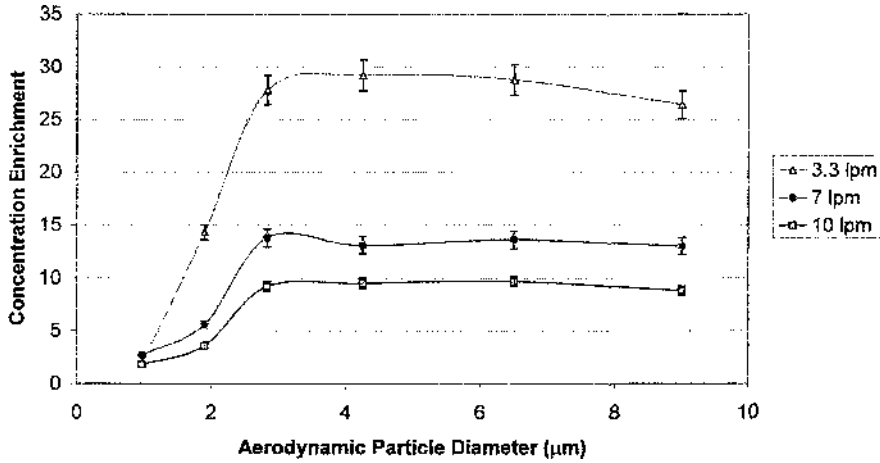


Figure 3. Concentration enrichment of each individual virtual impactor at 3 different minor flow rates. Total intake flow rate/impactor; 100 LPM.

for analysis of $PM_{2.5}$ because it might cause volatilization of ammonium nitrate. However, nitrate in the coarse mode in both the Netherlands (ten Brink et al. 1997) and Los Angeles (Solomon et al. 1988; Liu et al. 2000) is mostly associated with the nonvolatile sodium nitrate (Solomon et al. 1988; Liu et al. 2000), the concentrations of which are not expected to be altered by XRF.

RESULTS AND DISCUSSION

Laboratory Characterization of the Virtual Impactors

The results of the evaluation of the virtual impactors are shown in Figure 3. The concentration of generated monodisperse particles was in the range of 170 to 500 $\mu g/m^3$ and was enriched to 580–13,000 $\mu g/m^3$ and was thus several orders of magnitude higher than the lower LOD of the DataRAM (1–5 $\mu g/m^3$), while below the instrument's upper limit (40 mg/m^3). It should be noted here that mass concentrations obtained by the DataRAM are quite dependent upon particle size (Sioutas et al. 2000). Therefore particle concentrations measured by the DataRAM upstream and downstream of the virtual impactor were only used for determining the concentration enrichment of monodisperse particles, which is the ratio of the downstream to the upstream concentrations, and not for representing actual mass concentrations in the air stream.

Figure 3 shows the concentration enrichment for each individual virtual impactor at 3 minor flow rates as a function of aerodynamic particle diameter. The plotted data correspond to the averages of the 10 virtual impactors, whereas the error bars represent the standard deviation in the enrichment values between the 10 impactors. For a minor flow of 3.3 LPM, the concentration enrichment increases sharply from about 2 to about 28 as particle aerodynamic diameter increases from 1 to 2.5 μm. The enrichment is practically the same for particles in the aerodynamic diameter range of 2.5 to 9 μm. Similarly, for a minor flow of 7 LPM, the concentration enrichment increases sharply from 2.7 to approximately 13.5 as particle aerodynamic diameter increases from 1 to 2.5 μm. For particles having aerodynamic diameters in the range of 3 to 9 μm, the enrichment value is about 13–14 and practically independent of particle size. The same trends can also be observed for the 10 LPM minor flow configuration. The data shown in Figure 3 also indicate that the 50% cutpoint of the virtual impactor (defined as the aerodynamic particle size at which the enrichment factor is half of its ideal value) is approximately 2.0 μm and does not seem to depend significantly on the minor-to-total flow ratio. The slight decrease in concentration enrichment values (still higher than 85% of the ideal value) observed at 9 μm particles is probably due to some internal losses through the collection nozzle. The overall high concentration efficiencies of 9 μm particles, however, prove that there is no significant particle loss of these particles due to the 90° elbow. More importantly, these tests imply that the size distribution of enriched coarse particles in the CPC was the same as that of the ambient air, since the concentration enrichment does not depend on particle size—at least for particles larger than 2.5 μm in aerodynamic diameter.

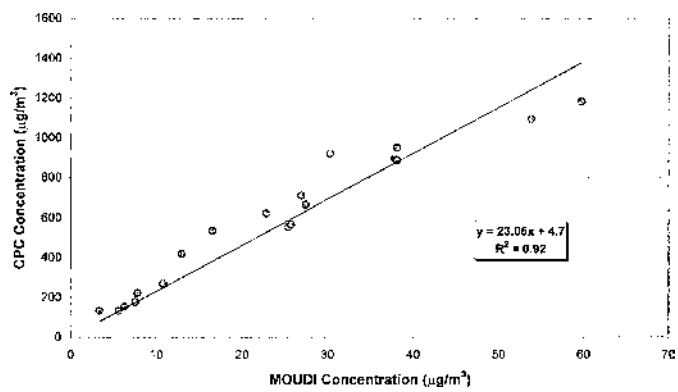


Figure 4. Comparisons between the CPC and MOUDI coarse PM mass concentrations.

Table 1
Comparisons between CPC and MOUDI based on mass, sulfate, and nitrate concentrations (in $\mu g/m^3$)

	Range of ambient concentration ($\mu g/m^3$)	Range of minor flow concentration ($\mu g/m^3$)	Mean EF[a] (±S.D.)	Coefficient of determination (R^2)
Mass concentration ($\mu g/m^3$)	3.4–59.7	131.9–1,181.2	25.9 ± 4.6	0.92
Sulfate concentration ($\mu g/m^3$)	0.32–2.04	9.60–65.24	30.0 ± 2.9	0.90
Nitrate concentration ($\mu g/m^3$)	1.1–15.4	29.4–325.8	25.9 ± 4.2	0.81

[a] Ideal enrichment factor (EF) determined by the flow ratio of total flow rate to minor flow rate, 1000 LPM to 33 LPM in this case.

The near-ideal concentration enrichment factors for particles larger than 2.5 μm in aerodynamic diameter clearly illustrate the impressive performance of round nozzle virtual impactors, which have been proven to be superior to those having acceleration and collection nozzles of rectangular geometry. Experimental flow visualization studies by Masuda and Nagasita (1988) and Gotoh and Masuda (2000), as well as modeling studies by Marple and Chien (1980), showed that end effects associated with rectangular geometry virtual impactors result in excessive particle losses and decrease in the sharpness of the particle collection efficiency curve. The previously mentioned studies also indicated that particle losses become particularly high as the minor-to-total flow ratio decreases. Our laboratory experiments indicate that even at a minor-to-total flow ratio of 3.3%, the collection efficiency of the virtual impactors of the CPC are high and internal losses are very low.

Field Evaluation Tests

Results of concentration comparisons based on mass, sulfate, nitrate, and selected trace elements and metals between the CPC and MOUDI are shown in Figures 4–8 and are summarized in Tables 1 and 2.

Figure 4 shows that ambient coarse PM concentrations ranged from 3 to 60 $\mu g/m^3$ and were enriched from roughly 132 to 1,200 $\mu g/m^3$. The average concentration enrichment factor obtained for the mass was 25.9 with a standard deviation of 4.6 (Table 1). CPC and MOUDI mass concentrations were also very highly correlated, with the coefficient of determination (R^2) based on linear regression being equal to 0.92. Given that the ideal enrichment factor for this minor-to-total flow rate configuration would be 30, these enrichment factor values indicate that the CPC operates with extraordinary collection efficiency (0.86 ± 0.15) and very few internal particle losses. Even though lower coarse particle mass concentrations (3.5–10 $\mu g/m^3$) were generally observed in the Netherlands during the field evaluation, there seems to be no significant difference between the actual enrichment factors obtained in Los Angeles and Bilthoven. This overall agreement is important, considering that these 2 locations have substantially different meteorological conditions (weather, temperature, and relative humidity) as well as aerosol sources, hence they are expected to have coarse PM with different chemical composition.

The results of comparing coarse particulate nitrate and sulfate concentrations collected by the CPC and MOUDI are shown in Figures 5–6 and Table 2. The average amounts of sulfate and nitrate in the coarse mode were 4.6% and 19.6% by mass, respectively. The average enrichment factor obtained for nitrate was 25.9 (±4.2) with R^2 of 0.81. Both enrichment and correlation coefficient values are very close to those based on mass concentrations. A slightly, but not statistically significant ($p = 0.29$), higher enrichment factor of 30.0 (±2.9) was observed when comparing sulfate concentrations between the CPC and MOUDI.

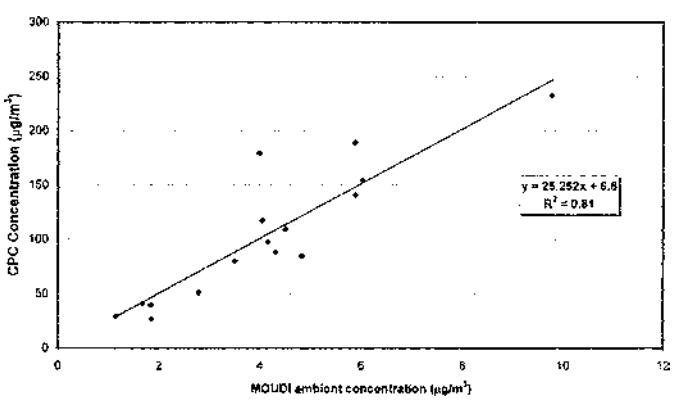


Figure 5. Comparisons of coarse PM nitrate concentrations between CPC and MOUDI.

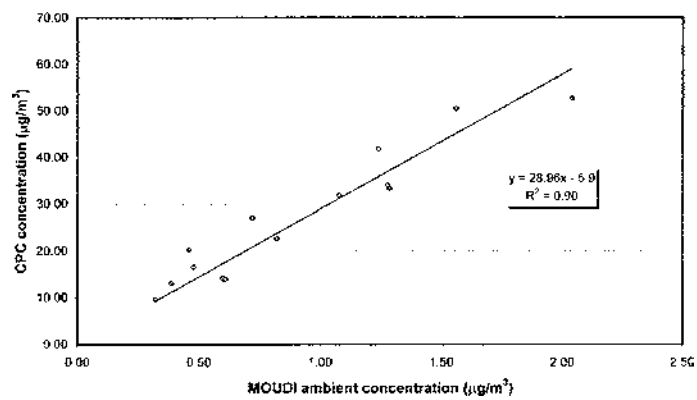


Figure 6. Comparisons of coarse PM sulfate concentrations between CPC and MOUDI.

The CPC and MOUDI comparison based on concentrations of trace elements and metals is shown in Figures 7a–j and summarized in Table 2. For each element, a total of 13 reliable CPC–MOUDI paired data were obtained. The following metals and elements were selected based on their relative high amounts in the coarse mode relative to the fine mode PM: Al, Si, Ca, K, S, Fe, Cu, Mn, Zn, and Ti. Results from our field tests indicated that the concentrations of Al, Si, and Ca, which originate from crustal material, contributed on average 2.0%, 5.4%, and 2.4% to the overall coarse PM mass, respectively (Table 2). Table 2 also shows that the average concentration enrichment factors of Al, Si, and Ca were 30.5 (±3.6), 28.8 (±4.4), and 28.9 (±5.2), respectively. Based on linear regression between the CPC and ambient metal concentrations, the coefficients of

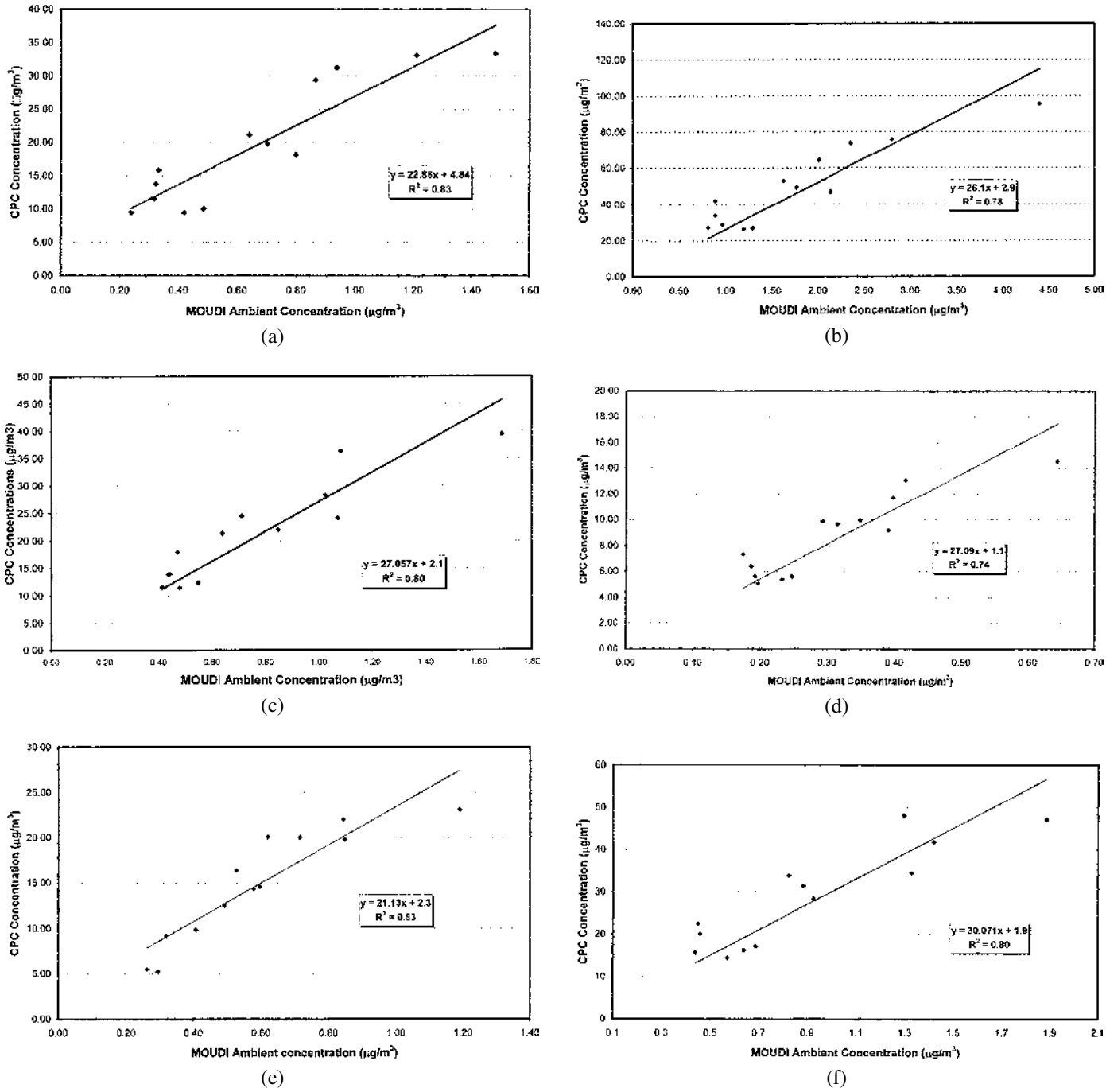


Figure 7. Comparisons of coarse PM concentrations between CPC and MOUDI for selected trace elements and metals: (a) Al, (b) Si, (c) Ca, (d) K, (e) S, (f) Fe, (g) Cu, (h) Mn, (i) Zn, (j) Ti. *(Continued)*

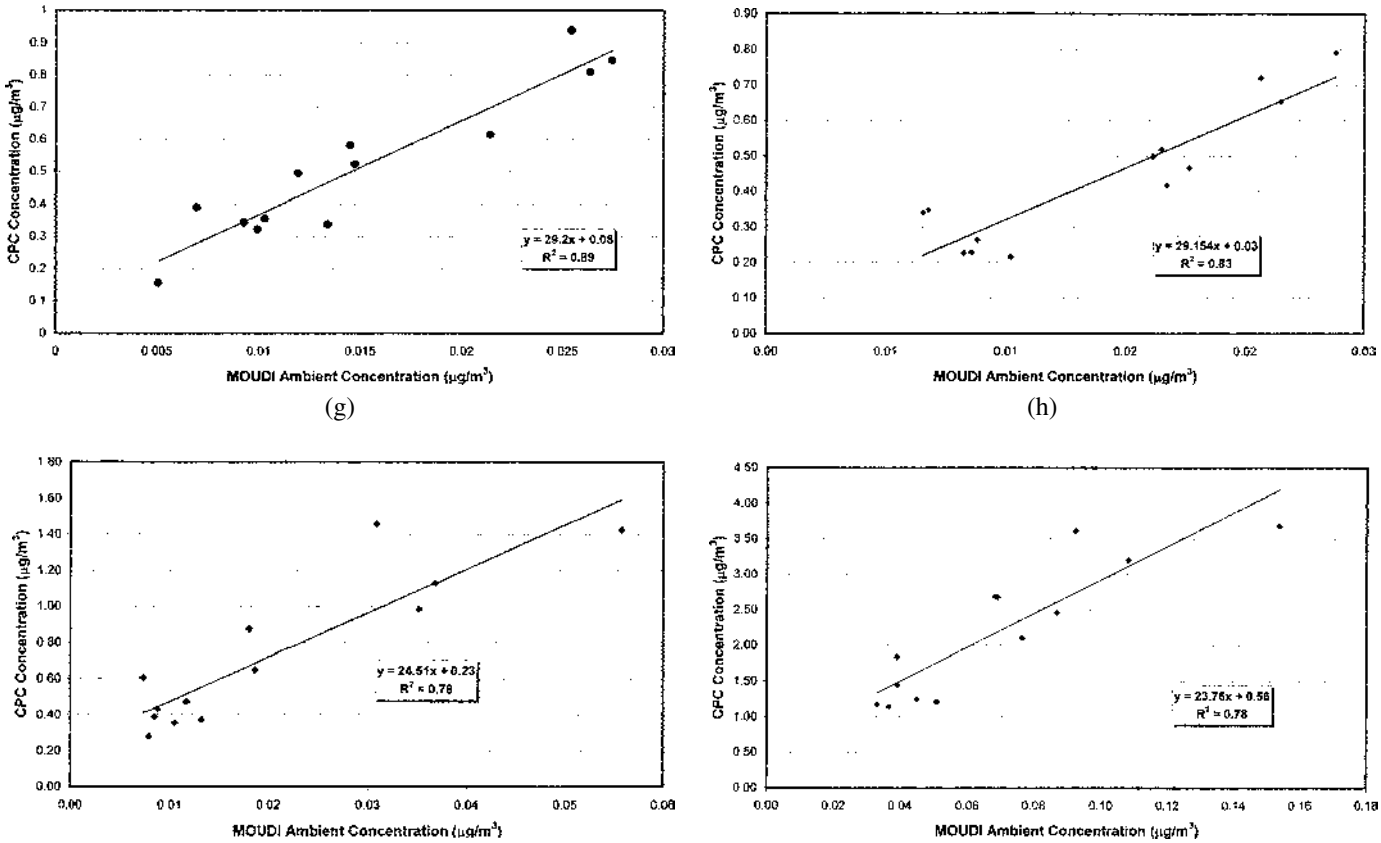


Figure 7. (Continued)

correlation (R^2) were 0.83, 0.78, and 0.80, respectively, as displayed in Figures 7a–c. The coarse mode particles also contained K, S, and Fe with mass percentages of 1.0%, 0.8%, and 2.8%, respectively. The enrichment factors for K, S, and Fe ranged from 24 to 32 (Table 2), with standard deviations between 3.3 and 5.6, and were thus similar to the results obtained for Al, Si, and Ca. Figures 7d–f show that CPC and MOUDI concentrations for K, S, and Fe were also highly correlated, with R^2 values of 0.74, 0.83, and 0.80, respectively. Slightly higher enrichment factors (30–33) were obtained for trace elements (Cu, Mn, Zn, and Ti), which may be in part due to some uncertainty generated by the very small (but detectable) amounts collected in the MOUDI samples. The total contributions of Cu, Mn, Zn, and Ti were <0.5% of the coarse mode mass. Nevertheless, the comparison of concentrations between the CPC and MOUDI of Cu, Mn, Zn, and Ti (shown in Figures 7g–j) indicates consistency with other species in terms of concentration enrichment.

Table 2
Ambient concentrations (μg/m^3) and EF^a for selected metal/elements based on 13 sets of comparisons between CPC and MOUDI

	Al	Si	Ca	K	S	Fe	Cu	Mn	Zn	Ti
Min. conc. (μg/m^3)	0.24	0.82	0.41	0.17	0.26	0.4	0.005	0.007	0.007	0.03
Max. conc. (μg/m^3)	1.48	4.4	1.69	0.64	1.19	1.9	0.027	0.024	0.056	0.15
Average mass fraction (%)	2.0	5.4	2.4	1.0	0.8	2.8	0.05	0.04	0.06	0.21
Mean EF	30.5	28.8	28.9	28.5	24.8	32.2	33.4	30.0	31.4	32.4
EF standard deviation	3.6	4.4	5.2	5.6	4.3	3.3	2.8	3.5	2.7	3.1
Slope of regression line	22.86	26.10	27.06	27.09	21.13	30.07	29.20	29.15	24.51	23.76

[a]Ideal EF determined by the flow ratio of total flow rate to minor flow rate, 1000 LPM to 33 LPM in this case.

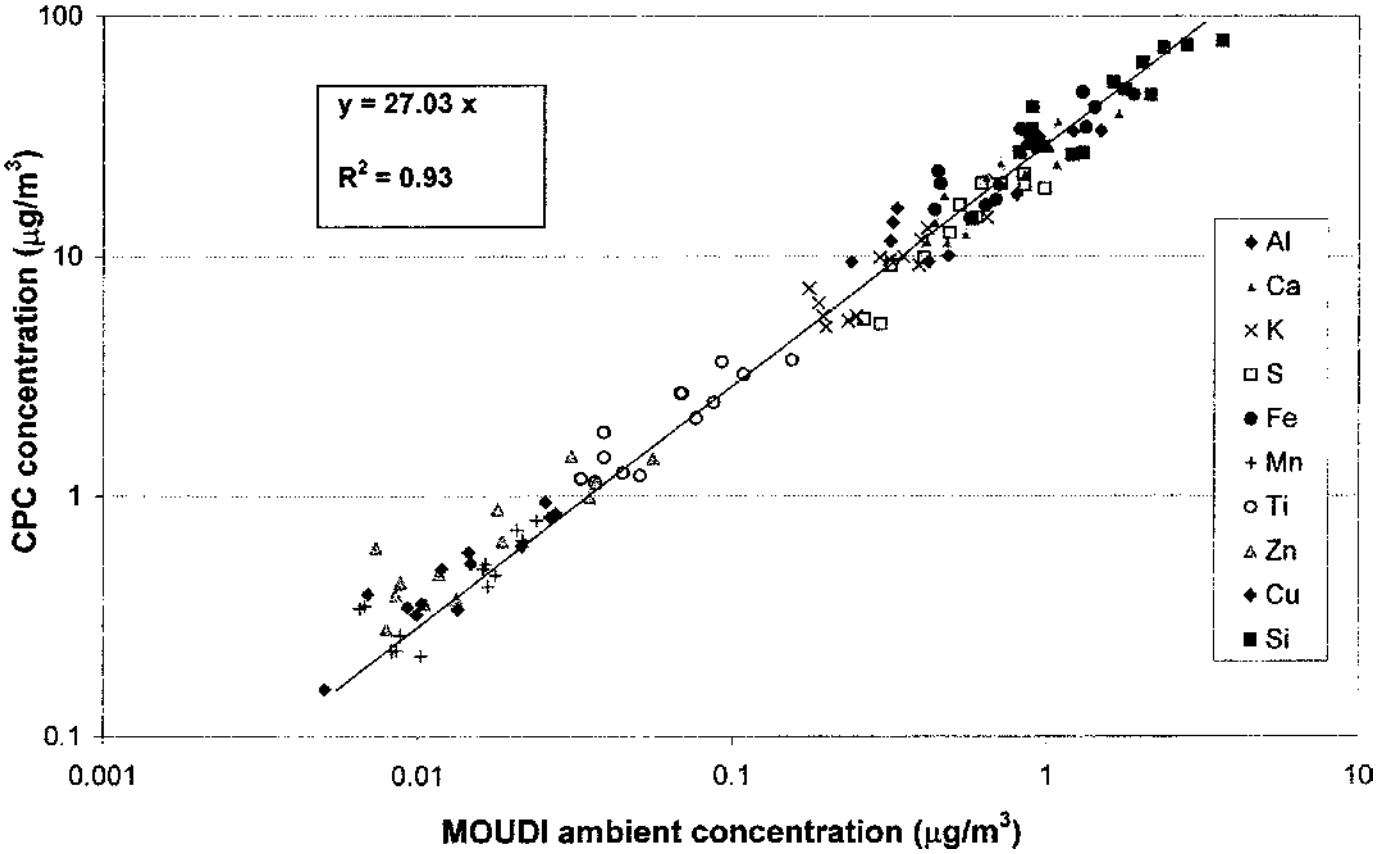


Figure 8. Comparison of multimetal/elemental concentrations between CPC and MOUDI based on coarse PM concentrations.

Particle separation and concentration by means of virtual impaction is a technique based on particle inertia, therefore the enrichment factor should be solely dependent on particle aerodynamic diameter and not chemical constituents. The CPC concentrations for all 10 metals/elements are plotted against those measured by the MOUDI in Figure 8. Integration of all the data in one graph was done to reduce potential analysis errors due to the XRF limits of detection. The linear regression of this integrated comparison indicated an overall average enrichment factor of 27 ± 7.6 for the CPC. Figure 8 also indicates that a very high correlation was obtained between the ambient and concentrated coarse aerosols ($R^2 = 0.93$) and that this correlation is independent of the amount of the chemical constituent in the aerosol.

CONCLUSIONS

A compact, portable CPC with a flow capacity of 1,000 LPM was assembled by connecting 10 virtual impactors in parallel. Characterization of the CPC in the laboratory and field testing in 2 locations confirmed that the CPC enriches coarse particles by a factor of approximately 26 (± 5) when operating with a minor flow of 33 LPM. This enrichment factor is based on the gravimetric analysis of mass, ion chromatography analysis of sulfate and nitrate, and x-ray fluorescence analysis of trace elements and metals.

Ambient coarse PM levels as low as a few micrograms per cubic meter can be concentrated for exposure to humans and animals as well as for rapid collection of samples for chemical analyses. The system itself, while compact and easily transportable, is variable in design and can be configured to fit many existing systems (sampling, exposure, etc.). The flow rates, also highly adjustable, determine the enrichment of the aerosol and thus give the researcher latitude in exposure studies. Therefore the system can be adapted for human exposures by simply increasing the minor flow rate (or increasing the minor-to-total ratio) until a desired concentration is attained. The compact size of the CPC (bulk dimensions 80 cm × 75 cm × 45 cm) makes it readily transportable to desired locations for exposure to coarse particles of varying chemical composition.

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