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A Cascade Air Sampler with Multi-nozzle Inertial Filters for $PM_{0.1}$

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ABSTRACT

We applied a 3-nozzle geometry to the inertial filter unit of a previously developed cascade air sampler, which originally consisted of a 4-stage ($PM_{10/2.5/1/0.5}$) impactor, and an inertial filter unit embedded in a single circular nozzle (for $PM_{0.1}$), and compared its performance against that of a single-nozzle inertial filter unit. The multi-nozzle design enabled the collection of multiple samples and the analysis of multi-chemical particle components in the size range of 0.1–0.5 µm. The total carbon was analyzed to determine the uniformity of the $PM_{0.1}$ collected on a filter downstream from the inertial filter unit in both samplers, and the differences between the individual nozzles of the 3-nozzle unit as well as those between the 1- and 3-nozzle units were identified based on the chemical composition. After adjusting the quantity of the fibers in each inertial filter (one per nozzle) of the 3-nozzle sampler with care on the fiber packing uniformity, the 3-nozzle and 1-nozzle units exhibited similar separation performance, with approximately a 5% lower pressure drop for the former. The differences in the collected particle mass and the total carbon between the individual nozzles of the multi-nozzle unit and between the single- and multi-nozzle units were found to be less than 10%. However, the 3-nozzle unit uniformly collected particles regardless of the loaded particle mass, whereas its 1-nozzle counterpart exhibited non-uniform collection with higher loads. These data, together with the lower pressure drop, show that the multi-nozzle design has practical applicability, thus opening possibilities for chemically analyzing $PM_{0.1}$.

Keywords: Nanoparticles; Separation performance; Multi-component analysis; Webbed metal fibers; Uniform deposition.

INTRODUCTION

Ultrafine particles (UFPs) or nanoparticles not only in the atmosphere but also in the workplace environment in nanomaterial processing have attracted considerable attention, since they can have an adverse influence on human health in that they can penetrate into the alveolar region (Kreyling *et al.*, 2002; Kashiwada *et al.*, 2006; Mayland and Pui, 2007; Heal *et al.*, 2012; Mueller *et al.*, 2012; Kim *et al.*, 2013; Pietroiusti and Magrini, 2014, 2015; Kurjane *et al.*, 2017). Chemical analyses of UFPs or airborne nanoparticles collected by air samplers under various conditions, therefore, are crucially important in terms of identifying emission sources and health risks based on the various chemical components. As a tool for collecting UFPs or nanoparticles, the authors developed an "inertial filter" technology, which involves enhancing the inertial effect on particles by using an elevated filtration velocity (20–30 m s^{-1}) as well as using a series of thin webbed fibers (5–15 µm) as impaction targets, permitting particles with diameters in the order of 100 nm to be separated at a moderate pressure drop (5–10 kPa) (Otani *et al.*, 2007; Eryu *et al.*, 2009; Furuuchi *et al.*, 2010a; Hata *et al.*, 2012; Thongyen *et al.*, 2015; Zhang *et al.*, 2017a, b). The inertial filter has the advantage of a small pressure drop, which permits it to be used in conjunction with small-scale instruments.

Collecting ultrafine particles at nearly ambient pressure with minimum evaporation loss of semi-volatiles has an

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important advantage, in that it permits the use of a simple air sampler to collect samples (Furuuchi *et al.*, 2010a, b; Hata *et al.*, 2012). The inertial filter can separate $PM_{0.1}$ particles while also collecting particles in a size range of 0.1–0.5 µm that are significantly influenced by anthropogenic emission sources. It has been reported that this size range of particles includes important fractions that contain polycyclic aromatic hydrocarbons (PAHs) and chlorinated polycyclic aromatic hydrocarbons (ClPAHs) from anthropogenic emission sources, which are similar to $PM_{0.1}$ (Hata *et al.*, 2013, 2014; Kakimoto *et al.*, 2016).

An accurate analysis of different components in the form of elemental carbon (EC) and organic carbon (OC) together with detailed information on the contribution of emission sources based on various chemicals is a very strong motivation for further optimizing this technique (Kudo *et al.*, 2012; Ikemori *et al.*, 2015, 2017; Kuwabara *et al.*, 2017). However, webbed metal fibers are much more difficult to handle than flat fibrous filters in that they are cut into sections of known mass. This is because a cutting tool has to divide a webbed stainless fiber sample accurately along the central axis of the flow in order to ensure that particle masses are accurately split. A multi-nozzle inertial filter unit consisting of inertial filters of a smaller flow rate represents a potential strategy for not only increasing the number of samples but also for decreasing the total pressure drop, as reported by Tsai *et al.* (2012) for a multi-orifice impactor for collecting ultrafine particles. Although there are limitations to the number of inertial filters that can be used because of difficulties associated with manufacturing small size nozzles and uniformly packing webbed fibers in an inertial filter nozzle, there should be a suitable configuration for achieving a successful goal for the above requirement. With a successful design of a geometry for a multi-nozzle inertial filter, the present sampler promises to contribute to a better understanding of the behavior and characteristics of ultrafine particles and $PM_{0.1}$.

In the present study, a multi-nozzle (3 nozzles) geometry was applied to an inertial filter unit in a cascade air sampler, which was previously developed by the authors. The original sampler consisted of 4-impactor stages ($PM_{10/2.5/1/0.5}$) followed by a single nozzle inertial filter unit ($PM_{0.1}$). The purpose of this study was to evaluate the performance of an air sampler for collecting $PM_{0.1}$ particles at near ambient pressure that can also provide multi-samples for the important fraction of 0.1–0.5 µm, thus allowing the analysis of multi-chemical components combined with a 3-nozzle inertial filter. The separation performance and pressure drop of inertial filters of the 3-nozzle unit were examined and the results were compared with those of a single nozzle inertial filter unit. A cascade air sampler containing the 3-nozzle inertial filter unit was applied for two different types of parallel air samplings along with a sampler with a 1-nozzle unit to validate its performance with respect to: 1) ambient air sampling and 2) laboratory sampling using generated soot. The uniformity of $PM_{0.1}$ particles collected on a filter that was located downstream from the inertial filter and differences between 1- and 3-nozzle units were evaluated based on a total carbon analysis of the bound particles.

Multi-nozzle Inertial Filter

Figs. 1(a)–1(e) show images of a cascade air sampler and an inertial filter unit (see Fig. 1(a)) consisting of a funnel and an inertial filter (IF) stage (Figs. 1(b) and 1(c), respectively) along with a single IF cartridge. The cascade air sampler consists of 4 stages of conventional type impactors with the following cut-off diameters: $PM_{10/2.5/1/0.5}$, followed by a stage with a single nozzle inertial filter for a cutoff size of 0.1 µm and a backup filter stage. The air sampler was designed to be operated at a flow rate of 40 L min^{-1} using Ø55 mm filters. Particles with aerodynamic diameters of 0.1–0.5 µm were collected on IF, while particles less than 0.1 µm, or $PM_{0.1}$, passed through the inertial filter were then collected on a backup filter. The aerosol flow downstream from the impactor stage for 0.5 µm particles was designed to be smoothly funneled to the inertial filter stage of an IF cartridge port, as shown in Figs. 1(b). Fig. 1(d) shows the geometry and parts of a single nozzle inertial filter consisting of a duralumin cartridge with a nozzle of diameter D_n = 5.25 mm and length L_n = 5.5 mm. Webbed stainless steel fibers (average fiber diameter [d_f] = 9.8 µm, steel type SUS316; Nippon Seisen, Japan) were located inside the nozzle. As shown in Fig. 1(e), the assembled IF cartridge was placed in a nozzle port. The pressure drop through the inertial filter was rather moderate at < 10 kPa compared with those of other types of samplers such as a low-pressure impactor (LPI; Hering *et al.*, 1978, 1979) and a Nano-MOUDI (Marple *et al.*, 2014; MSP, 2015). In order to collect particles as uniformly as possible on a backup filter, a sintered metal filter (Ø48 mm × *t*2.5 mm, nominal pore size = 100 µm, ESD-48-2.5-100; SMC, Japan) with a moderate pressure drop (~0.9 kPa at 40 L min^{-1}) was used as a filter holder.

Figs. 2(a)–2(c) respectively show a plane, a side cross section and a 3D cutting view of the new type of inertial filter unit for 3-parallel nozzles. As shown in Fig. 2(b), the inertial filter unit consisted of 2-sections: 1) a funnel stage for introducing the aerosol flow from an impactor stage (cutoff size = 0.5 µm) to 3 funnels to the inertial filters at the bottom of an upper section and 2) 3 inertial filter cartridges supported by a lower section (an inertial filter stage). These two sections were stacked so as to accurately align the funnels to each corresponding nozzle of the inertial filter cartridge. The geometry, configuration of the nozzles and funnels and manufacturing were determined based on an acceleration nozzle designed for a cascade virtual impactor (CAVI) (Prasserttachato *et al.*, 2006; Vejpongsa *et al.*, 2017), in which stainless steel nozzles were embedded in an aluminum casing to provide the accurate nozzle alignment. A total height and geometry of both ends of the $PM_{0.1}$ stage were identical to those of the single nozzle inertial filter unit so that the 1-nozzle unit can be easily replaced by the 3-nozzle unit.

Figs. 3(a)–3(d), respectively, show a funnel stage, an IF stage, parts and assembly drawing of an inertial filter cartridge designed for the 3-nozzle IF unit. The geometry and dimensions of the inertial filter cartridge were the

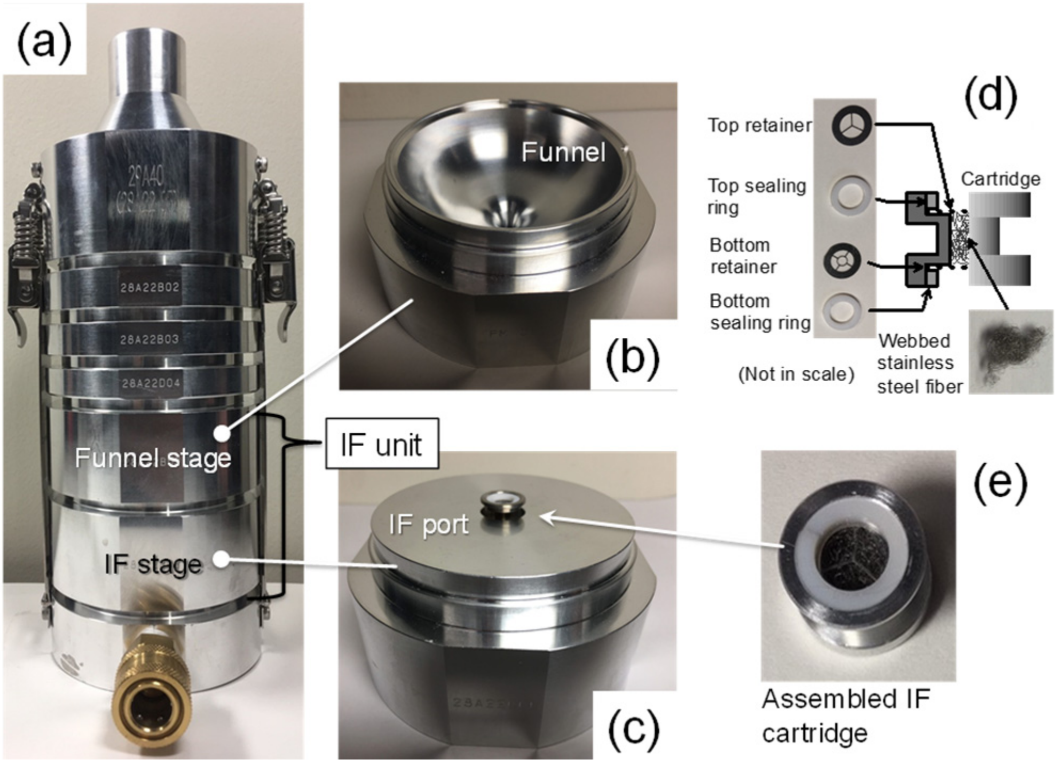

Fig. 1. A cascade air sampler for $PM_{0.1}$: (a) outside appearance, (b) funnel stage, (c) inertial filter (IF) stage with a single IF port, (d) geometry and parts of the IF cartridge, and (e) an assembled IF cartridge.

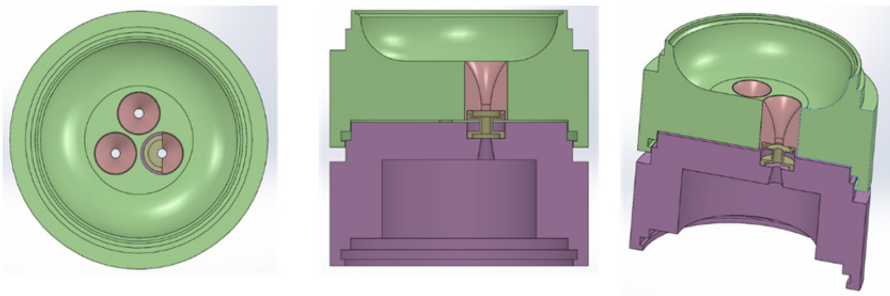

Fig. 2. Schematics of the 3-nozzle IF unit: (a) plane view, (b) side and cross section view and (c) a 3D cutaway view.

same with those of the 1-nozzle unit, except that the nozzle diameter was Ø5.25 and 3 mm, respectively for the 1- and 3-nozzle units. The amount of webbed stainless steel fibers used in the 3-nozzle cartridge, which is a key parameter for separation performance and pressure drop, was adjusted accurately at 1/3 (3.27 ± 0.01 mg) of that for the 1-nozzle cartridge (9.8 ± 0.01 mg) so as to achieve identical separation performance, where the optimal amount of fiber for the 1-nozzle cartridge was experimentally determined (Furuuchi *et al.*, 2010a, b). The specifications of the inertial filters used for 1- and 3-nozzle units are summarized in Table 1.

As reported by Tsai *et al.* (2012) and Marple *et al.* (2014), an increase in the number of nozzles could decrease the pressure drop of an impactor because of the smaller Reynolds number, although these results do not precisely describe the behavior only in the vicinity of the nozzle. However, inserting webbed fibers into the cartridge nozzle (Ø < 2 mm) in a uniform manner to obtain an acceptable level of performance is very difficult and the authors proposed another approach, in which a layered equal mesh (TEM grids) geometry for a smaller flow rate as 4–5 L min^{-1} is used (Thongyen *et al.*, 2015) and 1–2 L min^{-1} (Yamamoto *et al.*, 2015). For this reason, the number of nozzles and a nozzle diameter used were 3 and 3.0 mm, respectively.

METHODS

Separation Performance and Pressure Drop

Following the same procedure as reported previously (Furuuchi *et al.*, 2010a), the separation efficiency of a 3-nozzle inertial filter stage was evaluated using the setup shown in Fig. 4. The configuration consists of a test unit

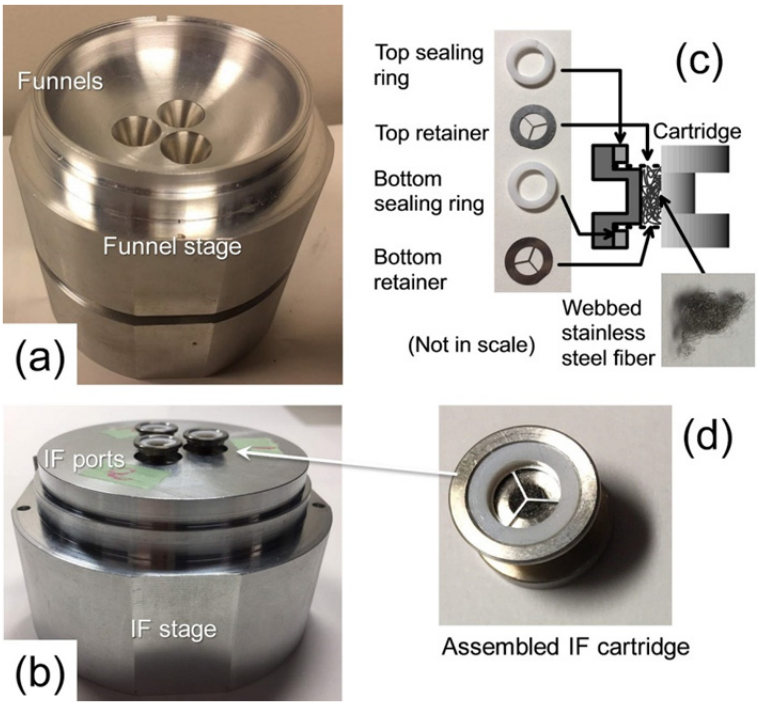

Fig. 3. An IF unit of 3 IFs: (a) funnel stage, (b) IF stage with 3 IF ports, (c) geometry and parts of the IF cartridge, and (d) an assembled IF cartridge.

Table 1. Specifications of inertial filters for 1- and 3-nozzle units.

Unit	d_f (µm)	Material	Type	L_n (mm)	D_n (mm)	Q (L min^{-1})	Fiber loading (mg)
1-nozzle	9.8	SUS 316	Webbed	5.5	5.25	40	9.80 ± 0.03
3-nozzle	9.8	SUS 316	Webbed	5.5	3	40	3.27 ± 0.01

D_n: nozzle diameter; d_f: average fiber diameter; L_n: nozzle length; Q: total sampling flow rate.

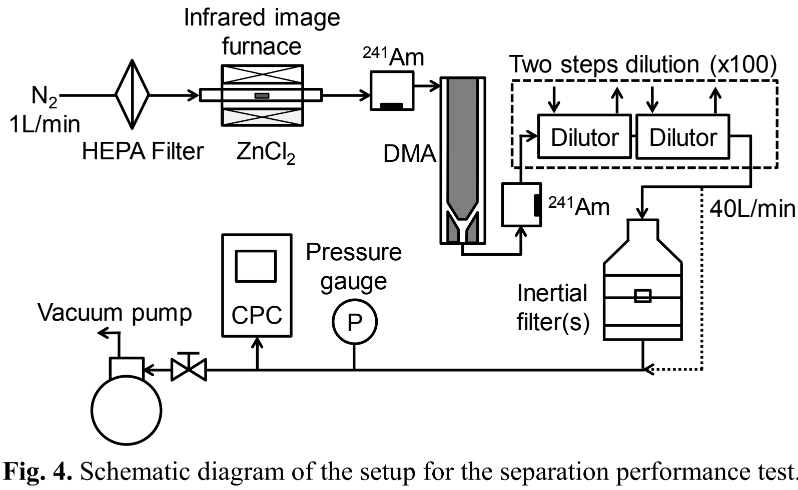

Fig. 4. Schematic diagram of the setup for the separation performance test.

for the inertial filter, an air pump, a mass flow meter, a mass flow controller and a condensation particle counter (CPC) (Model 3785; TSI Inc., U.S.A.) connected both upstream and downstream from the test unit consisting of an air sampler inlet, an inertial filter unit, a backup filter stage and a system for generating monodisperse aerosol particles. Polydisperse zinc chloride ($ZnCl_2$) particles, generated by an evaporation-condensation type aerosol generator, were adjusted to produce monodisperse particles using a Long DMA (Electrostatic Classifier 3080L, which includes a 3080 controller; TSI Inc., U.S.A.). The test aerosol was introduced to the test unit at a rate of 40 L min^{-1} after being diluted by clean air. The collection efficiency of a particle with diameter d_p was determined based on the particle number N counted by the CPC at an inlet of the test unit ($N_{in}(d_p)$) and downstream from the inertial filter unit ($N_{out}(d_p)$). For a size range larger than ~200 nm, separation performance was evaluated using a laser aerosol spectrometer (LAS) (Laser Aerosol Spectrometer 3340; TSI Inc., U.S.A.). The mobility equivalent diameter was converted to an aerodynamic diameter using the density of the test particles, as measured by an Aerosol Particle Mass Analyzer (APM-II Model 3601; Kanomax Japan, Inc., Japan). The aerodynamic diameter, as measured by DMA-CPC and the optical diameter, as measured by LAS, were confirmed to be equivalent within an acceptable range.

To obtain an identical separation performance between inertial filters of the 3-nozzle unit, the amount and packing uniformity of webbed stainless steel fibers are crucially important. Since the pressure drop through the inertial filter is a good indicator of the difference in fiber packing uniformity, the pressure drop of inertial filters for the 3-nozzle unit was measured for 10 sets. After mounting a single inertial filter cartridge on the inertial filter unit, the pressure P was measured both at inlet (P_{in}) and outlet (P_{out}) of the test unit using a digital vacuum gauge (VA-076L, Okano Works, Japan) at 1/3 of the designed total flow rate (13.3 L min^{-1}) with the other two funnels closed by tape. The pressure drop of the inertial filter unit with 3 nozzles was also evaluated at a flow rate of 40 L min^{-1} and the results were compared with that of the single nozzle unit.

Air Sampling for Particle and Carbon Mass Evaluation

For the validation of the collection performance of the air sampler with the 3-nozzle IF unit, the collected mass from the air sampling was compared between the samplers of the 1- and 3-nozzle IF units. Two different types of parallel air sampling by cascade air samplers of the 1- and 3-nozzle units were conducted: 1) ambient air sampling and 2) laboratory scale sampling of a generated soot aerosol. Particles were collected on quartz fiber filters (Pallflex Tissuquartz 2500QAT-UP; Pall Corp., Japan) of Ø55 mm that had been pre-baked at 350°C in an oven for 1 h then conditioned at 21.5 ± 1.5°C, and 35 ± 5% RH in a $PM_{2.5}$ weighing chamber (PWS-PM2.5; Tokyo Dylec Corp., Japan) for 48 h before and after the sampling. In order to decrease the blank values for carbon, all parts of the inertial filter unit and the bottom stage of the sampler as well as inertial filter cartridges and webbed stainless steel fibers were cleaned with ethanol (C_2H_6O; 76.9–81.4 vol.% disinfection grade) in an ultrasonic bath for 30 min.

Ambient Air Sampling

The two sets of the cascade air samplers of the 1- and 3-nozzle IF units were installed at the same location on a balcony on the sixth floor of a seven-story building at Kanazawa University. The parallel sampling was conducted for 3 days for each set of filter samples during 2 different periods. Sampling information is summarized in Table 2.

Soot Particle Sampling

Fig. 5 shows a schematic of the experimental setup used for the sampling of generated soot particles. Soot particles were generated by holding a perforated metal skimmer over the flame of a Bunsen burner (6-464-05; Worthef, Japan) with municipal gas at 3 L min^{-1}. The generated soot particles mixed with the room air were introduced to a dilutor (~37 L min^{-1}) and diluted further with clean air at 30 L min^{-1}. The diluted soot aerosol was introduced into the two sets of air samplers with 1- and 3-nozzle inertial filter units and particles were collected at 40 L min^{-1}. The sampling period was adjusted to between 30–60 min for various amounts of collected soot particles and repeated 3 times to evaluate the influence of the amount of collected

Table 2. Information concerning the parallel sampling of ambient air.

Sample No.	Period	Sampling period (2018)	IF Unit	Duration		Weather
				Start	Stop	
1	Period-1	20–23 Jul.	1-nozzle 3-nozzle	2018/07/20 19:12	2018/07/23 18:18	Sunny
2		23–26 Jul.	1-nozzle 3-nozzle	2018/07/23 18:58	2018/07/26 17:54	Sunny, cloudy
3		27–30 Jul.	1-nozzle 3-nozzle	2018/07/27 10:07	2018/07/30 11:22	Sunny, cloudy
4		30 Jul.–2 Aug.	1-nozzle 3-nozzle	2018/07/30 11:53	2018/08/02 9:30	Sunny
5		4–7 Aug.	1-nozzle 3-nozzle	2018/08/04 18:22	2018/08/07 18:28	Sunny, cloudy
6	Period-2	11–15 Sep.	1-nozzle 3-nozzle	2018/09/11 14:21	2018/09/15 9:26	Cloudy and rain
7		16–19 Sep.	1-nozzle 3-nozzle	2018/09/16 14:51	2018/09/19 9:00	Cloudy and rain
8		20–23 Sep.	1-nozzle 3-nozzle	2018/09/20 16:31	2018/09/23 9:31	Cloudy and rain
9		24–27 Sep.	1-nozzle 3-nozzle	2018/09/24 11:48	2018/09/27 17:17	Cloudy and rain
10		28 Sep.–01 Oct.	1-nozzle 3-nozzle	2018/09/28 12:30	2018/10/01 18:28	Sunny, rain

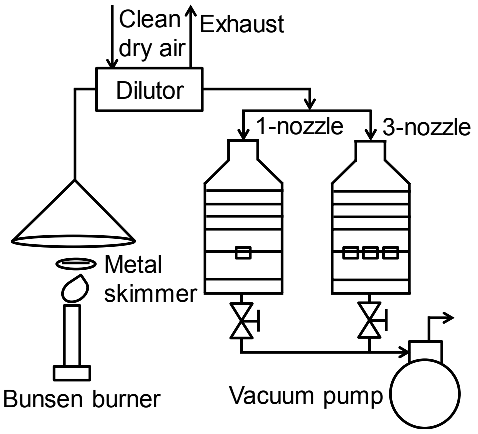

Fig. 5. Setup for obtaining soot particles.

particles. Since the soot generator was not isolated from room air, the influence of ambient particles was first checked: The mass and total carbon of $PM_{0.1}$ particles collected for the sampling period for the soot particles were confirmed to be less than 1.5 and 2% of those from soot particles that were sufficiently low so as not to affect the conclusion regarding the influence of the collected soot mass. The mass and number concentrations of soot particles supplied to samplers were not controlled, since this would be the case in sampling ambient air, so that the total mass of collected soot was used as a representative condition for the sampling. According to a previous report on the influence of particle loading on the separation performance of an inertial filter (Eryu *et al.*, 2011), the influence of particle loading on the separation performance of the inertial filter would be expected to be negligible both for 1- and 3-nozzle units under the present experimental condition.

Carbon Analysis

For both samples from the ambient and soot samplings, the total carbon (TC) contained by the particles collected by the inertial filters and backup filters ($PM_{0.1}$) for selected sets of samples both from the ambient air and soot particle samplings was determined. The TC on the backup filter was analyzed using a Sunset Laboratory Carbon Aerosol Analyzer, following the IMPROVE protocol (Chow *et al.*, 2004; Watson *et al.*, 2005), where a square portion (10 × 15 mm) was used for the analysis: 1 at the center and 2 at the middle of the filter in order to ensure a uniform particle collection (see Fig. 6). The TC value for $PM_{0.1\text{-}0.5}$ particles collected on the inertial filter was also determined by following the IMPROVE protocol. Webbed stainless steel fibers that were removed from the inertial filter cartridge were sandwiched by square sheets of quartz fibrous filter (10 × 15 mm, Pallflex Tissuquartz 2500QAT-UP; Pall Corp., Japan) for the protection between the quartz parts of the instrument located below and over the sample baking section. These cover sheets were pre-baked in a 350°C oven for 1 h then baked again in the carbon analyzer before the sample analysis in order to produce carbon free conditions during the TC analysis. Prior to each set of the carbon analysis, the TC value was calibrated by that of a reference chemical, or sucrose ($C_{12}H_{22}O_{11}$) (196-00015; Wako Pure Chemical Industries, Ltd., Japan). Minimum detection limits (MDLs) were determined by laboratory blanks to be 0.30 µg cm^{-2} (n = 6) for the quartz fibrous filter and 2.3 µg mg^{-1} (n = 7) for the webbed stainless steel fibers, respectively.

RESULTS AND DISCUSSION

Separation Performance

Figs. 7(a) and **7**(b) show collection efficiency curves on a particle number basis plotted against the aerodynamic diameter of particles, respectively, for the 3 different inertial filters used for the 3-nozzle inertial filter (IF) unit (13.3 L min^{-1}) and that for a 3-nozzle IF unit with 3-inertial filters (40 L min^{-1}) compared with that of a 1-nozzle unit (40 L min^{-1}). The average density of sodium chloride aerosol particles was estimated for the size range of 40–131 nm in the mobility diameter as 1770 kg m^{-3}. The blank loss of particles through the IF unit without webbed stainless steel fibers was subtracted for the calculation of collection efficiency. Particle loss from the top of an approaching nozzle stage to the exit of the inertial filter was confirmed to be less than 5% on a number basis both for 1- and 3-nozzle units. The separation efficiency curve for a 1-nozzle IF unit reported in a previous study is also compared and the findings are shown in Fig. 7(b). As seen from Fig. 7(a), although there was a slight difference between each nozzle of the 3-nozzle IF unit, the differences are negligible and are consistent with the overall separation efficiency curve of the 3-nozzle IF unit with 3 inertial filters. From Fig. 7(b), the performance of the 3-nozzle IF unit was also found to be consistent with that of the 1-nozzle IF unit as well as that reported in a previous study (Furuuchi *et al.*, 2010a). The aerodynamic behavior of particles in the inertial filter may dominate the separation performance because of the very large filtration velocity (~30 m s^{-1}) so that the influence of flow interactions occurring both upstream and downstream of the inertial filters would not be expected to be significant if the fiber loading of the inertial filters was adjusted accurately, as was done in this study.

Pressure Drop

The pressure drop though the inertial filter and related values are summarized in Table 3 along with other information regarding the type of inertial filter used and fiber mass loading. The system blank pressure drop was measured for each unit for a blank inertial filter cartridge without webbed stainless steel fibers and retainers for fibers and the values were subtracted from the totals. The coefficient of variation of the pressure drop for the inertial filters of the 3-nozzle IF unit was nearly 5% at the maximum, which can be regarded as acceptable, although it was much larger than that for the fiber loading. The pressure drop for the 3-nozzle IF unit was found to be nearly 5% less than that of the 1-nozzle set up. A lower average pressure drop of individual inertial filters than that of the IF unit with 3 inertial filters can be attributed to an un-symmetrical and complicated approaching flow to a single inertial filter mounted on the 3-nozzle IF unit with two nozzles blinded.

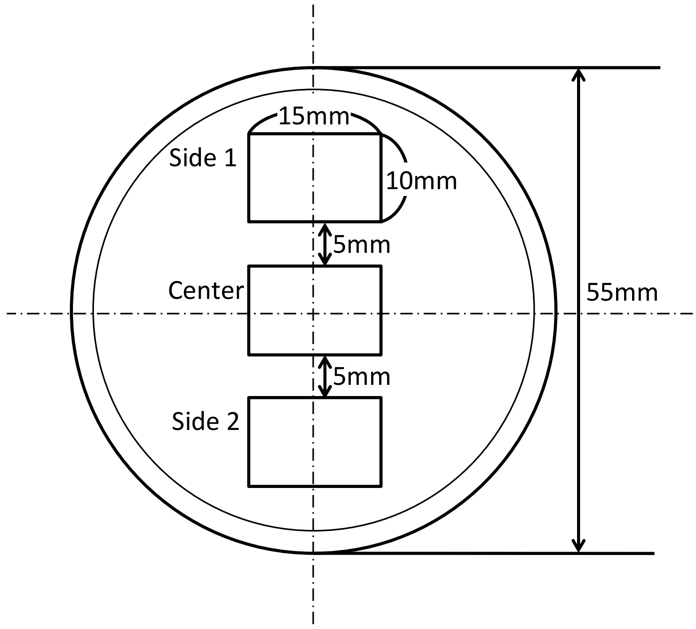

Fig. 6. Locations where samples of a backup filter ($PM_{0.1}$) for carbon analysis were obtained.

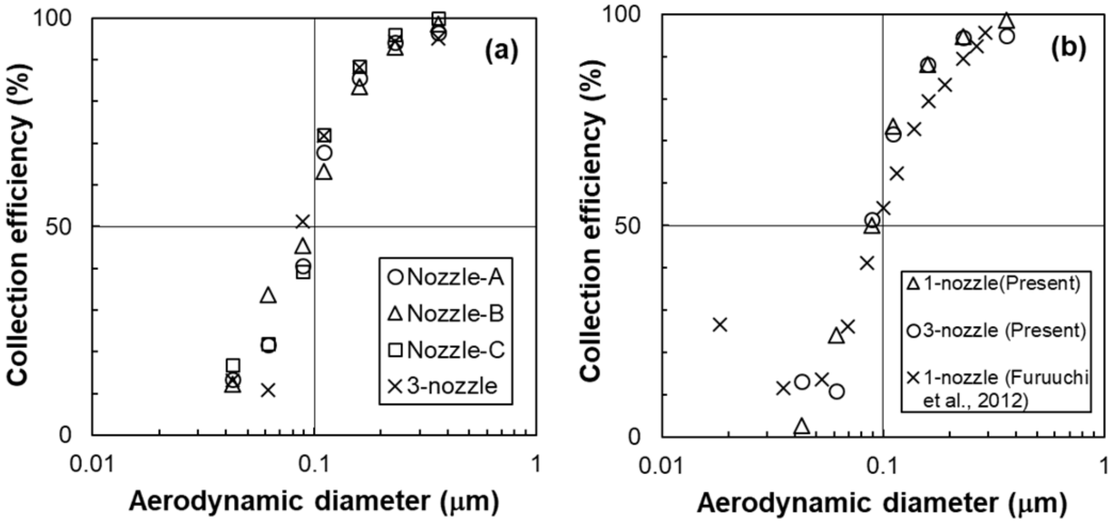

Fig. 7. Collection efficiency of 1- and 3-nozzle IF units, (a) each IF of the 3-nozzle unit compared with the overall efficiency of the 3-nozzle unit and (b) the 3-nozzle unit compared with the 1-nozzle unit from both present and previous studies.

Table 3. Pressure drop for the tested inertial filters.

Type of inertial filter (IF)	D_n (mm)	Q (L min^{-1})	Number fiber mass (mg)	Pressure drop (kPa)	Coefficient of variation (%)		Relative pressure drop (%)
					fiber	pressure	
IF (1)	5.25	40.0	9.80 ± 0.03	8.60 ± 0.32	0.19	3.69	100
IF (2)	3.00	40.0	3.27 ± 0.01	8.12 ± 0.27	0.13	3.38	94.4
IF (1/3)	3.00	13.3	3.27 ± 0.01	7.80 ± 0.40	0.14	5.10	90.7

D_n: nozzle diameter; Q: total sampling flow rate.

Particle and Carbon Mass

In Fig. 8, the cumulative mass fraction by particle size (Period 1) for ambient particles collected during parallel sampling are compared between samples from air samplers with 1- and 3-nozzle inertial filter (IF) units. The compatibility between samplers with 1- and 3-nozzle IF units appears to be fairly consistent with values obtained for other sets of ambient samples. The average values for the coefficient of variation (CV) (relative standard deviation, RSD) of d_{p50} and the geometric standard deviation were,

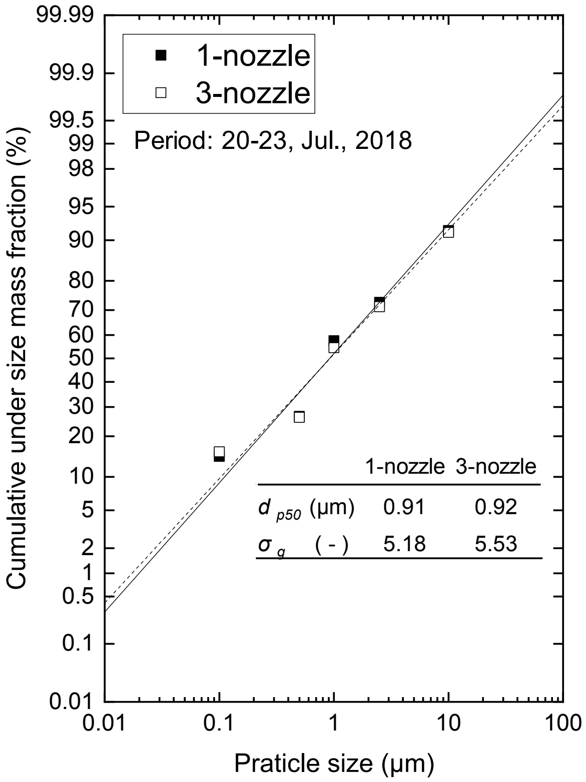

Fig. 8. Cumulative mass fraction of ambient particles collected by cascade air samplers with 1- and 3-nozzle IF units.

related to the separation performance of the inertial setup, was 10.9% between 1- and 3-nozzle IF units. These values provide reasonable validation of the overall performance of the cascade air sampler with a 3-nozzle IF unit.

The total particle mass on inertial filter samples obtained from ambient air sampling was compared between samplers with 1- and 3-nozzle IF units in Fig. 9(a), in which the particle mass was summed for the 3 inertial filters of the 3-nozzle IF unit. The coefficient of variation (CV) for the collected particle mass between the 1- and 3-nozzle IF units was ~9% for the total period of ambient air sampling, indicating a good compatibility between the two different units. The mass of particles collected on 3 inertial filters by ambient sampling for Period 1 and 2 are compared in Fig. 9(b). The CV value for particle mass fluctuation between the 3 inertial filters was 9.1, 10.4 and 9.7% respectively for Period 1, Period 2 and the overall period, which were slightly larger than that for the pressure drop.

The similarity of the TC mass on inertial filter samples between both sampler units and IFs was also confirmed from the viewpoint of chemical components. Results for the TC collected by the different IF units and the TC values for each inertial filter sample of the 3-nozzle sampler are compared in Figs. 10(a) and 10(b), respectively. The CV value related to the difference in the TC values between the 1- and 3-nozzle IF units was 5.7% for the total period of ambient air sampling. The CV values for TC between the 3 IF samples throughout the entire sampling period were approximately 5.9%. These results are rather consistent with

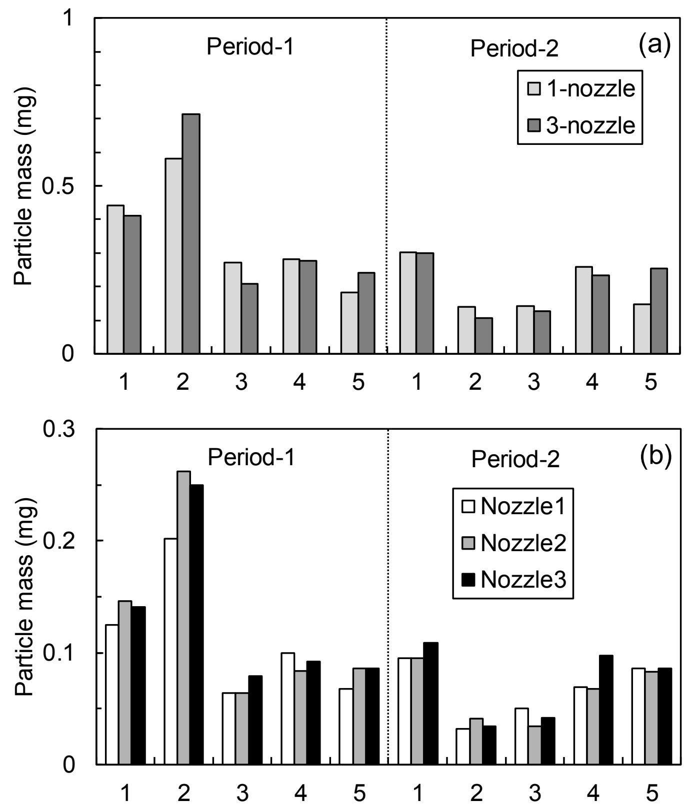

Fig. 9. Particle mass on IFs evaluated for samples from ambient air sampling: comparison of particle mass between (a) the 1- and 3-nozzle units (summed for 3 IFs) and (b) the IFs for the 3-nozzle IF unit.

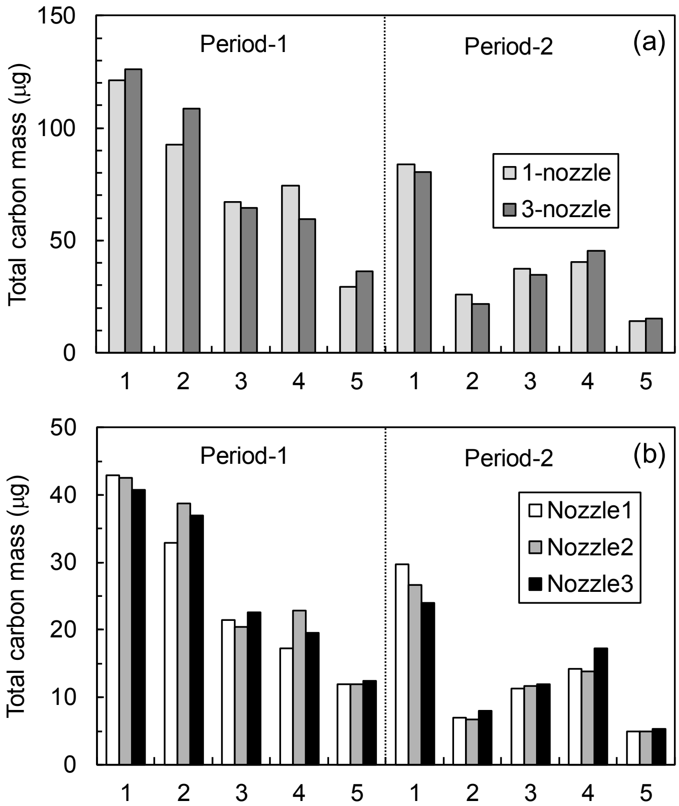

Fig. 10. Total carbon (TC) mass on IFs evaluated for samples from ambient air sampling: comparison of TC between (a) the 1- and 3-nozzle units (summed for 3 IFs) and (b) the IFs for the 3-nozzle unit.

respectively, 4.8% and 5.6% for 5 sets of parallel samples. The average CV for the amount of $PM_{0.1}$, which is closely the values for the particle mass data. Table 4 summarizes the CV values for the mass of particles and carbon.

Although the maximum CV values for the ambient samples were within an acceptable range (± 15%) for the parallel measurement of $PM_{2.5}$ (Ministry of Environment, Japan, 2011), the fluctuation in the mass of collected particles and particle-bound carbon was slightly larger than that in the pressure drop probably because of the influence of the micro structure related to the distribution of loosely packed webbed fibers on particle deposition. The use of a layered mesh inertial filter (Hata *et al.*, 2013; Thongyen *et al.*, 2015; Zhang *et al.*, 2017a, b) may be a solution for this issue.

Uniformity of Particle Deposition on the Backup Filter

The TC mass per unit filter area, as evaluated for filter samples obtained at the central and middle locations is shown in Figs. 11(a) and 11(b) for sampling soot particles with smaller and larger amounts of the total collected particle mass. A clear non-uniformity in the TC distribution across the filter area that showed a peak in the collected mass around the filter center was visually observed for the single nozzle unit at a larger particle loading, i.e., over 2–3 mg, while the values were nearly uniform for samples obtained by using the 3-nozzle unit, nearly regardless of particle loading.

In Fig. 12, the CV for the TC mass between three locations on the backup filter is plotted in relation to the total particle mass loading on the backup filter, where values both for soot and ambient particle samplings are shown. For the single nozzle unit, the CV increased with increasing particle loading. However, the CV was nearly constant for the 3-nozzle unit, indicating an advantage of the multi-component analysis of chemicals from one filter sample owing to the uniform deposition of particles across the filter area where a punched filter sample is typically obtained. Although the uniformity of collected particles is not only affected by the number of nozzles but by other parameters as well, such as a pressure drop through a filter holder, a distance between nozzles and a nozzle-filter distance, the present configuration appears to be successful regarding the overall performance for the operation of a $PM_{0.1}$ air sampler. There may be an optimized condition for the combination of the above parameters and more detailed investigations using CFD would be expected to provide a better solution. However, in the present study, the nozzle-filter distance and specifications of the filter holder were not changed from the original one for easy replacement between 1- and 3-nozzle units. Detailed investigations will be, therefore, be done in the future.

CONCLUSION

After adjusting the quantity of the webbed stainless steel fibers used in the inertial filters (one inserted in each nozzle) of the 3-nozzle sampler with care on the fiber

Table 4. Summary of coefficient of variation (CV) for the mass of particles and carbon.

Parameter	Comparison	Period-1	Period-2	Whole period
Particle mass	between 2-units	8.4%	10.3%	9.3%
	between 3-IFs	9.1%	10.4%	9.7%
Total carbon mass	between 2-units	6.7%	4.8%	5.7%
	between 3-IFs	5.4%	6.5%	5.9%

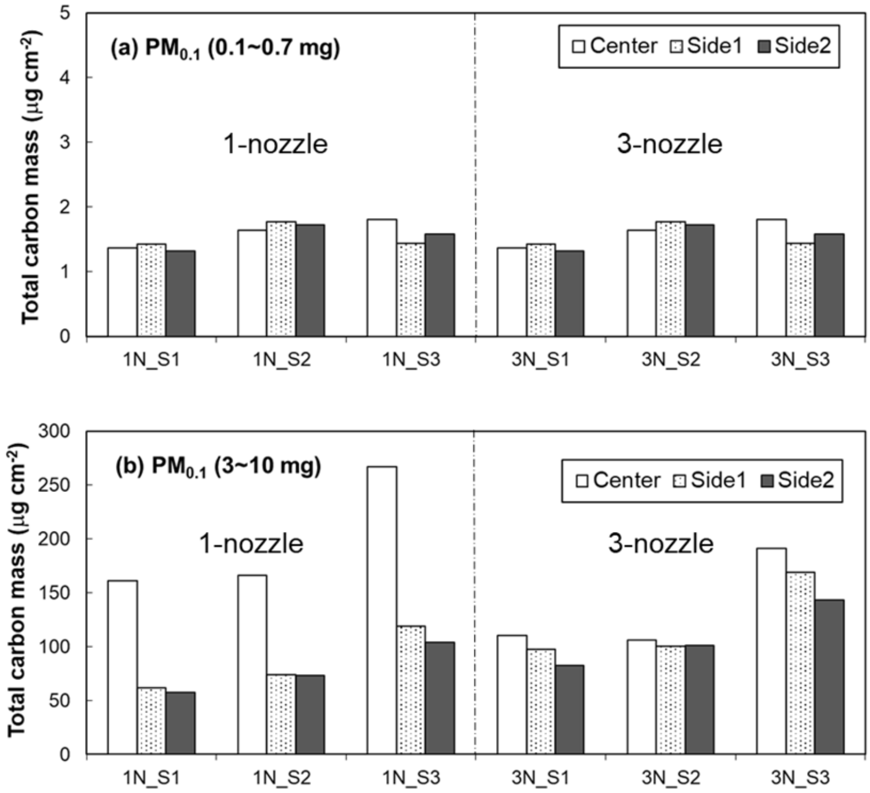

Fig. 11. TC mass at different locations on a backup filter obtained from the soot samples: (a) smaller $PM_{0.1}$ loading (0.1–0.7 mg) and (b) larger $PM_{0.1}$ loading (3–10 mg).

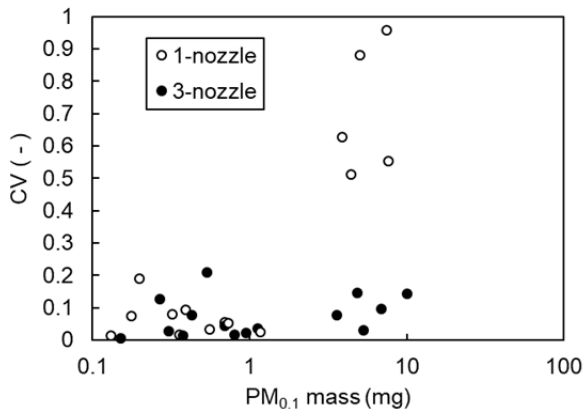

Fig. 12. Correlation between particle mass and coefficient of variation (CV) of carbon mass collected on different locations on the backup filter.

packing uniformity, the individual filters of the 3-nozzle unit, the 3-nozzle unit overall and the 1-nozzle unit displayed almost equal separation performance. With an error of less than 10%, the pressure drop, particle mass loading and carbon mass were consistent for the individual inertial filters of the 3-nozzle unit. Furthermore, the pressure drop was nearly 5% lower for the multi-nozzle unit than the single-nozzle unit.

We also evaluated the homogeneity of the particles collected by the backup filter, which was downstream of the IF unit, in each sampler by analyzing the total carbon in samples taken from the central and middle parts of the filter. The 1-nozzle unit exhibited non-uniform collection with higher particle mass loads, in contrast to the 3-nozzle unit, which produced an even distribution of particles across the filter area regardless of the particle load. Thus, the multi-nozzle geometry demonstrates clear advantages—uniform particle collection in addition to a lower pressure drop—over the single-nozzle design in multi-component analysis, indicating its applicability in the chemical analysis of $PM_{0.1}$.

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