

Development of a PM Sampler for Collecting Fine Particles via Condensation Magnification

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Abstract

In this study, a new PM (particulate matter) sampler was developed and fabricated to collect fine particles in the atmosphere, and laboratory and field tests were carried out to evaluate the performance of the sampler. The PM sampler, which was based on impingers, employed an aerosol condensation system as a PM magnifier to improve its collection efficiencies. Sodium chloride, ammonium sulfate and ammonium nitrate aerosols were used as test particles, because these components are rich in ambient aerosols.

As a result, it was found that the collection efficiency of the novel PM sampler was very high. Thus, it is believed that the PM sampler is an effective device for sampling fine particles. In addition, it was demonstrated that this work could contribute to the collection or removal of fine particles and be applied to the semi-continuous sampling of ambient aerosols for chemical composition analysis.

Key words : PM sampler, PM magnifier, Condensation, Chemical composition

1. INTRODUCTION

In the atmosphere, particles play an important role such as visibility degradation, heterogeneous chemistry and radiative balances. The roles of aerosol generally rely on the particle size, chemical composition, and number and mass concentration. Particles smaller than 2.5 μm in diameter have high deposition in the alveolar region during mouth inhalation. The hazard caused by fine particles depends on their chemical composition and the site within the human

respiratory system where they are deposited (Hinds, 1982). Therefore, the concentration of air borne fine particles is an important parameter for the evaluation of the degree of hazard in an atmospheric environment.

Since the U.S. Environmental Protection Agency (EPA) promulgated a new regulation for the mass concentration of suspended particulate matters smaller than 2.5 μm in diameter, referred to as PM_{2.5}, the investigation of fine particles has focused on the measuring and monitoring of PM_{2.5}. It is expected that the EPA's new primary standards will provide not only increased protection against a wide range of PM-related health effects but also appropriate

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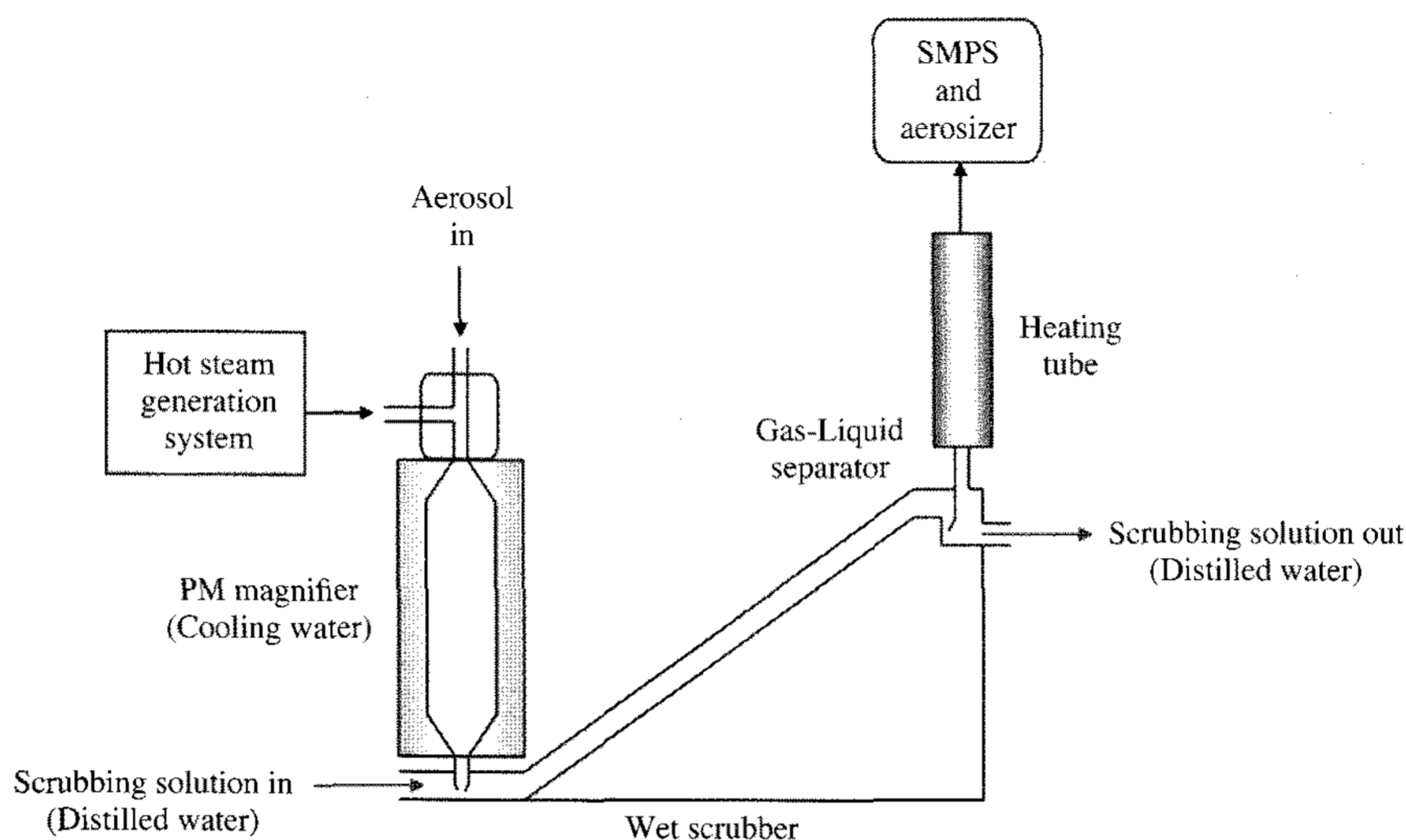


Fig. 1. Schematic of the novel PM sampler.

protection against PM-related public welfare effects (U.S. EPA, 1997).

Sampling of particles from an ambient atmosphere is an important step in atmospheric aerosol measurements. For accurate measurements of the chemical compositions of $PM_{2.5}$, fine particles have to be effectively sampled. Currently, various devices such as cyclones, impingers, filters, and impactors are commonly available for separating, collecting and sampling aerosol particles (Kim *et al.*, 2006a; Kim *et al.*, 2005; Tseng and Li, 2005; Kim *et al.*, 2002; Kim *et al.*, 2000; Lee and Kim, 2000). It is, however, well known that it is difficult to collect or sample aerosol particles with sizes ranging from 0.1 to 1.0 μm in diameter (Shaw *et al.*, 2003).

In order to sample the fine particles, samplers need to employ more effective method than any other previous device, such as impingers, impactors, cyclones, etc. In the present study, a PM sampler was developed to collect fine particles, and laboratory and field tests were carried out to evaluate the performance of the sampler. The PM sampler employed an aerosol condensation system as a PM magnifier, because particles enlarged by the PM magnifier could be easily collected by the PM sampler (Hong *et al.*, 2007; Lee *et al.*, 2005). In addition, the PM sampler with the PM magnifier was applied

to the semi-continuous measurement of a chemical composition analysis for fine particles in the atmosphere.

2. DESIGN AND EXPERIMENT

In this study, a novel PM sampler was designed and fabricated to collect fine particles by means of the condensation-magnification method (Kim *et al.*, 2006b; Suh *et al.*, 2005). The PM sampler consists of a hot steam generation system, a mixing part, a PM magnifier, a wet scrubber, a gas-liquid separator and a drier (see Fig. 1). The mixing part was made of high-density polyethylene (HDPE), and was designed to maximize the mixing effect when particles were mixed with water vapor. The PM magnifier was built to enlarge the size of aerosol particles by means of aerosol condensation (Park *et al.*, 2001; Park and Lee, 2000). The condensation chamber of the PM magnifier was maintained at super saturated condition to increase the size of aerosol particles, and so the mass of grown particles increased significantly. The acceleration nozzle was prepared and placed at the end of the PM magnifier, and thus the water absorbed particles were strongly impacted on to the surface and easily collected into the flowing

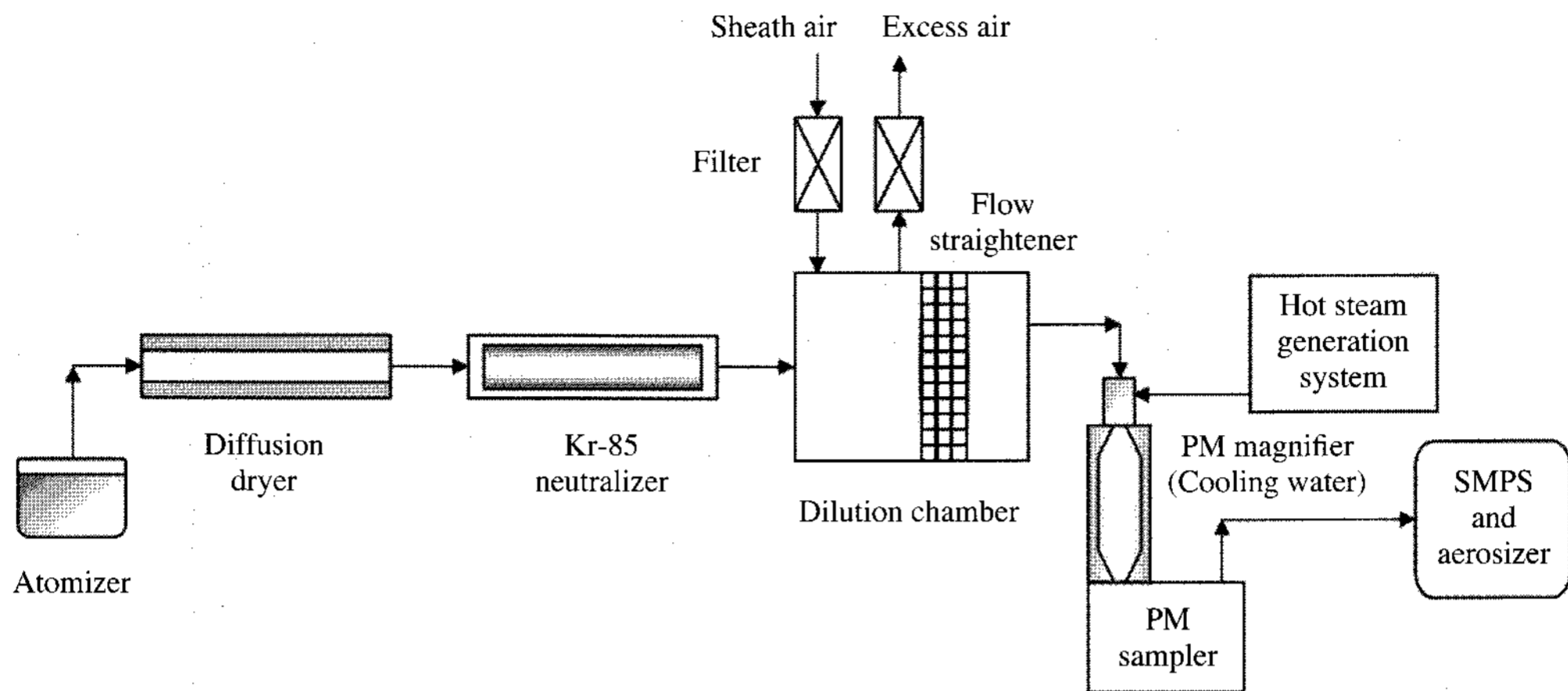


Fig. 2. Experimental set-up for characterization of the PM sampler.

distilled water (DW) in the PM sampler. The gas-liquid separator was also made to improve the collection efficiencies of particles. The PM sampler is similar with an impinger in that the dominant particle collection mechanisms of them are Brownian diffusion for fine particles and inertial impaction for large particles. However, it is different that the PM sampler uses continuous scrubbing solution, while an impinger is a batch type sampler.

Sodium chloride (NaCl , solid particles, 2.16 g/cm^3), ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$, solid particles, 1.77 g/cm^3), and ammonium nitrate (NH_4NO_3 , solid particles, 1.72 g/cm^3) aerosols were used for our experimental test to evaluate the PM sampler, because these components are generally rich in ambient aerosols. Therefore, these aerosols are very important for research on the sampling of ambient aerosols. The size of the test aerosols ranged from 0.1 to 2.5 μm in aerodynamic diameter.

A schematic of the test setup for evaluating the PM sampler's performance is shown in Fig. 2. The aerosols produced by a spray-drying type generator passed through a diffusion dryer, Kr-85 charge neutralizer (TSI Inc.) and dilution chamber. These aerosols were then introduced into the PM magnifier (condensation chamber), where they were mixed with hot steam. While the temperature of the water vapor (hot-steam) was 110°C , the temperature of the PM magnifier was maintained at 30°C to create

supersaturation conditions. In the PM magnifier, the cooling water circulation system was allowed to keep low temperature. At the exits of the PM magnifier and the reference chamber, the aerosols were sampled for evaluating the PM magnifier. In addition, the aerosols were sampled at the exits of the PM magnifier and the PM sampler to evaluate the performance of the PM sampler. The testing conditions for the sampling flow rates, the volume of the condensation chamber and distilled water flow rate for generating hot-steam were 2 L/min, 20 cm^3 and 0.17 mL/min, respectively. Thus, the residence time in the PM magnifier was 0.6 sec at the flow rate of 2 L/min. The length and volume of the PM magnifier were the same as those of the reference chamber, which minimized the experimental errors due to particle losses.

The particle size distributions were measured by the Aerosizer (API Inc., Model Mach II) and SMPS (Scanning Mobility Particle Sizer, TSI Inc.) to determine the condensation effect of the PM magnifier. The particle collection efficiency of the PM sampler was evaluated after the condensation test.

3. RESULTS AND DISCUSSION

The degree of condensational growth of the aerosol particles was calculated using the following equa-

tion:

$$\begin{aligned} & \text{Degree of condensational growth (\%)} \\ &= \frac{GMD_{grown}}{GMD_{original}} \times 100 \end{aligned} \quad (1)$$

where $GMD_{original}$ and GMD_{grown} are the geometric mean diameter (GMD) of the original and grown aerosols, respectively.

Fig. 3 illustrates the changes of the size distribution of sodium chloride, ammonium sulfate and ammonium nitrate particles. The GMD of the sodium chloride, ammonium sulfate, and ammonium nitrate particles (about $0.63 \mu\text{m}$ as an original GMD) increased to 0.95 , 1.2 and $1.3 \mu\text{m}$, respectively. Thus, the degrees of condensational growth for these aerosols were about 151, 185 and 210%, respectively. It was found that these particles were soluble and their size increased easily under condensation conditions. In addition, it is expected that the ammonium nitrate aerosol has grown more than any other aerosol because the solubility of the aerosols is in the order of ammonium nitrate (NH_4NO_3) > ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$) > sodium chloride (NaCl) particles. Therefore, it is concluded from these experimental results that the solubility of aerosols is an important variable in the aerosol condensation and the degree of condensational growth depends on the solubility of the particles. The GMD of the original and grown aerosols and their degrees of condensational growth are listed in Table 1, 2 shows the solubility of the test aerosol particles, such as sodium chloride, ammonium sulfate and ammonium nitrate aerosols.

The particle collection efficiency of the PM sampler, η , is defined as follows (Kim *et al.*, 2003a; Kim *et al.*, 2002):

$$\text{Collection efficiency, } \eta(\%) = \frac{C_{up} - C_{down}}{C_{up}} \times 100 \quad (2)$$

where C_{up} and C_{down} are the aerosol particle concentrations in upstream and downstream, respectively. C_{up} and C_{down} were calculated as the averages of at least 7 measurements. However, the highest and lowest recorded concentrations were discarded when we calculated them.

Fig. 4 represents the measured particle collection

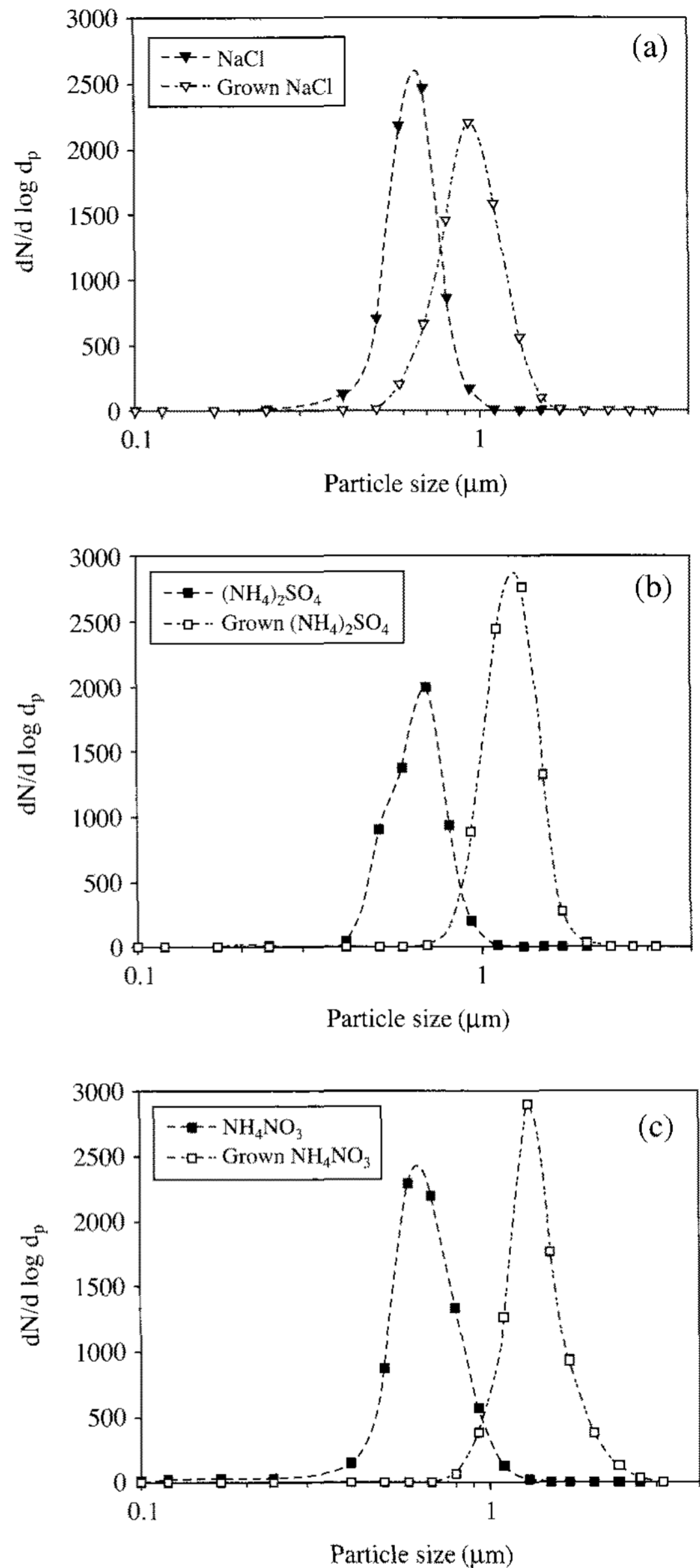


Fig. 3. The size increase of sodium chloride (a), ammonium sulfate (b) and ammonium nitrate particles (c).

efficiency of the PM sampler with the PM magnifier as an aerosol condensation system. NaCl particles were used for this experiment. Obviously, the efficiency curve of the PM sampler without the PM magnifier looks U curve which is the common shape of the efficiency curves of general aerosol samplers.

Table 1. Condensational growth rate of the aerosols and comparison of the GMD of the original aerosols with that of grown aerosols.

Aerosols	GMD of original aerosols (μm)	GMD of grown aerosols (μm)	Condensational growth rate (%)
NaCl	0.63	0.95	151
$(\text{NH}_4)_2\text{SO}_4$	0.65	1.20	185
NH_4NO_3	0.62	1.30	210

Table 2. Solubility of the aerosol particles tested in the experiment.

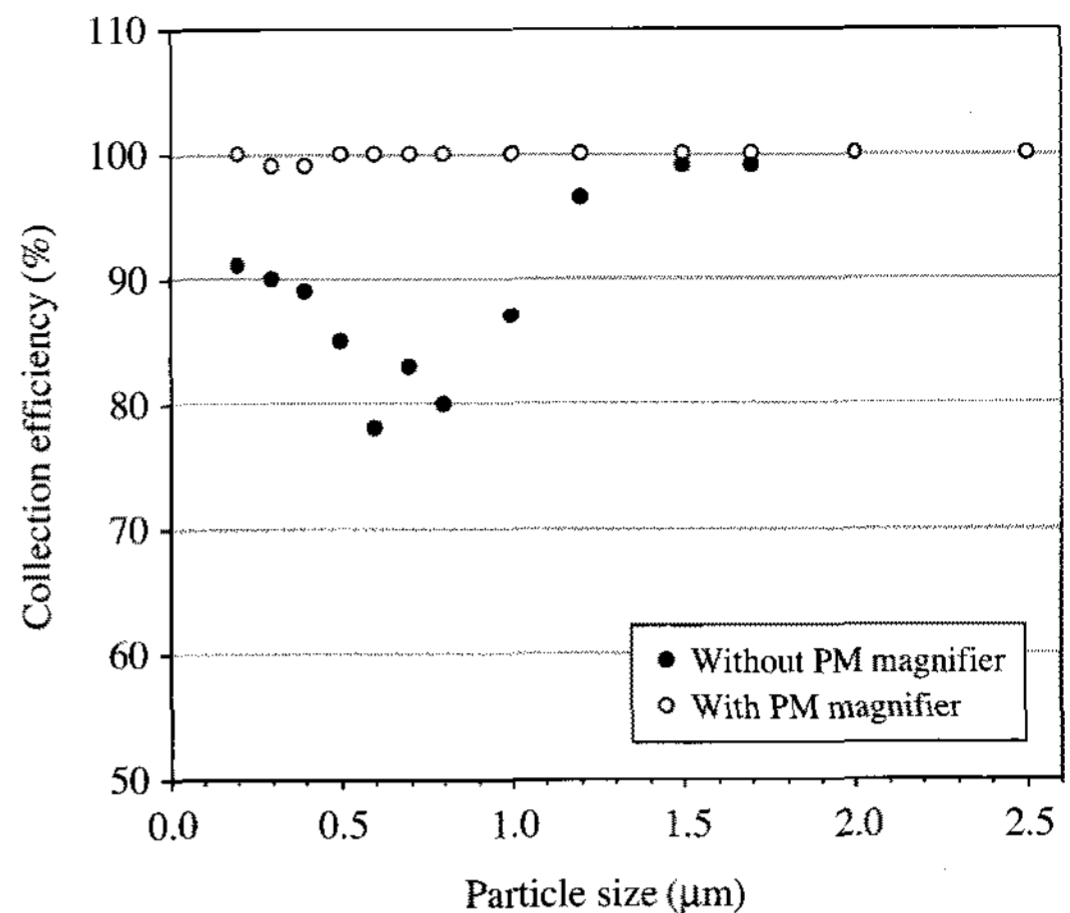
	NaCl	$(\text{NH}_4)_2\text{SO}_4$	NH_4NO_3
Density (g/cm^3)	2.16	1.77	1.72
Solubility ($\text{g}/100 \text{ cc}$, cold water)	35.7	70.6	118.3

Reference: Handbook of chemistry and physics, 60 edition, CRC Press, page: B-55, B-56, B-125

As mentioned above, the reason is that the dominant particle collection mechanism is Brownian diffusion for fine particles and inertial impaction for large particles in wet scrubbers (Kim *et al.*, 2003b). The minimum collection efficiency was observed around $0.6 \mu\text{m}$ where both the mechanisms were weak.

As shown in Fig. 4, the collection efficiencies of the PM sampler having the PM magnifier were much higher than those of the PM sampler without the PM magnifier. The collection efficiency for the PM sampler was about 100% in the whole particle size range. As mentioned above, it is believed that particles are condensed by the aerosol condensation system and the grown particles are collected much more due to increased inertial impaction.

This work can contribute to the collection or removal of fine particles from the air, and can be applied to the sampling of ambient aerosols for chemical composition analysis which is focused on the small particles (Hong *et al.*, 2008). Fig. 5 shows the application of the PM sampler with a PM magnifier to the chemical composition analysis of fine ambient aerosols ($\text{PM}_{2.5}$). In this field test, the major ions which were measured by two different sampling methods were compared each other: One was the semi-continuous ion monitoring system using our PM sampler and the other a previous method, which was the 12-

**Fig. 4. Collection efficiency of the PM sampler via the PM magnifier with NaCl particles.**

hour filter-based method (Hong *et al.*, 2008; Park *et al.*, 2004).

The semi-continuous ion monitoring system consists of three major parts; an aerosol sampling part such as $\text{PM}_{2.5}$ cyclone (URG-2000-30EH, 16.7 L/min) inlet connected to denuder systems (URG-2000-30 242-3CSS, 16.7 L/min), particle collection part, and analytical part using ion chromatography unit. In this system, samples were drawn through a $\text{PM}_{2.5}$ cyclone and denuders to remove interfering gases. Then, the introduced aerosols were easily collected in our PM sampler. The dissolved samples were continuously analyzed by the on-line two channel ion chromatography system. By taking into account the IC sensitivity, the sample flow rate, and the liquid flow rate, the detection limit (DL) of the whole system was estimated for individual species: Na^+ and NH_4^+ ; $0.20 \mu\text{g m}^{-3}$, K^+ ; $0.25 \mu\text{g m}^{-3}$, Ca^{2+} and Mg^{2+} ; $0.50 \mu\text{g m}^{-3}$, Cl^- , NO_3^- , and SO_4^{2-} ; $0.10 \mu\text{g m}^{-3}$. In case of filter method, DL was determined as two times the uncertainty of the field blank divided by air volume (m^3), the nominal volumes of 12 h sampling. They were $0.02 \sim 0.07 \mu\text{g m}^{-3}$ for cations and $0.04 \sim 0.05 \mu\text{g m}^{-3}$ for anions.

Fig. 5 indicates that the semi-continuous ion monitoring system could measure particular modes in ionic species of fine ambient aerosols (see the

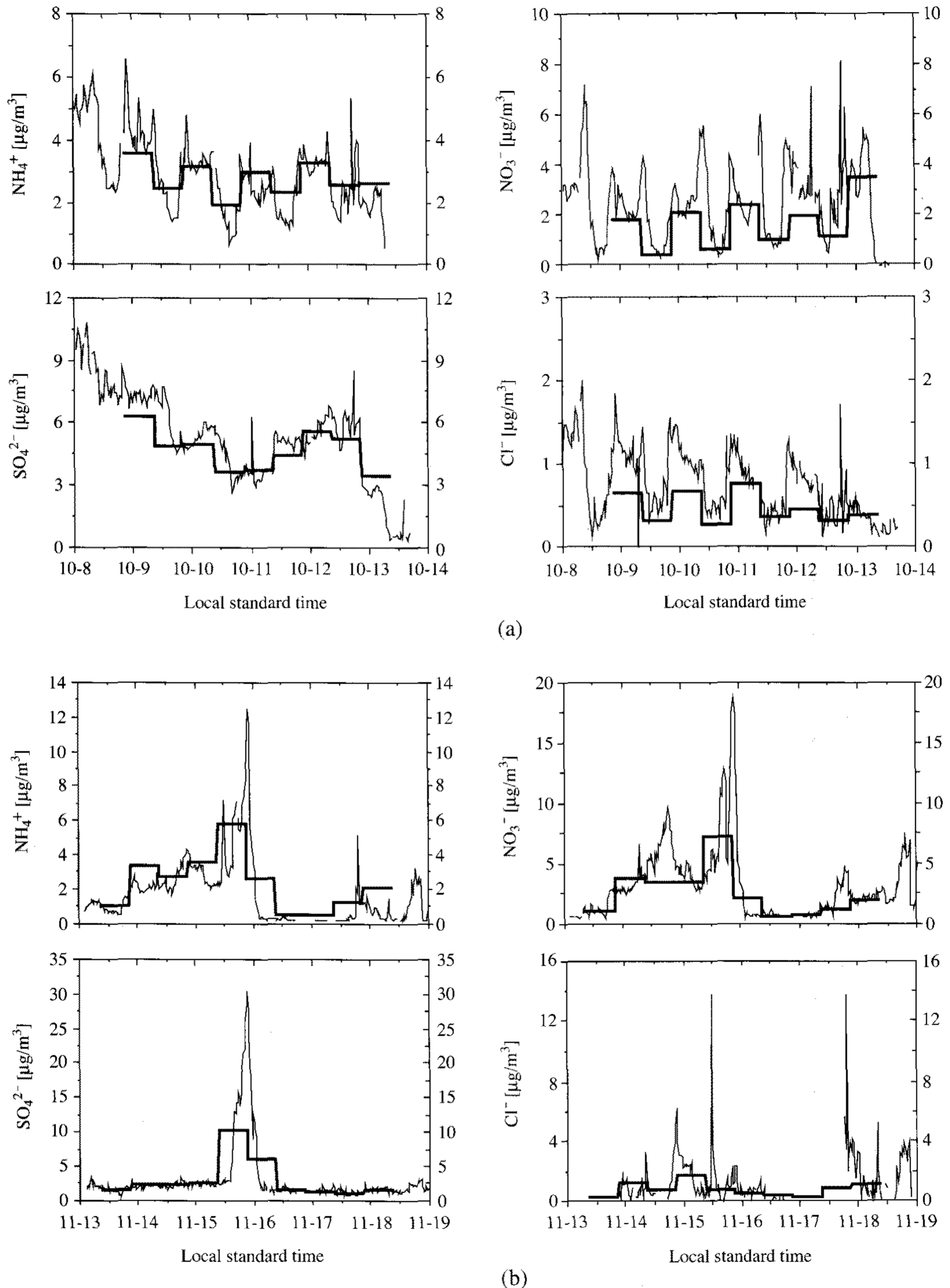


Fig. 5. Comparison of the major ions measured by the semi-continuous ion monitoring system with those measured by the 12-hour filter method (—: semi-continuous ion monitoring system, —: filter measurement; (a) Oct. 8~Oct. 14, (b) Nov. 13~Nov. 19).

data measured at the afternoon on Nov. 15, 2003), and the filter-based method could not measure in the right manner these short-lived events. In addition, the data measured by the semi-continuous ion monitoring system showed that concentrations of inorganic species in fine ambient aerosols were varying continuously during the time interval of filter-based technique. Therefore, it is believed that the data with short time resolution are very useful to interpret the chemical characteristics of aerosols.

4. CONCLUSIONS

In the present study, a new PM sampler was developed to collect fine particles, and laboratory and field tests were carried out to evaluate the performance of the sampler. In conclusion, it is believed that the solubility of aerosols is an important variable in the aerosol condensation, and the degree of condensational growth is directly proportional to the solubility of the particles. As a result of the PM sampler, it was found that the collection efficiencies of the PM sampler having the PM magnifier were much higher than those of the PM sampler without the PM magnifier. It is believed that particles are condensed by the aerosol condensation system and the water absorbed particles are collected much more due to increased inertial impaction. In addition, our results of the laboratory and field tests demonstrated that our novel PM sampler could contribute to the collection of fine particles and could be applied to the sampling of ambient aerosols for chemical composition analysis in that this sampler could make a semi-continuous ion monitoring method more effective.

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