Development of a battery-driven passive sampling system for electrostatically trapping atmospheric particles

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ABSTRACT
A passive (without a pump) sampler for electrostatically trapping particles suspended in the gas-phase was developed. The newly developed system is powered by AA size cell battery, which then converted to around 1300 V (DC). The system was tested in positive and negative charges by a combustion-made magnesium oxide as well as the outdoor particles. The particles suspended in the gas-phase were also measured by an online particle-sizer system. The collected particles were mainly measured by optical- and electron-microscopes, besides UV-Vis-NIR and XRF methods. The results show that the system is able to trap particles with size less than 1μm (submicron particles).

Key words: aerosol; electrostatic charge; particle number concentration; combustion; PM
1. Introduction

A need exists for “easy-to-operate” collection method to more understand the chemistry and dynamics of particles suspended in the gas phase (aerosols). Conventional passive samplers had been used mainly for collecting the gaseous- rather than particulate- matters (PM). In the case of micron-sized (few μm) particles, a portable passive sampler based on charged electret (resin) was proposed and tested by 3–7 μm particles (Brown, et al. 1994), and they also applied the system in urban area (Brown et al., 1998). In the case of non-electrified type, for submicron particles (0.1~1 μm), a metal mesh-covered type sampler combining with the analysis using scanning electron microscopy (SEM) was proposed by Wagner & Leith (2001). They developed a deposition velocity model by focusing on particle deposition as a function of particle size. Without using a mesh, a personal type sampler was developed for micron-sized (up to 100 μm) particles (Vinzents, 1996; Yamamoto, 2011). The passive sampler developed in the present study differs from the previous type passive samplers reported. A metal substrate was used as a collector surface and positive or negative high voltage (~1300 V) was applied on it. Laboratory-made model submicron-sized particles and outdoor aerosol particles were collected and analyzed to prove the ability of the newly developed sampler.

2. Design and experimental evaluation

The schematic diagrams of the passive sampler shown in Figs. 1 (a, b). The body of the sampler was composed using stainless-steel cover which is grounded. A 61 mm diameter stainless-steel mesh cover was put on the both side of the passive sampler cover Fig. 1. (c). The collection region (6 mm × 6 mm in square size silicon wafer) is located in the centre. A charging system was fabricated by AA size cell battery-driven device, which was a part of a commercial device for killing the insects (e.g. Mosquito Swatters). The voltage produce from the device was ±1.3 kV (positive or negative polarity). The purpose of mesh cover is to make sure the wind speed after calculation inside the passive sampler is below 1 m/s (Tammet, 2001), and to prevent deposition of large particles onto the collection surface. The electric field distribution (for positively charged substrate) inside the passive sampler was obtained by solving Poisson equation (Griffiths, 2012) in associated passive sampler geometry numerically using MATLAB (Matrix Laboratory, MathWorks) in Fig. 1. (d). The result shown that the electric field strength around the silicon substrate is between 250 and 300 kV/m. The present charging system differs from an electrostatic precipitator, which uses corona-charge.
Fig. 1. Schematic diagram of sampler from (a) side, and (b) from top, (c) Three samplers experiment apparatus, from left is plus, without charge and minus, and (d) Numerical simulation for electric field strength inside the sampler (positively charged substrate).

Two series of sampling experiments were carried out using laboratory-generated model (Mg-based) particles and outdoor particles by same passive sampler. As for the outdoor collecting site, a veranda at our building at Tokyo University of Agriculture and Technology (TUAT) was selected. TUAT is in the west Tokyo, approximately 20 km from Shinjuku, which is one of urban area in Tokyo, 30 km from Takao Mountain (~600 m) and 30 km from Tokyo Bay. The coordinate of the study site is 35°41’59.6”N 139°31’11.1”E. The sampling point is situated at second floor of building (5 meters from ground level), which same height in the middle of canopy (trees). The smooth surface of silicon wafer can maintain the collected particles could be analyzed with small hindrance. To minimize the contamination of the surface, silicon wafer was cleaned using a reported method (Kern, 1990). For collecting the model particle, magnesium oxide (MgO), the sampler was placed inside the 400 litres chamber (Fig. 2). The air inlet was directly connected to the atmospheric air by the channel on the top of the chamber, which allows the air to enter freely. To prevent outside particles entering the chamber, a HEPA filter system was set inside the air inlet.
Fig. 2. Particle generation (combustion of Mg in 400 L chamber) and a system for real-time measurement of size distribution.

Fig. 3. A result (velocity, m/s) of CFD numerical simulation for the chamber, when flow was pumped out via a pipe.

Fig. 3. shows the numerical simulation based on a CFD (Computational Fluid Dynamic) software (COMSOL Multiphysics, Stockholm) for the flow pattern inside the chamber. The flow is laminar even though the outflow is pumped out in moderate pumping speed up to 20 litres per minute in air outlet. "Slow" air velocity in the chamber was needed to ensure the motion of micron and submicron size particle following the path of the air flow or low Stokes number (Hinds, 1999). A magnesium ribbon (Wako Pure Chemical Industries, Ltd, Tokyo) was cut into 0.8 g per run. 0.5 L bottle (glass) was used as a diluter which allow 10-times dilution before the sample measured by a real-time Optical Particle Sizer (OPS 3330, TSI Corp, Minnesota). Chamber temperature was approximately maintained to room temperature (298K) and the measuring time was 30, 60, and 90 minutes. The passive samplers will be put inside the chamber in advance before running the experiment. After Mg ribbon was burned for few seconds, 4 USB-driven fans, which used to mix the air and in the same time the real-time sizing measurement by OPS will be "on". After 2 minutes mixing, the fans will be "off" and after 10 minutes, the fans will be "on" again for cleaning chamber, after took out all the samplers beforehand. The passive samplers were transported to the analytical site in a protective case. The mesh cap will be opened and the substrates took out for further analysis. In the case of outdoor particles, the collections time were also the same with the chamber. To maintain the durability of the high-voltage, all collecting experiments were performed by pulsing ("on" or "off") the charge manually with the interval time less than 1 second. The size and morphology of the deposited particles was observed using SEM (JEOL, JSM 6335F, Tokyo) and optical microscope (Keyence, VH-2450, Tokyo). For elemental- and another optical-analysis, an X-ray fluorescence spectrometer (XRF, JSX-3100R II, JEOL Corp., Tokyo) and a microspectroscopy system (transmittance/reflectance type UV-Vis/NIR, MSV-300, JASCO, Tokyo) were used. However, XRF and UV-Vis/NIR did not detect any signal (element) from the substrate because the "layer" of the collected particle was too thin for these techniques to detect.
3. Results and Discussion

Morphologies, number concentrations and particle size distributions of collected particles were obtained from optical microscope and SEM images. Random fields of images were selected, and the size distribution was analyzed by an image analysis software (ImageJ, NIH, Maryland) and a reported method (Wagner and Leith, 2010). Examples of analyzed results were shown in Fig. 4. The average size of the deposited particles is in sub-micron range (Fig. 4), which is in agreement with the size of particles suspended in the gas phase (measured by OPS) which was 0.3 μm. The outdoor (charged) particles were measured and shown the same size range with the laboratory-made MgO particles.

![SEM images of collected MgO after 90 minutes and their particle size (number) distributions](image)

Fig. 4. SEM images of collected MgO after 90 minutes and their particle size (number) distributions (a) positively charged substrate, (b) negatively charged substrate.

Fig. 5 shows the difference between images obtained from SEM and optical microscope for outdoor particles. Considering the limit of these instruments, it is clear that the size ranges of SEM are "sharper" in the case of submicron particles. It should be noted that SEM uses vacuum conditions, which may change the adhesion of deposited particles. Table 1 show the number concentration versus collection time at different polarities (positive or negative charged). It is not clear why the ratios of number concentrations of negatively charged Mg-based particles are lower than unity. For a reference, the mass-based data of suspended particle materials (SPM, with size up to 10 μm) published officially by Tokyo Metropolitan Government is also shown. There is a high value of SPM on 2014/2/27 data. The number concentration our collected outdoor (submicron) particles was not higher than other collection
day (2014/1/27). On 2014/2/27, the ratio of positive/negative charged particles ("pollution index" (Pawar (2013))) was 8.3, which was the highest value among our collected data. High value of "pollution index" may be having relation with high SPM value. Without considering the size of particles, Pawar (2013) claimed that the pollution index around the unity is "good" for human health. The "pollution index" of our outdoor (submicron) particles was higher than unity. From Trans-Siberian railroad measurement, Vartiainen et al. (2007) reported their "pollution index" averagely were slightly higher than unity, in the case of their "large" ions (7.5 ~ 40 nm), however the "index" was smaller than unity in the case of "small" ions (around 1 nm). They claimed that their "index" appeared to correlate with the background aerosol particle number concentration. When the "index" is larger than unity, probably the charged particles were newly generated and collected from a source that emitted more positively than negatively charged particles. On the other hand, we found that PM$_{2.5}$ (size range up to 2.5 μm) collected on the filter media (in Yokohama city, Japan, between 2013/6 and 2014/2) were mainly negatively charged particle (Okuda T., 2015).

Fig. 5. Images of outdoor particles (collected on positively charged substrates).
The finding of the present study suggest that the role of background ionization did effect the charge of the outdoor particle but the charge probably will be constantly neutralized by opposite–charged ions, which lead to almost same amount of particle in positively and negatively charged substrate (Yu et al., 2000). This present study may throw up many questions in need of further investigation. Further work needs to be done to establish to resolve the cause and reason of difference number concentration of charged particles based on collection sites and events.

4. Conclusion

In summary, we have presented a system for collecting particle suspended in the gas-phase based on electrostatic force. Regardless of the different materials (elements) used during the experiment, this technique can collect particles in the range of submicron (less than 1 μm). There were slightly differences in the particle number concentration between positively and negatively charged substrates. We expect this technique open to up an entirely new range of particles for better monitoring outdoor and indoor air qualities.

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References


