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Performance evaluation of an electrometer system for ion and aerosol charge measurements

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Abstract−An aerosol electrometer system for measuring ion and aerosol charge using electrostatic detection technique was developed and presented. It consists of a size-selective inlet, a particle charger, an ion trap, a Faraday cup, an electrometer, and a data acquisition and processing system. In this system, an aerosol sample first passes through the size-selective inlet to remove particles outside the measurement size range based on their aerodynamic diameter, and then passes through the unipolar corona charger that sets a charge on the particles and enters the ion trap to remove the free ions. After the ion trap, the charged particles then enter the Faraday cup electrometer for measuring ultra low current of about 1 pA induced by ion and aerosol charge collected on the filter in Faraday cup corresponding to the number concentration of ion and aerosol. Signal current is then recorded and processed by a data acquisition system. Finally, the detailed description of the operating principle of the system as well as the preliminary experimental testing results of ion and aerosol charge measurements were also introduced and discussed.

Key words: Aerosol, Ion, Faraday Cup, Electrometer

INTRODUCTION

Detection and measurement of ion and aerosol charges have become an important topic in atmospheric pollution monitoring and source characterization. In recent years, considerable interest has been given to submicron-sized aerosol particles, defined as aerosols with diameter less than 1 μm, for two main reasons. First, such particles have been associated with adverse health effects in areas of high concentrations, and second, aerosols are believed to have a significant influence on atmospheric quality, climate at a local and global scale and processes in various industries such as food, pharmaceutical and medical, electronic and semiconductor industries [1]. Ion and aerosol charge detectors have been developed to monitor indoor and outdoor aerosols for pollution and process control industry for this purpose. A widely used instrument capable of detecting ion and aerosol charge is an electrical aerosol detector (EAD). A typical EAD consists of two key components: one for aerosol charging, and the other for measurement of the current or charges on charged aerosols with an electrometer. Readout of an EAD depends strongly on the charging technique used.

There have been numerous studies and developments on the EAD, with recent developments reviewed by Intra and Tippayawong [2]. Many previous studies concern the measurements of number and surface area concentration of nanoparticle and fly ash [3-6], ambient ion and aerosol charge measurement [7,8], aerosol integral parameter measurement [9], and nanoparticle size distribution measurement [10]. An available commercial instrument designed to measure net charge on aerosol particles is the TSI Model 3070A Electrical Aerosol Detector [11]. An alternative instrument that can also be used to detect aerosol particles is a condensation particle counter (CPC) which uses particle growth and optical property [12,13]. These commercial instruments are widely used for detecting airborne ultra fine particles and provide high-resolution measurement, but they are very expensive and large. A CPC does not operate in ambient temperatures outside the control range of 10 to 34 ºC, and the pump and flow sensor of the CPC cannot control the flow when the pressure at the aerosol inlet, the make up air inlet, or the pump exhaust is too high or too low. The CPC must be carefully moved to protect the optics from contamination with a working fluid like alcohol. In addition, the CPC has a size-dependent counting efficiency, with low detection efficiency for particle size less than ~30 nm [13].

The movability of instruments should be considered in monitoring ion and airborne aerosol particles. To avoid this problem, an inexpensive detector, suitable for detection of ion and aerosol number concentrations, was developed and experimentally tested in this study. This system is based on unipolar corona charging and electrostatic detection of highly charges. A detailed description of the operating principle of the system as well as the preliminary experimental testing results of ion and aerosol charge was also introduced and discussed.

MATERIALS AND METHODS

1. Aerosol Electrometer System

Fig. 1 shows the schematic diagram of the aerosol electrometer system developed in this study. The system is composed of a size selective inlet, a particle charger, an ion trap, a Faraday cup, an electrometer circuit, and a data acquisition and management system. In this study, a flow system is regulated and controlled by means of mass flow controllers with a vacuum pump. Adjustable DC high voltage power supply modules, a Bertan model PMT-05CP and PMT-

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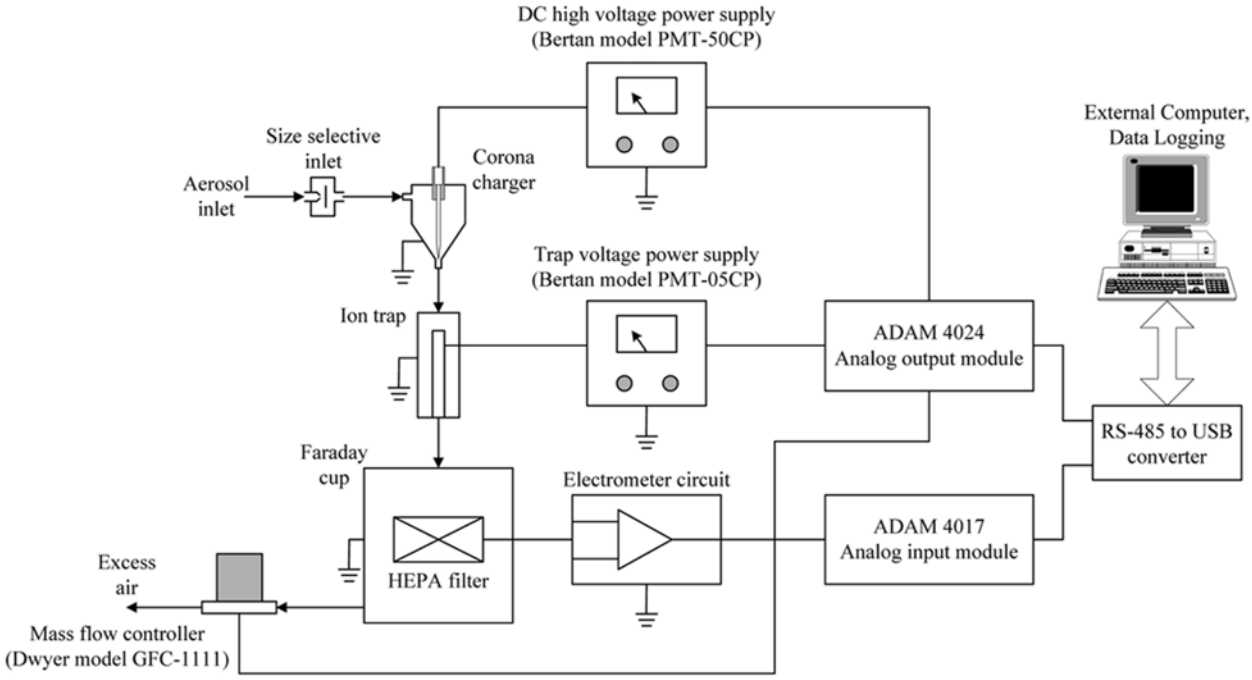

Fig. 1. Schematic diagram of the aerosol electrometer system.

50CP, are used to maintain the voltage difference of the ion trap and particle charger. The output voltages of the modules were controlled by the ADAM-4024 analog output module. In this system, sampled aerosols are first passed through a size-selective inlet to remove particles with diameter larger than 1.0 μm, based on their aerodynamic diameter upstream of the system [14]. Submicron aerosols are then directly introduced into the corona-needle charger to charge the aerosol particles by ion-particle collisions via diffusion charging and field charging mechanisms [15]. Charged aerosol particles exiting from the charger are passed through an ion trap, with the voltage set at 150 V to remove the high electrical mobility of free ions after the charger; the free ions can potentially reach the detector and ruin the measurement [16]. The electrical charges carried by particles are measured in a Faraday cup electrometer downstream of the ion trap. To transfer charges gathered at the filter to an electrometer that is outside the faraday cage, a BNC connector is connected to the filter holder. In this work, the outer surface of the filter holder is electrically connected to a BNC connector by a spring-loaded contact. The whole measurement system including electrometer, connectors, and cables can achieve noise levels, on average, of about 100 fA RMS over a sampling time of 100 ms. Thus, the signal current, I_i, of collected charges on the filter in the Faraday cup can be calculated by [15]

$$I_i = N_i e Q \quad (1)$$

where N_i is the total ion number concentration, e is the elementary unit of charge (1.6×10^{-19} C), and Q is the volumetric air flow rate into a Faraday cup. In the case of aerosol charge, the signal current equation, I_p, has to be rewritten as [17]:

$$I_p = n_p(d_p) N_p e Q \quad (2)$$

where N_p is the total particle number concentration, and n_p is the mean charge level of aerosol particles as a function of particle diameter. Finally, the output signal from the electrometer circuit is in the range of 0 to +10 V. It is then sent to the ADAM-4017 analog input module, which is a 16-bit, 8 channel analog input module, controlled and data sampled by an external personal computer via RS-485 to USB converter interface. Software running on an external computer was developed, based on Microsoft Visual Basic programming for all data processing. The software is able to display the ion current and number concentration with a time response of approximately 1 s.

2. Experimental System

In the case of ion measurement, high number concentration of ions was generated by corona discharge with corona-needle charger, typically larger than 3×10^{12} ions/m^3. An air sample was first dried with the dryer. Thus, any remaining water was removed. Dried air sample was filtered through a HEPA filter, and was then drawn into the charger. The ion penetration through the charger was reported to be about 93.7% and 7.7% for positive and negative coronas, respectively [18]. In the case of aerosol charge measurement, the schematic diagram of the experimental setup is shown in Fig. 2. It consists of a combustion aerosol generator (CAG), a dryer, a dilution chamber, a HEPA filter, and a vacuum pump. The CAG was used to generate polydisperse, carbonaceous diffusion flame aerosols for this experiment [4,19]. The particle size distribution of polydisperse aerosols obtained by the electrical mobility spectrometer (EMS) was in the range between approximately 50 nm to 500 nm with particle number concentrations of approximately 10^{11}-10^{12} particles/m^3 with the geometric mean diameter of 208 nm and the geometric standard deviation of about 1.840 [20]. During the measurement, the vacuum pump was switched on and the aerosol sample was sucked into the system using an isokinetic sampling system. The aerosol particles were first dried with the dryer. Before aerosol particles entered the system, the particles were diluted and mixed with clean air, which had been filtered through a HEPA filter, in the mixing chamber. The

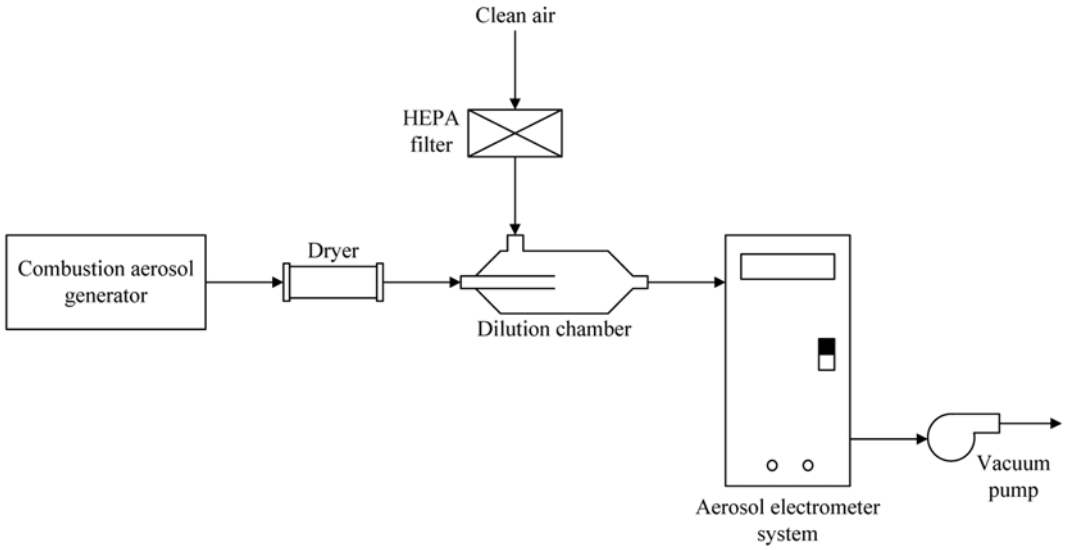

Fig. 2. Schematic diagram of the experimental setup for preliminary testing of the aerosol electrometer system.

system was operated at aerosol flow rate in the range of 5.0-15.0 L/min. To reduce errors due to time variations in the aerosol concentrations, repeat measurements were commenced at least 5 min after the introduction of the aerosol into the measurement system.

RESULTS AND DISCUSSION

1. Ion Measurement

Fig. 3 shows time variation of ion number concentration and signal current from the Faraday cup electrometer. The system was operated at charger voltage of 3.5 kV, ion trap voltage of 150 V, air flow rate of 10 L/min, and operating pressure of 1 atm. In the case of the charger and ion trap voltages being off, there was no ion. Measured signal current from Faraday cup was 0 pA. The number concentration of ions was calculated from measured signal current by Eq. (1). It was shown that ion number concentration was found to be about 1.6×10^{12} ions/m^3, corresponding to measured signal current of about 47 pA when the charger voltage was on, and the ion trap voltage was off. On the other hand, when both charger and ion trap voltages were on, most ions were removed inside the ion trap. For the effect of air flow rate, the variation of measured ion current from Faraday cup electrometer with air flow rates is shown in Fig. 4. Three different operating conditions of the air flow rates were tested. The flow rate was varied by adjusting the outlet mass flow controller in the range between 5.0-15.0 L/min. Ion current was found to be in the range of approximately 22-68 pA, corresponding to the ion number concentration of about 1.5×10^{12} ions/m^3. It was also shown that increasing the flow rate resulted in the increase in ion current. It is well known that the ion current is a function of the air flow rate (Eq. (1)). It was evident that when the air flow rate was increased (short charging time), the ion loss inside the charger due to electrostatic loss was relatively low. Therefore, the ion can be drawn off the charger more easily by faster flowing air. In addition, the effect of air flow rate on corona discharge current of the charger was also reported by Intra and Tippayawong [18].

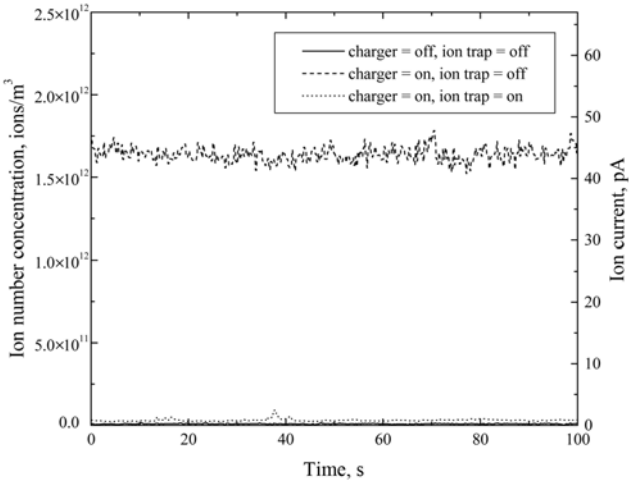

Fig. 3. Time variation of measured ion number concentration and signal current.

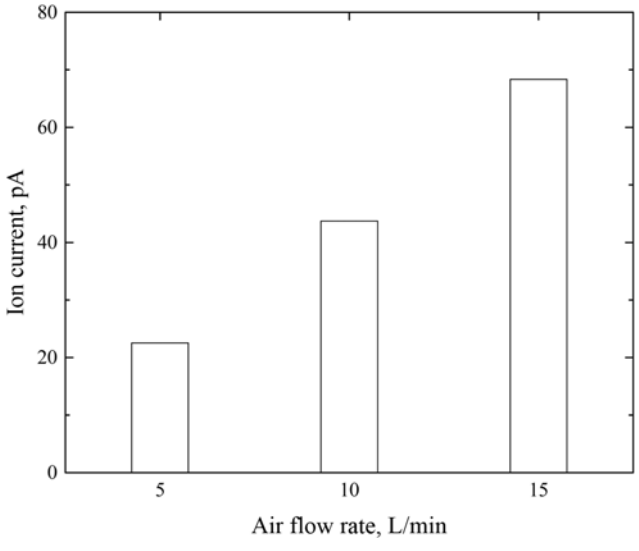

Fig. 4. Variation of measured ion current with air flow rates.

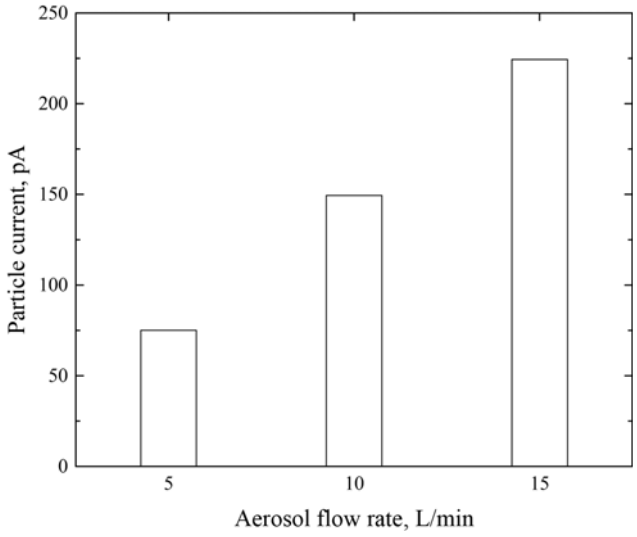

Fig. 5. Variation of measured particle current with aerosol flow rates.

2. Aerosol Charge Measurement

In the case of aerosol charge measurement, the fraction charged as a function of the particle diameter was estimated from White's theory [1]. The average particle penetration through the charger was reported to be about 48%. Fig. 5 shows the variation of measured particle current with aerosol flow rates. Signal current was measured to be in the range of about 75-225 pA, corresponding to the mean particle number concentration of approximately 9.5×10^{11} particles/m^3. An increase in the aerosol flow rate resulted in an increase in measured signal current, because the signal current was approximately proportional to the aerosol flow rate. The larger aerosol flow rates led to more collected charged particles, giving rise to a larger induced current. In addition, high particle number concentration may have led to large signal current because more particles had chances to be collected in this situation. Time variation of measured particle number concentration and signal current from the Faraday cup electrometer at aerosol flow rate of 10.0 L/min are also shown in Fig. 6.

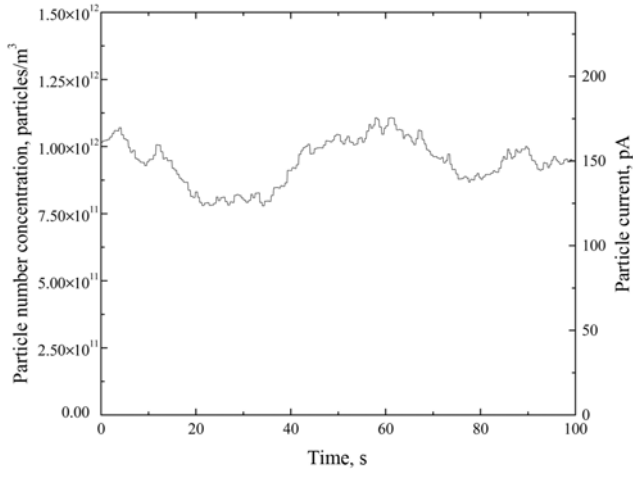

Fig. 6. Time variation of measured particle number concentration and signal current.

CONCLUSIONS

A simple system for measuring ion and aerosol charge with a Faraday cup electrometer has been developed and evaluated in this paper. The detecting method was based on unipolar corona-needle charging and electrostatic detection of highly charges. The system was also experimentally evaluated with the corona discharge charger and the combustion aerosol. Experimental testing results of ion and aerosol charge measurements obtained were very promising. It was demonstrated that the system can be used in detecting the number concentration of ion and aerosol charge of approximately 0 to 2×10^{12} per m^3, corresponding to signal current of approximately 0-250 pA with a time resolution of less than 1 s.

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