A Submicron Electrical Aerosol Detection System with a Faraday Cup Electrometer

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Abstract

Submicron-sized aerosol particles, defined as aerosols with particle diameters less than 1 μm, suspended in air have significant effects on the human health, global climate, air quality and processes in various industries such as food, pharmaceutical and medical, electronic and semiconductor industries. Automotive engines have long been recognized as a major source of submicron-sized aerosol particles. Development of aerosol detection and size distribution measurement methods has been primarily motivated by the need to find better means of monitoring and controlling indoor and outdoor aerosols for pollution and process control industry. In this study, a submicron electrical aerosol detection system for measuring particle number concentration in the size range between 1 nm – 1 μm using electrostatic charge measurement technique was developed. It consists of a size selective inlet, a particle charging system, an ion trap, a Faraday cup electrometer, a signal conditioning and processing system, and an I/O control and human-computer interface. 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 pass through the unipolar corona charger that sets a charge on the particles and enter 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 about 10^{-12} A induced by charged particles collected on the filter in Faraday cup corresponding to the number concentration of particles. Signal current is then recorded and processed by a data acquisition system. A detailed description of the operating principle of the system as well as main components was presented. The performance of the prototype electrometer circuit used in this work was evaluated and compared with a commercial electrometer and good agreement was found from the comparison. Finally, the preliminary experimental testing results were also shown and discussed.

Keywords: aerosol, particle, Faraday cup, electrometer

1. Introduction

Detection and measurement of aerosol particles have become an important topic in atmospheric pollution monitoring and source characterization. In recent years considerable interest has been shown to submicron-sized aerosol particles, defined as aerosols with particle diameters 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]. A submicron-sized aerosol particle instruments have been developed to monitoring indoor and outdoor aerosols for pollution and process control industry for this purpose [2, 3].

There are several commercial instruments using various methods of detecting and measuring the size distribution and number concentration of particles. Available instruments include a Scanning Mobility Particle Sizer (SMPS) using electrical mobility of particles [4], a Condensation Particle Counter (CPC) which uses particle growth and optical property [5, 6], an Electrical Aerosol Detector (EAD) which uses electrostatic charge measurement technique [7], and an Electrical Low Pressure Impactor (ELPI) using inertia impaction of particles under low pressure [8]. These commercial instruments are widely used for measuring airborne ultra fine particles and provide high-resolution measurement, but they are very expensive and larges sizes. According to the instruction manual for CPC (Model 3010, TSI Inc), a CPC does not operate in ambient temperatures outside the control range of 10ºC to 34ºC, and the pump and flow sensor of a 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 [6]. In addition, the CPC should be carefully moved in caution to protect the optics contamination from
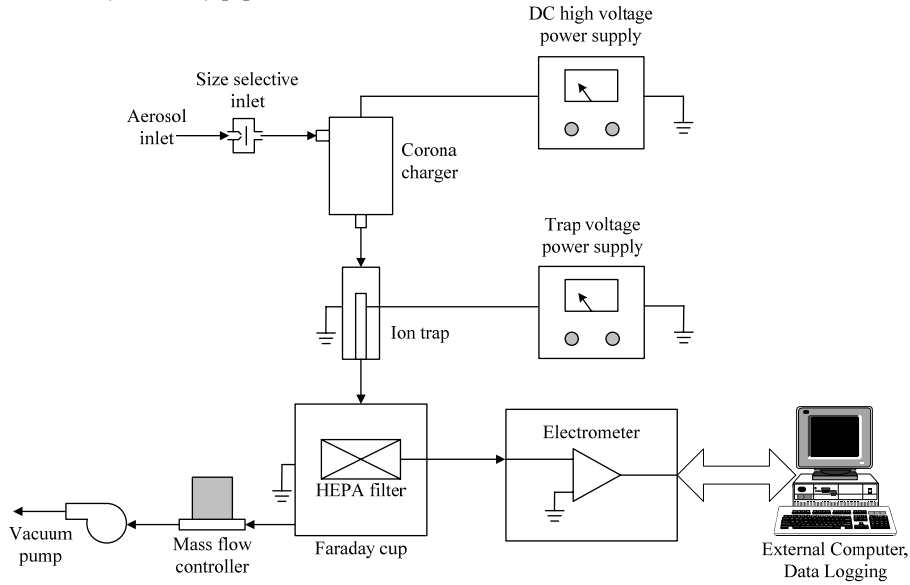
working fluid like alcohol (C_4H_9OH) [6].

Figure 1. Schematic diagram of the submicron electrical aerosol detection system.

The movability of instruments should be considered in monitoring airborne aerosol particles. To avoid this problem, an inexpensive detector, suitable for detection of particle number concentration in the submicron size range, was built and experimentally tested in this study. This system is based on unipolar corona charging and electrostatic detection of highly charged particles. A detailed description of the operating principle of the sensor was presented. The performance of the prototype electrometer circuit used in this work as well as the preliminary experimental testing results were also shown and discussed.

2. A Submicron Electrical Aerosol Detection System

The following paragraphs give a detailed description of main components of the detection system. Figure 1 shows the schematic diagram of the submicron electrical aerosol detection system, developed in this study. The system is composed of a flow system is regulated and controlled by means of mass flow controllers with a vacuum pump, a size selective inlet to remove the particle outside the measurement range, a particle charger using corona discharge technique to charge the particles, an ion trap to remove the high electrical mobility of free ions after charger, a Faraday cup to collect charged particles, an electrometer for measuring signal current from the Faraday cup, and a computer controlled data acquisition and management system.

2.1 Size Selective Inlet

The inertial impactor was used to remove particles larger than a known aerodynamic size, upstream of the system. The aerodynamic particle size at which the particles are separated is called the cut-point diameter. In the impactor, the aerosol flow is accelerated through a nozzle directed at a flat plate. The impaction plate deflects the flow streamlines to a 90° bend. Particles with

sufficient inertia are unable to follow the streamlines and impact on the plate. Smaller particles are able to follow the streamlines and avoid contact with the plate and exit the impactor. The particle collection efficiency of the impactor, E, is determined from [9]

$$E = \left[1 + \left(\frac{d_{50}}{d_p} \right)^{2s} \right]^{-1} \qquad (1)$$

where d_p is the particle diameter, and d_{50} is the particle cut-off diameter at 50% collection efficiency can be calculated by [1]

$$d_{50} = \sqrt{ \frac{9 \pi \eta D^3 \text{Stk}_{50}}{4 \rho_p Q_a C_c} } \qquad (2)$$

where C_c is the Cunningham slip correction factor, η is the gas viscosity, D is the acceleration nozzle diameter, Stk_{50} is the Stokes number for the particle cut-off diameter at 50% collection efficiency, ρ_p is the particle density, and Q_a is the aerosol flow rate.

2.2 Particle Charger

The corona-needle charger used in the present study consists of a coaxial corona-needle electrode placed along the axis of a cylindrical tube with tapered ends [10]. The needle electrode is made of a stainless steel rod 3 mm in diameter and 49 mm length, ended in a sharp tip. The angle of the needle cone was about 9° and the tip radius was about 50 μm, as estimated under a microscope. The outer cylindrical is made of aluminum tube 30 mm in diameter and 25 mm length with conical shape. The angle of the cone was about 30° and the orifice diameter was about 4 mm. The distance between the needle electrode
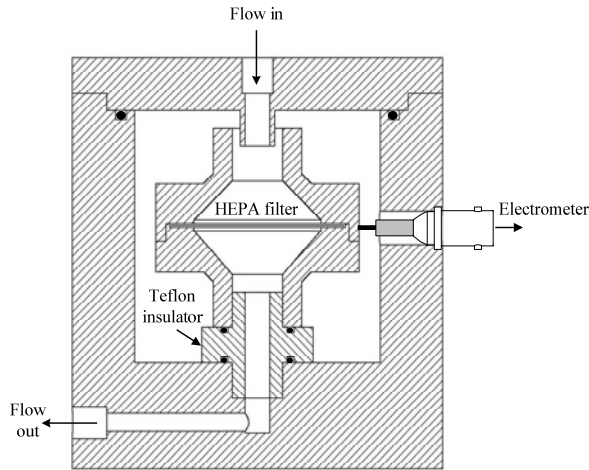
and the cone apex is 2 mm.

Figure 2. Schematic diagram of the Faraday cup.

The corona electrode head is connected to a DC high voltage supply, while the outer electrode is grounded. An adjustable DC high voltage power supply is used to maintain the corona voltage difference, typically of the order of 1.0 – 5.0 kV. The corona discharge generates ions which move rapidly in the strong corona discharge field toward the outer electrode wall. Aerosol flow is directed across the corona discharge field and is charged by ion-particle collisions via diffusion charging and field charging mechanisms.

2.3 Ion Trap

The ion trap was used to remove the high electrical mobility of free ions after the charger. As the free ions can potentially reach the detector and ruin the measurement, a trap field is introduced just after the corona charger. The trap field is across the aerosol flow and has a 200 V, and the trap penetration, P_{trap}, is given by [1]

$$P_{trap} = 1 - \frac{2\pi Z_i V L}{Q_a \ln(r_2/r_1)} \qquad (3)$$

where Z_i is the mobility of ion (equal to 0.00014 m^2/V.s for the positive ion), V is the trap voltage, L is the trap length, and r_1 and r_2 are the inner and outer radii of the electrode, respectively.

2.4 Faraday Cup

Figure 2 shows schematic diagram of the Faraday cup. To completely shield the HEPA (high efficiency particulate air) filter collecting the charged particles, external case is made of a stainless steel, and HEPA filter is electrically disconnected from the external case with Teflon stand. The Faraday cup plays a role to prevent electric noise to measure very low current caused by charged particles, which are collected by an internal HEPA filter. If the object of measurement is not shielded completely, noise which is 1000 times of resolutions to

be expected. To transfer charges gathered at the HEPA filter to an electrometer that is outside the faraday cage, BNC connector is connected to HEPA filter. Because material of HEPA filter is conductor such as glass fiber, charges collected in the filter can move to the electrometer through the low noise cable and BNC connector without delay. In the case of existing aerosol electrometer airflow is curved at 90 degrees while air is drifted from sampling probe to the filter. It can become the cause of charge loss. To solve this problem airflow into faraday cage is straighten not to change the direction of the flow and loss the charge. The particle number concentration, N_p, is related to the signal current, I_p, at HEPA filter is given by [11]

$$N_p = \frac{I_p}{n_p(d_p)eQ_a} \qquad (4)$$

where n_p is the number of elementary charge units, e is the elementary unit of charge (1.6 × 10^{-19} C), and Q_a is the volumetric aerosol sampling flow rate into a Faraday cup. The average number of elementary charges carried by particles with diameter, d_p, and is given by following equation [1]

$$n_p(d_p) = \frac{d_p kT}{2K_E e^2} \ln\left[1 + \frac{\pi K_E d_p \overline{c}_i e^2 N_i t}{2kT}\right] \qquad (5)$$

where $\overline{c}_i$ is the mean thermal speed of the ions (240 m/s), k is the Boltzmann's constant (1.380658 × 10^{-23} J/K, for air), T is the temperature, K_E is the constant of proportionality, N_i is the ion concentration, and t is the residence time of the particle charger. For the corona-needle charger, an approximate expression for the $N_i t$ product can be derived [10]:

$$N_i = \frac{I_i d}{\pi(r_1 + r_2)\sqrt{(r_1 - r_2)^2 + L^2} e Z_i V} \qquad (6)$$

where I_i is the charging current, d is the distance between the electrode tip and the cone apex, r_1 and r_2 are the inner and outer radii of a conical frustum, respectively, L is the length of the charging zone, and V is the corona voltage.

2.5 Sensitive Electrometer

The schematic presentation of an electrometer circuit design for aerosol detection system is shown in Figure 3. This circuit is a simple current-to-voltage converter, where the voltage drop caused by a current flowing through a resistor is measured. The circuit adopted two cascaded negative feedback amplifiers. Extra component in this circuit is primarily for fine offset voltage adjustment and input/output protection. A 12V power supply capable of providing 100 mA is required. The feedback capacitor and RC low-pass filter were used to reduce high-frequency noise and to prevent oscillations of the amplifier output [12]. In order to avoid expensive

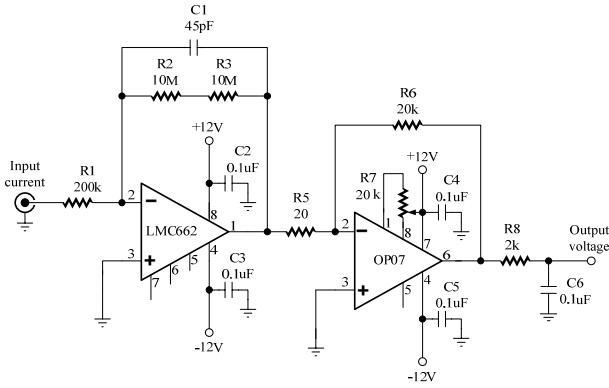construction, commercially-available low-cost monolithic operational amplifiers were used.

Figure 3. Schematic diagram of the sensitive electrometer circuit.

The commercially-available operational amplifiers used in this circuit is the LMC662, which was designed for low current measurement and featured ultra-low input bias current (2 fA maximum) and low offset voltage drift (1.3 μV/°C) [13]. The output voltage, V_o, of this circuit is given by the following equation:

$$V_o = I_i R_1 \left(\frac{R_2 + R_3}{R_1} \frac{R_6}{R_5} \right) \qquad (7)$$

where I_i is the input current, R_1 and R_5 are the input resistors of the first and second amplifiers, respectively, R_2 and R_3 are the feedback resistors of the first amplifier, and R_6 is the feedback resistors of the second amplifier. This circuit gives an output voltage of 10 mV per 1 pA of input signal current. The electrometer circuit was calibrated with a current injection circuit, high-impedance current source [12]. It consists of an appropriately high-standard resistor (10 GΩ) and an adjustable voltage source in the range between 0 – 5 V. The output current of this circuit can simply be calculated from the Ohm's law.
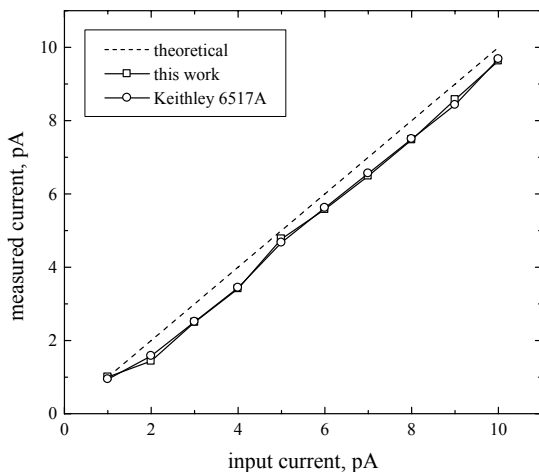

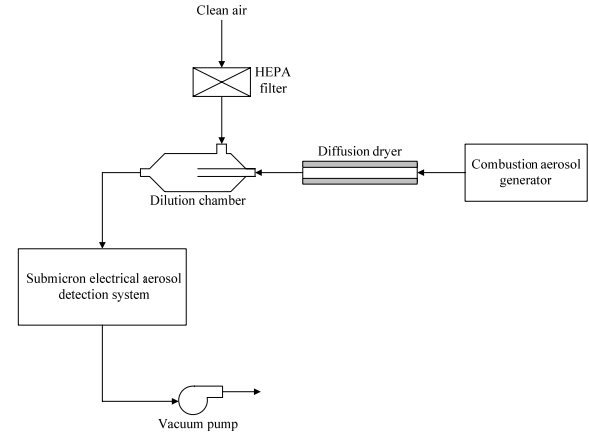Figure 4. Performance comparison between the prototype and commercial electrometer.

Figure 5. Schematic diagram of the experimental setup for preliminary testing of the submicron electrical aerosol detection system.

The range of the output current is from 1 pA to 10 pA. It should be noted that the electrometer circuit input was operated at virtual ground potential during calibration and subsequent current measurement. The output voltage from the electrometer circuit was measured and recorded by a highly-accurate digital voltmeter. The voltage reading was then translated into the current measurement. The comparison of measured current from this work and a commercial electrometer, Keithley model 6517A, with high-accuracy current source is shown in Figure 4. It was shown that the measured current was rising linearly as input current increased. Generally, the currents measured from this work were found to agree very well with those measured by the Keithley model 6517A. Very small difference about 5% was obtained.

2.6 Data Acquisition and Processing System

The measurement is controlled and data sampled by an external personal computer via RS-232 serial port cable. 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 particle number concentration.

3. Preliminary Experimental Testing

Figure 5 shows the schematic diagram of the experimental setup for preliminary testing of the submicron electrical aerosol detection system. The combustion aerosol generator was used to generate a polydisperse carbonaceous diffusion flame aerosol for this experiment. Stable polydisperse aerosols with particle number concentrations of approximately 10^{12} – 10^{14} particles/m^3 were obtained [14]. The particle size obtained by scanning electron microcopy (SEM) was in the range between approximately 10 nm – 10 μm. Figure 6 shows the particle morphologies of agglomerates obtained from the scanning electron micrograph, taken with a JEOL JSM-6335F Field Emission Scanning

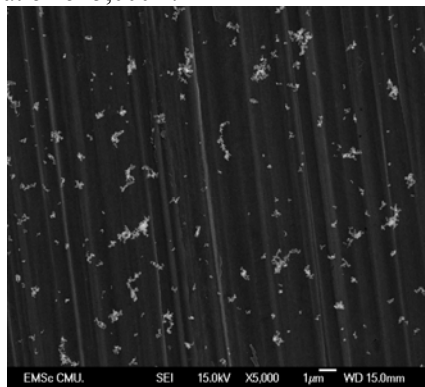Electron Microscope, operated at 15 kV and magnification of 5,000X.

Figure 6. Scanning electron micrograph of sampling particle from the generator.

The particles were first dried with the diffusion drier. Thus, any remaining water was removed. Before aerosol particles entering the system, the particles were diluted and mixed with clean air, which had been filtered through a HEPA filter, in the mixing chamber. The system was operated at aerosol flow rate in the range of 1.0 – 4.0 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.

In this paper, four different operating conditions of the aerosol flow rate were preliminary experimental tested on the particle number concentration measurements of the system. Variation of aerosol flow rate was carried out by adjusting the inlet mass flow controller in the range of 1.0 to 4.0 l/min and the operating pressure was about 1000 mbar. Figure 7 shows variation of measured particle number concentration and signal current with aerosol flow rates. The measured signal current and the particle number concentration were found in the range of approximately 90 – 700 pA and 3 – 7×10^{13} particles/m^3, respectively. It was found that an increase in the aerosol flow rate resulted in an increase in measured signal current corresponding to the particle number concentration because the signal current was approximately proportional to the aerosol flow rate.

4. Conclusions and Future Work
The system for detecting the number concentration of submicron-sized aerosol particles with a Faraday cup electrometer has been presented and described in this paper. The detecting method was based on unipolar corona charging and electrostatic detection of highly charged particles. It was able to detect particle number concentration in the submicron size range. A prototype of the system has been constructed and evaluated. Preliminary experimental testing results obtained were very promising. It was demonstrated that the system can be used in detecting the number concentration of the particles.

The following paragraphs give specific recommendations for further research work on both the theoretical and experimental parts of the detector development.
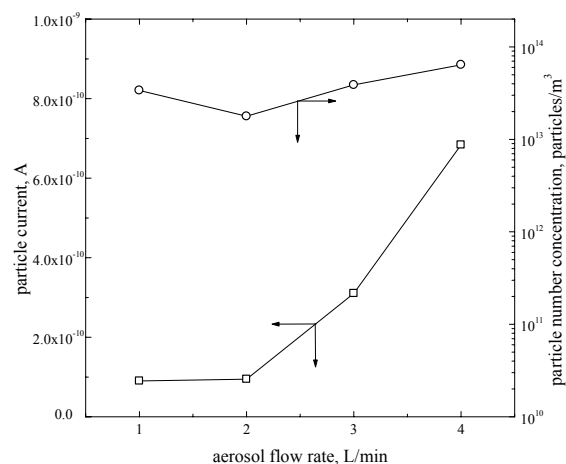

Figure 7. Variation of measured particle number concentration and current with aerosol flow rates.

- There are various techniques and devices exist for generating aerosol samples to testing and calibration of any instrument that measures aerosol particles. One of the most widely used techniques of generating monodisperse aerosol particles is by using the Tandem DMA method. The main advantage of this method is the wide range of particle sizes it can generate. Further research, may involve the Tandem DMA.
- Calibration and comparison of the instrument with other particle measuring devices such as SMPS, CPC, EAD, and ELPI should be conducted further.
- In order to measure transient behavior of airborne particles, such as those found in automotive exhaust gas, the time response of the instrument should be further improved.

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