An Electrostatic Sensor for Nanometer-Sized Aerosol Particles Detection

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In this study, an electrostatic sensor was developed for detecting the number concentration of nanometer-sized aerosol particles. It consists of a size selective inlet, a corona charger, an ion trap, a Faraday cup, an electrometer, a signal conditioning and processing system, and an I/O control and human-computer interface. In the present sensor, aerosol flow is regulated and controlled by means of mass flow meters and controllers with a vacuum pump. 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. Finally, 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 also evaluated and compared with a commercial electrometer, Keithley model 6517A, and good agreement was found from the comparison.

Key Words: aerosol, nanoparticle, electrostatic, electrometer, sensor.

1. Introduction

Nanometer-sized aerosol particles, defined as aerosols with particle diameters less than 0.1 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 [1]. Detection and measurement of nanometer-sized aerosol particles have become an important issue. For this purpose, nanoparticle sensors were developed to monitoring indoor and outdoor aerosols for pollution and process control industry. There are several commercial instruments using various methods of detecting particle number concentration. Available instruments include a SMPS (Scanning Mobility Particle Sizer) using electrical mobility of particles, a CPC (Condensation Particle Counter) which uses particle growth and optical property, an EAD (Electrical Aerosol Detector) which uses electrostatic charge measurement technique, and an ELPI (Electrical Low Pressure Impactor) using inertia impaction of particles under low pressure [2]. 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. In addition, the CPC should be carefully moved in caution to protect the optics contamination from working fluid like alcohol (C_4H_9OH) [3]. The movability of instruments should be considered in monitoring airborne aerosol particles.

To avoid this problem, an inexpensive sensor was developed in this study, suitable for detection of particle number concentration in the nanometer size range. This sensor 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 sensor performance also was evaluated and compared with a commercial instrument.

2. Description of the Sensor

Fig. 1 shows the schematic diagram of the electrostatic sensor for detecting nanometer-sized aerosol particles was developed in this study. The sensor 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 tec-

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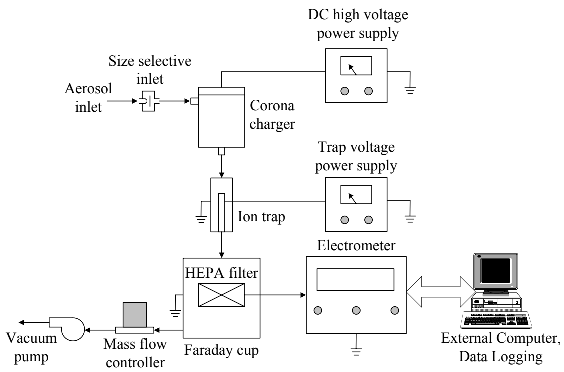

Fig. 1 Schematic diagram of the electrostatic sensor.

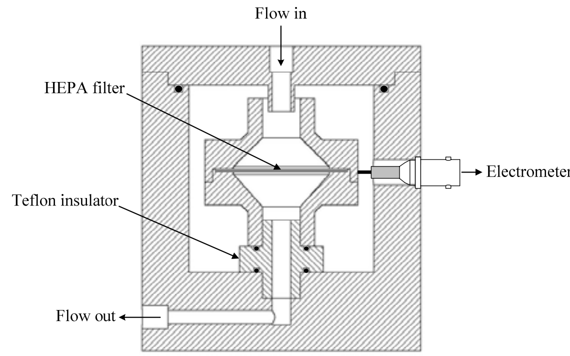

Fig. 2 Schematic diagram of the Faraday cup.

hnique, 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^o 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.

2.2 Unipolar corona charger

The particle charger in the present study consists of a coaxial corona-needle electrode placed along the axis of a cylindrical tube with tapered ends [4]. The needle electrode is made of a stainless steel rod 3 mm in diameter and 49 mm in length, ended in a sharp tip. The angle of the needle cone was approximately 9^o and the tip radius was approximately 50 μm, as estimated under a microscope. The outer cylindrical is made of aluminum tube 30 mm in diameter and 25 mm in length with conical shape. The angle of the cone was approximately 30^o and the orifice diameter was approximately 4 mm. The distance between the needle electrode and the cone apex is 2 mm. 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 3.0 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.

2.4 Faraday cup

Fig. 2 shows the schematic diagram of the Faraday cup used in this study. It consists of an outer housing, a HEPA (High Efficiency Particulate Air) filter, a filter holder, and a Teflon insulator. To completely shield the filter holder collecting the charged particles, the outer housing is made of a stainless steel, and filter holder is electrically isolated from the outer housing with Teflon insulator stand, while the outer housing is grounded. The Faraday cup plays a role to prevent electric noise for measuring ultra-low electric signal current (pA) from collected charged particles on an internal HEPA filter inside the Faraday cup corresponding to the total number concentration of the particles. If the filter holder 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 circuit that is outside the Faraday cup, BNC connector is connected to HEPA filter.

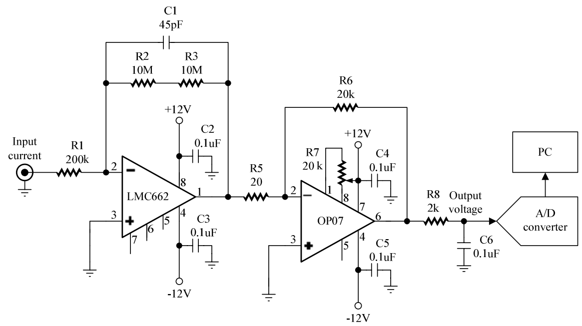

Fig. 3 Schematic diagram of the sensitive electrometer circuit.

Because material of HEPA filter is a conductor such as glass fiber, charges collected in the filter can move to the electrometer via the BNC connector and low noise cable without delay. In the case of existing aerosol electrometer airflow is curved at 90^o 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 cup is straightened 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, at HEPA filter is given by

$$N_p = \frac{I}{peQ_a} \tag{1}$$

where 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.

2.5 Sensitive electrometer

A sensitive electrometer is used to measure the electric signal current, which are typically in the range 1 to 10 pA, from the Faraday cup. The schematic presentation of an electrometer circuit design for aerosol detection system is shown in Fig. 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. The 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 [5]. In order to avoid expensive construction, commercially-available low-cost monolithic operational amplifiers were used. 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/^{o}C) [6]. The output voltage, V_o, of this circuit is given by the following equation:

$$V_o = I_i R_1 \left(\frac{R_2 + R_3}{R_1} \frac{R_6}{R_5} \right) \tag{2}$$

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.

2.6 Data acquisition and processing system

The output voltage of the electrometer circuit in the range of 0 to +5V was connected to a unipolar 12-bit analog to digital converter (ADC), controlled by I^2C bus from the external personal computer via RS-232 serial port interface. The digital ADC signal was processed by computer software, based on Microsoft Visual Basic programming for all data processing. The software is able to display the particle number concentration.

3. Electrometer Calibration and Testing

The electrometer circuit is one of the most important parts influencing accurate particle number concentration measurement corresponding to signal current in the sensor system. In the present paper, a laboratory test facility was developed and constructed to evaluate performance of a prototype electrometer circuit. Fig. 4 shows the experimental setup used to evaluate the fabricated electrometer circuit performance. In this study, the electrometer circuit was calibrated with a current injection circuit, high-impedance current source [4]. This circuit consists of an appropriately high-standard resistor (10 G) and a highly-accurate adjustable voltage source in the range between 0 to +5 V. The output current of this circuit can simply be calculated from the Ohm's law. 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

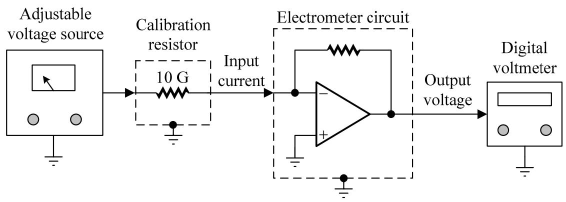

Fig. 4 Schematic diagram of the experimental setup for the electrometer test.

electrometer circuit was measured and recorded by a highly-accurate digital voltmeter. The voltage reading was then translated into the current measurement.

Fig. 5 provides comparison of measured current from this work and a commercial electrometer, Keithley model 6517A, with a high-accuracy current source. It can be found 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. A very small difference of about 5 % was obtained. It is worthy to point out that there were some interferences on the connector at small potentials. Additionally, leakage of currents through the body of the connector can potentially impair the performance of the electrometer significantly. A detailed investigation of this problem may be improved and experimental studied further [5].

4. Conclusion and Future Work

The electrostatic sensor for detecting nanometer-sized aerosol particles developed at Rajamangala University of Technology Lanna and Chiang Mai University 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 nanometer size range. A prototype of the prototype electrometer circuit has been constructed, evaluated, and compared against a commercial electrometer, Keithley model 6517A. The results obtained were very promising. It was demonstrated that the electrometer can be used successfully in detecting the signal current corresponding the particle number concentration.

Among the various techniques and devices exist for producing 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 a Tandem DMA method. The main advantage of this method is the wide range of particle sizes it can generate. Further research, may involve a Tandem DMA method. Finally, calibration and comparison of the instrument with other particle measuring devices (e.g. SMPS, CPC, EAD, and ELPI) should be conducted further.

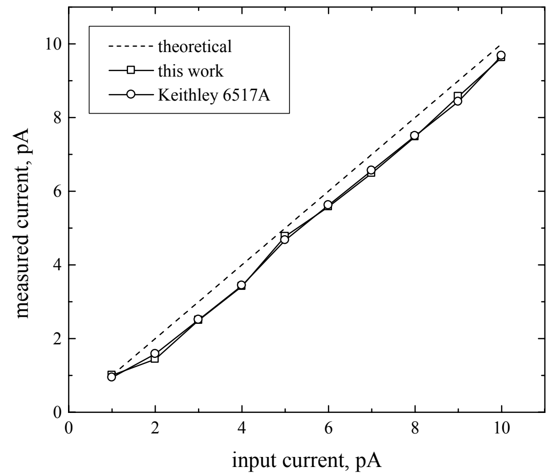

Fig. 5 Performance comparison between the prototype and commercial electrometer.

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