Development of a fast-response, high-resolution electrical mobility spectrometer

Panich Intra*,† **and Nakorn Tippayawong****

*College of Integrated Science and Technology, Rajamangala University of Technology Lanna, Chiang Mai 50300, Thailand
**Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand

Abstract−A short electrical mobility spectrometer (EMS) for measuring aerosol size distribution has been developed and presented [Intra and Tippayawong, *Korean J. Chem. Eng.*, 26, 1770, 2009]. In this work, further improvement of the short EMS into a fast-response, and high resolution instrument is presented. This was done by (i) improvement in particle charging, (ii) utilization of faster flow rate, and (iii) adoption of higher number of electrode rings. The so-called "long" EMS consists of three main parts: a particle charger, a long multi-channel size classifier column, and a multi-channel electrometer. Performance of the long EMS was preliminarily tested using polydisperse, carbonaceous aerosol particles generated by a diffusion flame. Preliminary test results showed that the long EMS performed comparatively well, and gave faster response and higher resolution than the short EMS. It was a valuable aerosol instrument available for measuring size distribution of aerosol particles.

Key words: Aerosol, Particle, Electrical Mobility, Spectrometer, Electrometer

INTRODUCTION

Electrical mobility analysis is an important class of aerosol size distribution measuring techniques. A comprehensive historical review of the electrical aerosol measurements was proposed by Flagan [1]. The most widely used instruments are based on the design developed by Liu and Pui [2] and Knutson and Whitby [3]. An overview of contemporary electrical aerosol size spectrometers was published by Intra and Tippayawong [4,5]. In general, an electrical mobility instrument has an aerosol charger, an electrical mobility classifier, and an aerosol detector. The principle of operation of this instrument is as follows. The aerosol to be tested is charged by unipolar/bipolar diffusion charger and then classified by electrical mobility in an annular column where the inner electrode is at a high voltage and deflects the charged particles within the flow stream in such a manner as to extract only those within a narrow band of the overall electrical mobility aerosol distribution. These particles are then counted in an aerosol detector such as a particle counter and an aerosol electrometer.

Numerous electrical mobility instruments are commercially available to size or classify particles in the sub-micrometer and nanometer range [2,6-9]. These instruments are most suitable for site-specific, high resolution particle size distributions, but these instruments are large, expensive, and complicated to use due to multiple flow controls and several size classification channels. There is an immediate need for a compact, portable, inexpensive, and easy to deploy instrument which can measure the real-time size distribution with reasonable accuracy. In our previous work, a short electrical mobility spectrometer (EMS) was developed and presented [10]. The short EMS was based on the multi-channel particle spectrometer, firstly proposed by Tartu University [7] and later improved by Cambridge

University [9,11]. The short EMS consists of an aerosol generator, a flow system, a size selective inlet, a particle charger, a size classifier, a signal current detector and a computer controlled data reduction system. It has a size selective inlet 50% cut point of approximately 1 μm in diameter. There is a 10 channel electrometer detector for particle size resolution. The short EMS is capable of aerosol size distribution measurements in the range of approximately 10 nm to 1,000 nm in diameter with a time response of approximately 45 s. The particle number concentration that the short EMS can measure is in the range of approximately 10^{11} to 10^{13} particles/m^3.

In this work, an attempt was made to improve the measured particle size resolution, the particle number concentration range, and the time response of the short EMS. Therefore, a new long EMS was designed, developed and tested. The design concept and results of preliminary tests of a prototype instrument were presented and discussed.

DESIGN OF THE LONG EMS

1. Overall Design Goals and Requirements

The goal of this work was to design and build a high resolution instrument capable of the measuring size distribution of submicron aerosol particles, typically in the size range of 10 nm to 1,000 nm. This was an improvement of the existing short EMS. The instrument would need to have the ability to continuously monitor particle number concentration in the range of approximately 10^9 to 10^{14} particles/m^3 with a characteristic time response no longer than 1 s. The instrument should also be capable of prolonged, continuous operation without interruption.

Measurement of particle size distribution in this work requires three steps: charging of aerosol particles, classification of aerosol into different particle size ranges, and measuring of the number concentration of the particles in each of those size ranges. For particle charging, unipolar charging by the corona discharge had already

†To whom correspondence should be addressed.
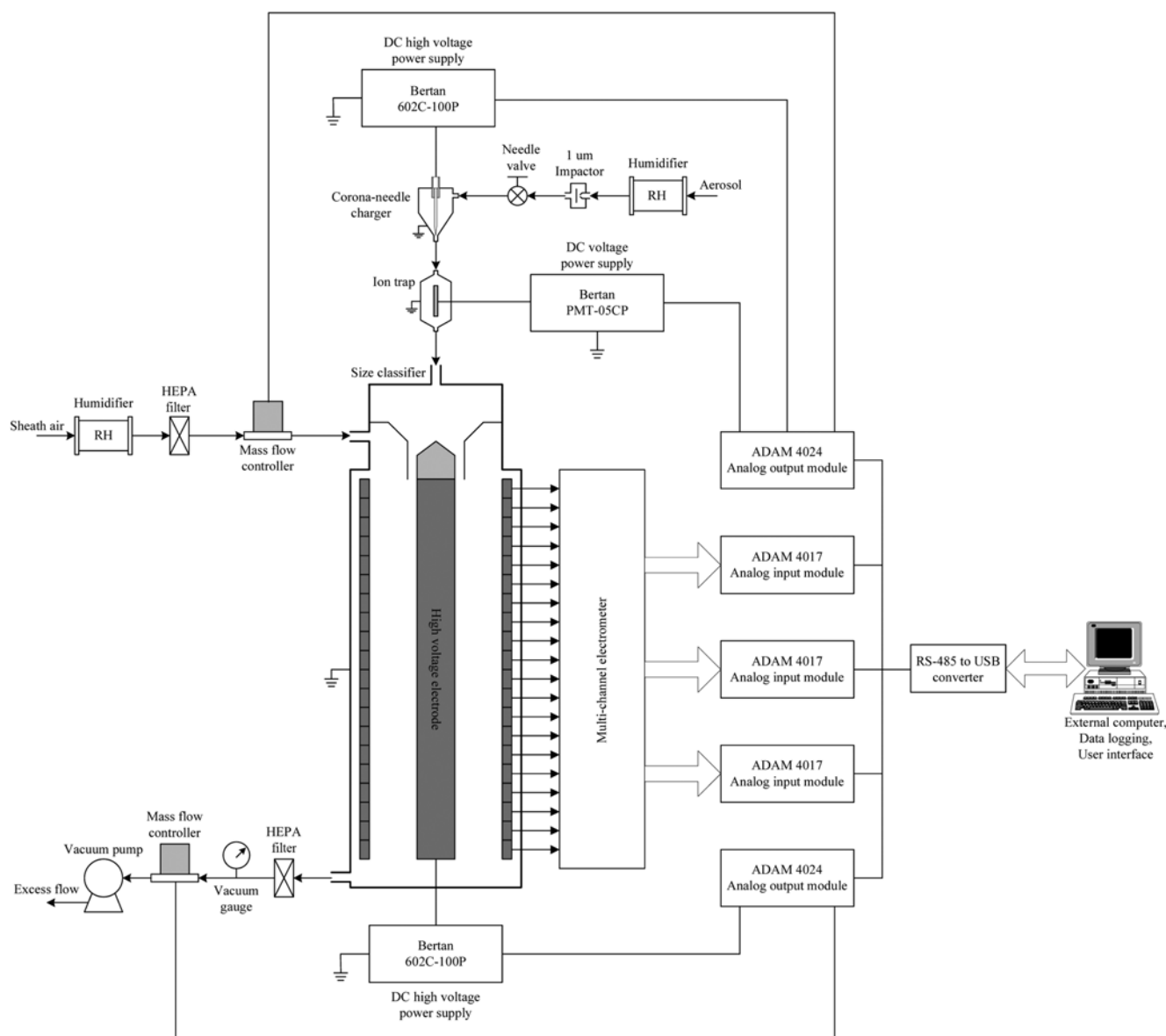E-mail: panich_intra@yahoo.com

Fig. 1. Schematic diagram of the long EMS.

been adopted. The advantage of this charging method is that it can generate a great number concentration of ions. The unipolar charging has also advantages over bipolar charging as it does not reach an equilibrium charge distribution, therefore potentially enabling the attainment of a higher charging efficiency [12]. For particle size classification, electrical mobility classification was deemed capable and reliable enough for classifying submicron aerosol particles. Primary performance requirements of the classifier are dictated by size range and time response specifications of the instrument as a whole. For fast time response, multi-channel measurement technique was used in this work. For particle detection in this work, the charge current measurement using a sensitive electrometer had already been selected. To maintain good resolution across the particle size range, the number of electrometer rings should be increased. Thus, multiple electrometer circuits were used in this design. Finally, the spectrometer design is subject to a number of practical constraints. The ability to use such an instrument in field tests is very important. Thus,

portability is a consideration: this spectrometer should be relatively compact, lightweight, robust, and low cost. Overall dimensions and weight were such that it was easy to handle and move around.

2. Principle of Operation

Fig. 1 shows a schematic diagram of the long EMS. It consists of a size selective inlet, a corona-needle charger, an ion trap, a multi-channel size classifier, a multi-channel electrometer, a data acquisition and processing system, and a DC high voltage power supply. The flow control system was regulated and controlled by means of a mass flow meter and controller. The fluid flow was forced by a vacuum pump. A high efficiency particulate-free air (HEPA) filter, Pall capsule model 12144, was used to remove any particles. The first filter was placed upstream of the sheath air flow controller and the second filter was placed downstream of the classifier column in front of the total flow controller. The aerosol sample first passed through the corona-needle charger. Particle charging is carried out by exposing aerosol sample to the cloud of unipolar corona ions,

and then charged via ion-particle collisions by diffusion and field charging. The charged aerosol passes into the multi-channel size classifier column, configured as coaxially cylindrical electrodes. There are two separate streams which are aerosol and sheath air flows. The charged aerosols enter the multi-channel size classifier column close to the inner electrode by a continuous flow of air, surrounded by a sheath air flow. Because the inner electrode is kept at a positive voltage, the charged particles are then deflected outward radially according to the electrical mobility and they are collected on a series of electrically isolated electrometer rings along the outer wall of the classifier. Multi-channel electrometers connected to these electrometer rings measure currents corresponding to the electric charge of aerosol particles of a given mobility which is related to the particle size. Finally, signal currents are then recorded and processed by a data acquisition system.

3. Components and Description

3-1. Size Selective Inlet

In this study, the inertial impactor was used to remove the particle outside the measurement range, 1.0 μm, based on their aerodynamic diameter upstream of the system [13]. It consists of an acceleration nozzle and an impaction plate. The acceleration nozzle in the diameter of 1 mm and the impaction plate are made of a stainless steel. The distance between the acceleration nozzle and the impaction plate was 1 mm. In the impactor, the aerosol flow is accelerated through an acceleration nozzle directed at an impaction plate. The impaction plate deflects the flow streamlines to a 90° bend. The particles larger than the cut-off diameter of the impactor impact on the impaction plate, while the smaller particles follow the streamlines and avoid contact to the impaction plate and exit the impactor.

3-2. Corona-needle 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 [14]. 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, estimated under a microscope. The outer cylindrical is made of stainless steel 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. 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 module, a Bertan model 602C-100P, is used to maintain the corona voltage difference, typically of 3.5 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. The performance of the charger is a function of the ion concentration in the charging zone, and therefore continuous monitoring of the ion current from the corona-needle to the outer electrode is necessary. The current measurement is translated to ion concentrations given the mean ionic mobility and the electric field strength in the charging zone [14]. This ionic concentration is then used as an input for the charging models.

3-3. Ion Trap

In this study, 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 ion trap has a geometrical configuration similar to the unipolar corona-wire charger and the wire-cylinder electrostatic precipitator [15]. It consists of a coaxial wire electrode placed along the axis of a metallic cylinder tube. The outer electrode is made of stainless steel tube 28 mm in diameter and 15 mm in length. The wire electrode is made of stainless steel wire 300 μm in diameter and 15 mm in length. DC voltage supply module, a Bertan model PMT-05CP, was applied to the wire electrode, typically of 150 V, while the outer metallic electrode is grounded. The most important topic while operating the ion precipitator is about setting a proper voltage to deposit the ions. This voltage will ensure that all ions can be removed but most charged particles are not influenced.

3-4. Multi-channel Size Classifier

The multi-channel size classifier is responsible for classifying the incoming charged polydisperse aerosol into groups of different size particles. The particles are classified into different sizes via the principle of electrical mobility technique. Therefore, the particles are separated according to their electrical mobility diameter. The relationship between electrical mobility diameter and physical size is proportional to the net electrical charge on the particle, hence the importance of accurately knowing the aerosol charge distribution. The multi-channel size classifier has one long column, consisting of coaxially cylindrical electrodes. Its geometrical configuration is similar to those reported by Intra and Tippayawong [10]. Outer chassis is made of a 481 mm long aluminum tube with an internal diameter of 55 mm. Inner electrode is made of a 25 mm in diameter stainless steel rod. Width of the aerosol inlet channel is 2 mm. The inner electrode was polished to an extremely fine surface finish to avoid undesirable electric field effect on particle motion due to nonuniform electric field from small surface scratches and imperfections. It is important to ensure that both flow and electric fields are laminar and uniformly distributed inside the analyzing column. There are two streams: polydisperse aerosol and sheath air flows. In our previous work, numerical flow and electric fields and Brownian diffusion effects inside the classifier was evaluated and discussed [16,17]. The inner electrode of the classifier is maintained at a DC high voltage, while the outer chassis of the analyzer is grounded. An adjustable DC high voltage power supply, a Bertan model 602C-100P, is used to maintain this voltage difference, generally in the range between 1.0-3.0 kV. A series of electrically isolated electrometer rings were positioned at the inner surface of the outer chassis of the analyzer column. The 22 electrometer rings used result in the classification of every measured aerosol into 22 mobility ranges. The electrometer rings have a width of 19 mm. The first electrometer ring is located 20 mm downstream the aerosol inlet, while a 1 mm gap is allowed between the electrometer rings for electrical isolation. Virtual ground potential input of highly sensitive multiple electrometers is connected to these electrometer rings via a low noise BNC connector to measure signal currents. The size range of particles collected on the electrometer rings can be varied by adjusting the aerosol and sheath air flow rates, the voltage applied to the inner electrode, and the operating pressure. In our previous work, the prediction model of the multi-channel size classifier was calibrated with the scanning electron microscope [18]. It was shown that the size
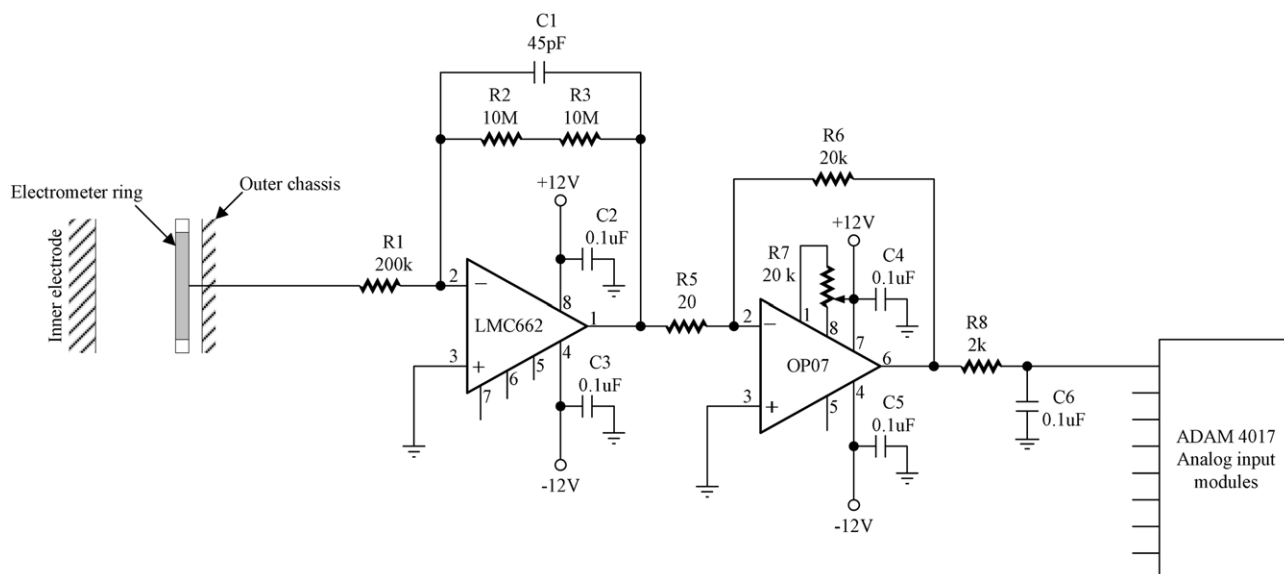
Fig. 2. One channel of the multi-channel electrometer.

determination from the long EMS was compared with that obtained from SEM results and good agreement was found from the comparison.

3-5. Multi-channel Electrometer Circuit

The number concentration of the aerosol particles being measured can be determined by measuring the signal currents at each of the electrometer rings. One channel of the multi-channel electrometer circuit design for the system is shown in Fig. 2. 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. The feedback capacitor and RC lowpass filter were used to reduce high-frequency noise and to prevent oscillations of the amplifier output [19]. To avoid expensive construction due to the need for multi-channel electrometers, commercially available low-cost monolithic operational amplifiers were used. The commercially available operational amplifier 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 $\mu V/^{\circ}C$) [20]. The zero offsets are temperature-dependent, and therefore the electrometers are temperature-stabilized to about 32 °C, eliminating offset drift. This circuit gives an output voltage of 20 mV per 1 pA of input signal current. The electrometer circuit was calibrated with a current injection circuit, high-impedance current source [19]. The ratio and standard deviation of measured current from this work and a commercial electrometer, Keithley model 6517A, with high-accuracy current source at each channel are shown in Fig. 3. It was found that the measured current ratio was in the range of 0.7-1.40 corresponding to the standard deviation in the range of 1.018-1.048. The measured current ratio and the standard deviation of this work were increased when input current was smaller than 5 pA. Generally, the currents measured from this work were found to agree very well with those measured by the Keithley model 6517A. Very small difference (<5%) was obtained. In the absence of any charged aerosol particles, the
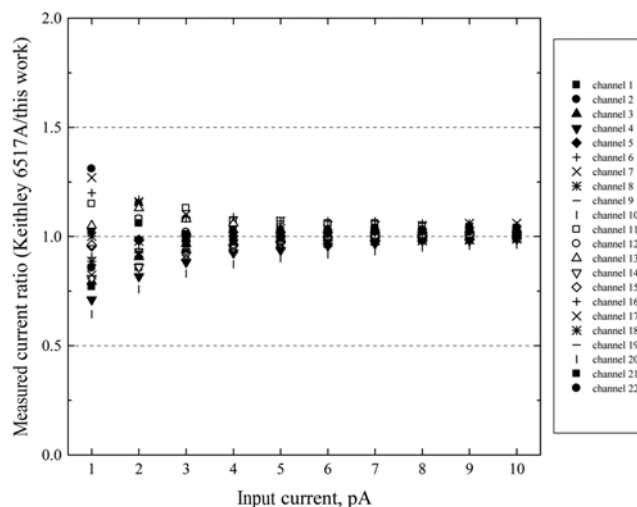

Fig. 3. Performance comparison between the prototype and commercial electrometer.

noise from each electrometer ring of the long EMS was less than ±0.5 pA. The time-dependent signal current drift corresponding to temperature was also found. Use of monolithic operational amplifiers on the electrometer construction has a drawback of temperature-dependent bias current. This made the electrometer prone to a temperature change induced drift. To take into account temperature drifting and electrometer bias currents, all electrometers were set at zero before actual measurement. It was possible to further reduce the electrometer drift by using an automated zeroing procedure executed at constant intervals during longer measurement periods. As a precaution, the electrometer zero offset was measured and recorded at the beginning and end of the measurement.

3-6. Flow System

Aerosol and sheath air flows were regulated and controlled by means of thermal mass flow meters and controllers with a vacuum pump. In the present study, commercial gas mass flow controllers,
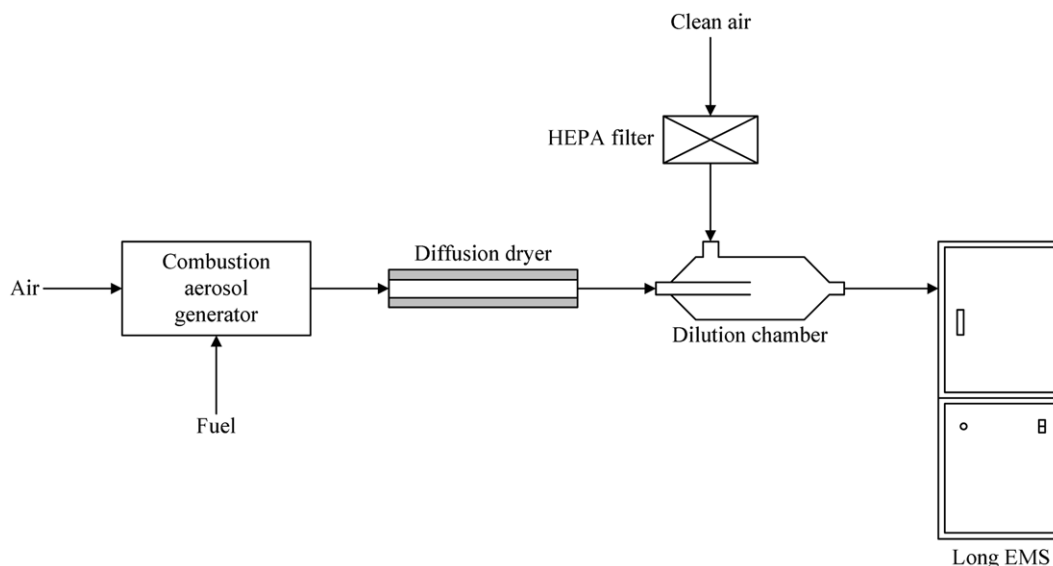
Fig. 4. Setup for characterization of the long EMS.

Dwyer model GFC-1111 and GFC-1142, were used. In the configuration which was used, it has a flow rate range of 0 to 15 l/min for model GFC-1111, and 0 to 100 l/min for model GFC-1142, respectively. The vacuum pump was used to deliver the aerosol and sheath air flows into the classifier column. In the present study, a dry running rotary vane vacuum pump, Busch model SV 1003, was used. It has an ultimate pressure of 0.15 bar, and a nominal displacement volume rate of 3 m³/h. For the connecting tube system, the polyethylene tubing (5 mm I.D.×8 mm O.D.) was used in this system. The upstream air flow was conditioned by a perforated screen to ensure uniform laminar flow, prior to it entrance to the size classifier column.

3-7. Data Processing and Control

The output voltages of the Bertan model 602C-100P and model PMT-05CP were controlled by the ADAM-4024 analog output module for charger, classifier, and ion trap voltages, respectively. The input signal for flow control of both flow controllers was also controlled by the ADAM 4024. For the data processing system, the output signals from the multi-channel electrometer are in the range of 0 to +10 V. They are then sent to the three of ADAM-4017 analog input module, which is a 16-bit, 8 channel analog input module. The ADAM-4017 and ADAM- 4024 were controlled and data sampled by an external personal computer via RS-485 to USB converter interface. A 12VDC power supply capable of providing 3 A is required for the system. 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.

EXPERIMENTAL EVALUATION

1. Aerosol Generators

In this study, a combustion aerosol generator (CAG) was used to generate a polydisperse aerosol. Polydisperse aerosols were produced by a laminar diffusion burner with a kerosene fuel in the nom-

inal "presooting" condition. Under normal conditions, the vast majority of soot generated by the flame would be oxidized, giving a very low particle number concentration. A quench-air flow across the tip of the diffusion flame assisted in the production of highly concentrated aerosols, while it also served to carry the aerosol downstream of the combustion chamber. The quenched flame exhaust was then quickly diluted using a blower to provide an ultrafine carbonaceous aerosol. The number concentration and particle size distributions can be generated by varying the air and fuel flows in the combustion chamber, the level of the flame nozzle from the top of the chamber, and the quench air flow. The sample particles from the CAG were also characterized by the scanning electron microscope and the energy dispersive spectroscopy for morphology and chemical composition, respectively. The particle size distribution from the CAG was in the range between approximately 10 nm to several hundred nanometers.

2. Experimental System and Procedure

The complete experimental apparatus used in the measurement of the aerosol particle size distribution can be seen in Fig. 4. The long EMS was operated at aerosol flow rate of 3.0 L/min, pre-filtered sheath air flow rate of 25.0 L/min, size classifier voltage between 1.0 kV and 3.0 kV, and operating pressure of 0.85 bar. Aerosol sampling was carried out using an isokinetic sampling system. The aerosol particles were first dried with the diffusion drier, so any remaining water was removed. Due to the high particle concentration in
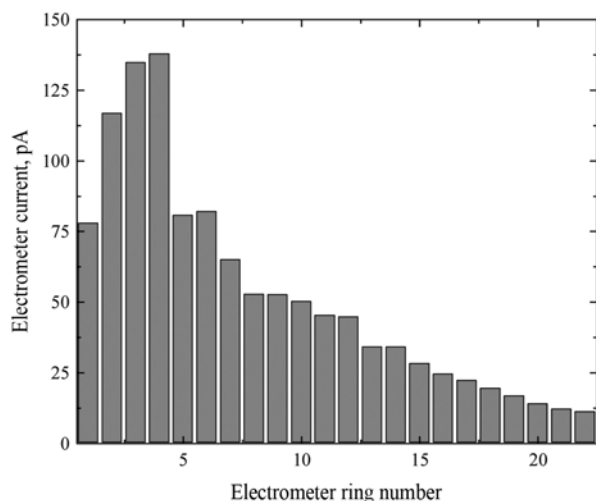
Table 1. The operating conditions for the long EMS

Operating conditions	Values
Test particle material	Carbon
Particle size range	10-1,000 nm
Inner electrode voltage	1.0-3.0 kV
Aerosol flow rate	3.0 L/min
Sheath air flow rate	25 L/min
Operating pressure	0.85 bar
Operating temperature	30 °C

the particle stream flow rate of the exhaust, before aerosol particles entered the long EMS, the particles were diluted and mixed with
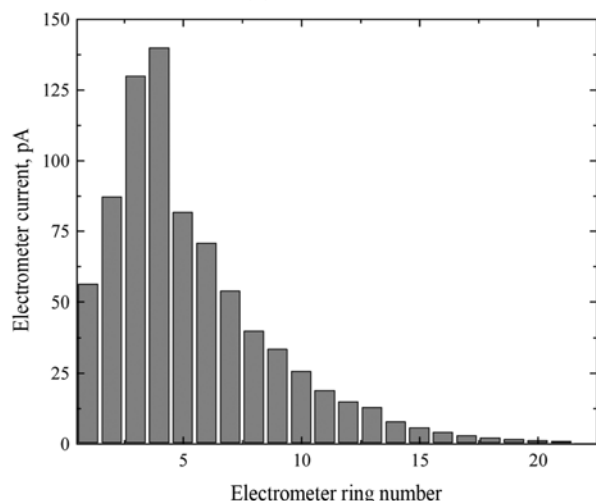
clean air, which had been filtered through a HEPA filter, in the mixing chamber. The operating condition for the long EMS is shown in Table 1.
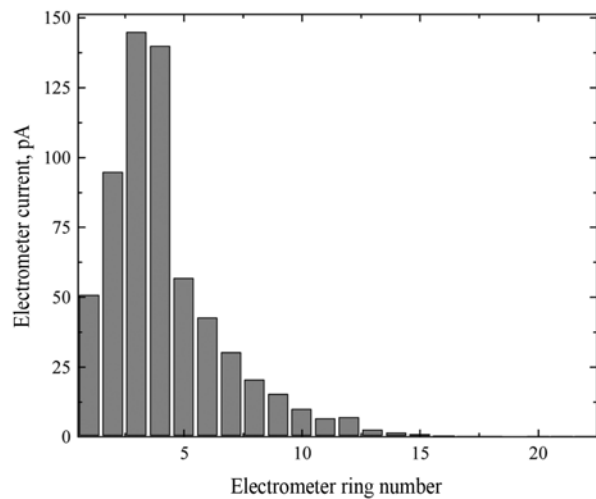
RESULTS AND DISCUSSION

Fig. 5 shows measurement of signal current at each electrometer ring of the classifier. Three different operating conditions were experimentally studied, in the effect of electric field strength on the particle current measurements of the long EMS. Because the electric field strength within the spectrometer was a function of applied inner electrode voltage, the magnitude of the potential applied to the inner electrode varied between 1.0 to 3.0 kV. The electrical current of the tested aerosol particles obtained from each electrometer rings was in the range between 0 to 145 pA. It was also found that when higher electric field was created within the size classifier col-

Fig. 6. Typical aerosol size distribution and electrometer current measured by the long EMS.

(a) 1.0 kV

(b) 2.0 kV

(c) 3.0 kV

Fig. 5. Measured particle currents at each electrometer ring of the long EMS.

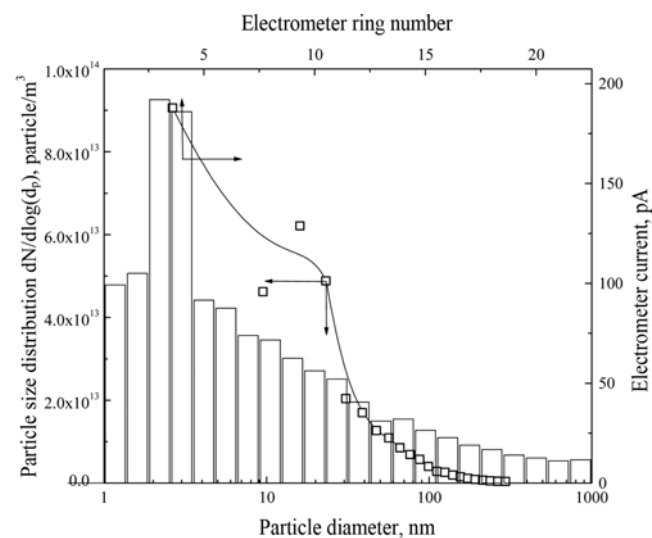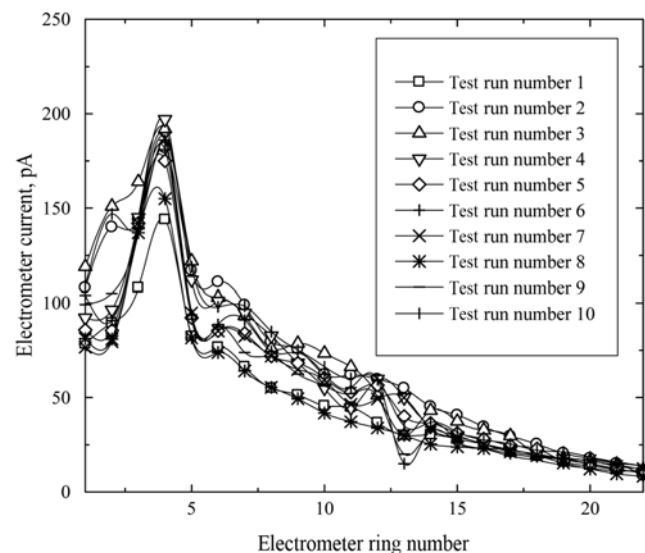**Fig. 7. Measurement repeatability of the long EMS.**

umn of the long EMS, more charged particles were precipitated and deposited on the first electrometer ring. This was expected because the electrical mobility of charged particles being collected at each electrometer ring was inversely proportional to the electric field strength. The inverse ratio of the inner electrode voltages should be equal to the shift in particle mobility due to the change in electric field strength.

Fig. 6 shows typical aerosol size distribution and electrometer current measured by the long EMS. The long EMS operating conditions were 3.0 l/min aerosol flow rate, 25.0 l/min sheath air flow rate, and 1.0 kV inner electrode voltage, respectively. Polydisperse aerosols were shown to have number concentrations of approximately 10^{14} particles/m³. Particle size distribution obtained by the long EMS was in the range between 10 nm to several hundred nanometers. Stability and reproducibility of the CAG was described by comparing electrometer currents of soot particles produced at the same operation point but at different times, shown in Fig. 7. The repeatability of test run results is essential to the quality of a particle sizing instrument. Repeatability was defined as deviation of the results acquired from the same sample and measured by the same instrument many times. The repeatability of the measured electrometer current at each electrometer ring for a 10 times recording was shown. The peak current was found to be at the 4th electrometer ring. Slight deviations in electrometer current at each electrometer ring were observed. These deviations were not large, compared to the absolute values of these currents. To enhance measurement repeatability, deviations from the measured current should be minimized. The possible error source was the stability and variability of the aerosol generator. It was known that the stability of the instrument was dependent on temperature and humidity. Vibrations and fluctuations in the power supply can also lead to discrepancies in the measurements.

The improved system was simple, low cost, efficient and reliable for measuring the size distribution of submicron aerosol particles. Table 2 shows a comparison between the short and long EMS. The long EMS was capable of measuring the size between approximately 10 nm to 1,000 nm in diameter and the particle number concentration of 10^9 to 10^{14} particles/m³, with a time response of about 1 s. It proved to have better measurement resolution and time response. Overall dimensions and weight were such that it was easy to handle and move around. Collected aerosol particles in the filter can be further analyzed for physical and chemical properties. Chemical composition of the size resolved particles can be also studied. However, the detection limit was more pronounced for smaller particles because they carry less charge, and it was lower for slower sampling rates where the longer averaging time reduces the noise. Use of an electrometer in the system limits the sensitivity of the instrument when detecting samples with low concentrations. This sensitivity was limited by signal to noise ratio.

CONCLUSIONS

A long EMS appropriate for high resolution and fast response size distribution measurements of aerosol particles has been designed and tested in this work. The instrument employed a unipolar corona discharge charger to charge the aerosol samples, a multi-channel classification column to separate the particles based on their electrical mobility, and multi-channel sensitive electrometers to detect and measure the particle number concentration at the individual channels. Performance of the long EMS was tested using polydisperse, carbonaceous aerosol particles generated by a diffusion flame. Preliminary test results showed that the long EMS performed well and was a valuable tool available for measuring size distribution of aerosol particles corresponding to particle number concentration.

REFERENCES

1. R. C. Flagan, *Aerosol Sci. Technol.*, **28**, 301 (1998).

Table 2. Comparison between the short and long EMS

	Short EMS	Long EMS
Measurement technique	Electrical mobility	Electrical mobility
Size range	10 to 1,000 nm	10 to 1,000 nm
Concentration range	10^{11} to 10^{13} particles/m³	10^9 to 10^{14} particles/m³
Time response	45 s	1 s
Charger type	Corona charger	Corona charger
Charging method	Unipolar diffusion and field charging	Unipolar diffusion and field charging
Particle detector	Electrometers	Electrometers
Electrometer channels	10	22
Aerosol inlet technique	Tangential inlet	Tangential inlet
Aerosol flow rate	1 l/min	5 l/min
Sheath air flow rate	10 l/min	25 l/min
Operating pressure	34.5 kPa	25.25 kPa
Electrode applied voltage	500 V to 3 kV	500 V to 3 kV
Classifier length	131 mm	694 mm
Inner electrode radius	10 mm	12.5 mm
Outer electrode radius	25 mm	27.5 mm

2. B. Y. H. Liu and D. Y. H. Pui, *J. Aerosol Sci.*, **6**, 249 (1975).

3. E. O. Knutson and K. T. Whitby, *J. Aerosol Sci.*, **6**, 443 (1975).

4. P. Intra and N. Tippayawong, *Mj. Int. J. Sci. Technol.*, **1**, 120 (2007).

5. P. Intra and N. Tippayawong, *Songklanakarin J. Sci. Technol.*, **30**, 243 (2008).

6. TSI Incorporated, *Operation and service manual for scanning electrical mobility sizer model 3936*, Minnesota, USA (2006).

7. H. Tammet, A. Mirme and E. Tamm, *Atmos. Res.*, **62**, 315 (2002).

8. TSI Incorporated, *Operation and service manual for engine exhaust particle sizer model 3090*, Minnesota, USA (2004).

9. G. Biskos, K. Reavell and N. Collings, *Aerosol Sci. Technol.*, **39**, 527 (2005).

10. P. Intra and N. Tippayawong, *Korean J. Chem. Eng.*, **26**, 1770 (2009).

11. B. R. Graskow, *Design and development of a fast aerosol size spectrometer*, Ph.D. Thesis, University of Cambridge, UK (2001).

12. P. Intra and N. Tippayawong, *J. Electrostat.*, **67**, 605 (2009).

13. P. Intra, *CMU. J. Nat. Sci.*, **7**, 257 (2008).

14. P. Intra and N. Tippayawong, *Chiang Mai J. Sci.*, **36**, 110 (2009).

15. P. Intra and N. Tippayawong, *Int. J. Appl. Electrom. Mech.*, Submitted.

16. P. Intra and N. Tippayawong, *Korean J. Chem. Eng.*, **26**, 269 (2009).

17. P. Intra, P. B. Lasman and N. Tippayawong, *Int. J. Eng. Appl. Sci.*, **2**, 16 (2010).

18. P. Intra and N. Tippayawong, *J. Aerosol Res.*, **21**, 329 (2006).

19. A. Yawootti, P. Intra and N. Tippayawong, *32nd Electrical Engineering Conference*, Prachinburi, Thailand, 28-30 October (2009).

20. National Semiconductor Corporation, *LMC662 Data Sheet* (2003).