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Experimental characterization of a short electrical mobility spectrometer for aerosol size classification

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Abstract−A prototype of a short column electrical mobility spectrometer (EMS) for size measurement of aerosol particle was design, constructed, and experimentally characterized. The short EMS consists of a particle charger, a size classifier column, and a multi-channel electrometer. Its particle size resolution is derived from a 10 channel electrometer detector. The short EMS is capable of size measurements in the range between 10 nm to 1,000 nm with a time response of about 50 s for full up and down scan. Particle number concentration in which the short EMS can measure ranges from 10^{11} to 10^{13} particles/m^3. The operating flow rate of the short EMS is set for the aerosol flow rate of 1.0-2.0 *l*/min and the sheath air flow rate fixed at 10.0 *l*/min. The inner electrode voltage of the classifier can be varied between 500-3,000 VDC. The short EMS operates at sub-atmospheric pressure, typically at 526 mbar. Validation of the short EMS performance was performed against a scanning electron microscope (SEM). Good agreements were obtained from comparison between sizes determined from the short EMS classifier and the SEM analysis. Signal current from the detector was also analyzed to give rise to number concentration of particles. Experimental results obtained appeared to agree well with the theoretical predictions.

Key words: Aerosol, Particle, Electrical Mobility, Size Distribution, Spectrometer

INTRODUCTION

Electrical mobility instruments are widely used to measure and classify airborne particle size distribution in submicron range [1]. Intra and Tippayawong [2] offer reviews of the recent development of this technique. Available commercial instruments include the electrical aerosol analyzer (EAA) [3], the scanning mobility particle sizer (SMPS) [4], the electrical aerosol spectrometer (EAS) [5], the engine exhaust particle sizer (EEPS) [6], and the differential mobility spectrometer (DMS) [7]. 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.

Recently, the design of a small electrical mobility instrument called the short EMS [8,9] was introduced. The short EMS is based on a similar principle to that reported by Tammet et al. [5], Graskow [10], and Biskos et al. [7]. Nonetheless, there are collective differences between the present short EMS and each of existing instruments, which are as follows: (i) the concept of the present classifier is based on a compact, inexpensive and portable unit. Short column classifier and a small number of detection channels are used to reduce diffusion effect of the particle inside the classifier [11]. Overall dimensions and weight are such that it is easy to handle and move around; (ii) the instrument adopts a tangential aerosol inlet upstream of the first electrode ring to ensure uniform particle distribution across the annular aerosol entrance to the classifier column; (iii) rather than diffusion charging, the instrument employs unipolar corona (diffusion and field) charging method; and (iv) the applied voltage is set to maintain at low level, well below the corona onset voltage, to avoid unintentional charging of the particles inside the size classifier column. The short EMS consists of a particle charger, a short multi-channel size classifier column, and a multi-channel electrometer (Fig. 1). Particle charging is accomplished by exposing an aerosol sample to a cloud of unipolar corona ions inside the corona-needle charger, and then charged via ion to particle collisions. The charged aerosol passes into the size classifier column, configured as coaxially cylindrical electrodes. A DC high voltage is applied to the inner electrode, while the outer electrode is grounded. There are two separate streams, aerosol and sheath air flows. The charged aerosols enter the size classifier column. An electric field formed between the electrodes makes the particles deflected radially outward, and particles having specific mobility are collected on electrically isolated electrometer rings, positioned at the inner surface of the outer electrode. A multi-channel electrometer connected to these electrometer rings measures signal currents corresponding to the number concentration of particles of a given mobility, which is related to the particle size. Signal currents are recorded and processed by a data acquisition system.

In our previous work [8,9], a prototype of the short EMS was designed, built, and tested. Its performance in evaluating particle size using signal current to evaluate the number concentration of aerosol was compared with a field emission-scanning electron micro-

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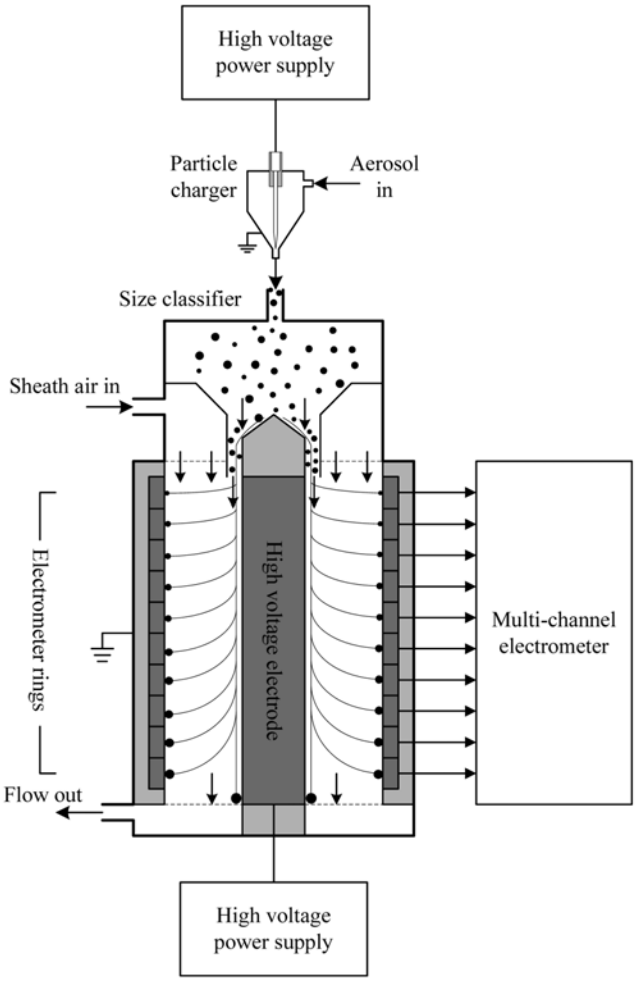


Fig. 1. Schematic diagram of the short EMS.

scope (FE-SEM) observation method. Nonetheless, the measured particle size range and classification performance of the previous instrument needs be examined further. To improve the measured particle size range and classification performance of the previous instrument, therefore, the influence of the electric field strength and aerosol flow rate, the time response, and the measurement repeatability on particle size and number concentration measurement range of the size classifier of the short EMS were experimentally studied and discussed in the present paper. A detailed description of the operating principle and performance of the short EMS is also presented.

DESCRIPTION OF THE SHORT EMS

As shown in Fig. 1, the short EMS consists of three main components: a particle charger, a short multi-channel size classifier column, and a multi-channel electrometer. The aerosol sample first passes through the corona-needle aerosol charger [12]. As shown schematically in Fig. 2, it consists of a coaxial corona-needle electrode placed along the axis of a cylindrical tube with tapered ends. The corona electrode head is connected to a positive 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 2.0-5.0 kV. The corona discharge generates positive 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 attachment of ions produced by the corona discharge. Ions are transported by the electric field and/or by thermal diffusion. Particle charging due to the ions transported by electric field is called "field charg-

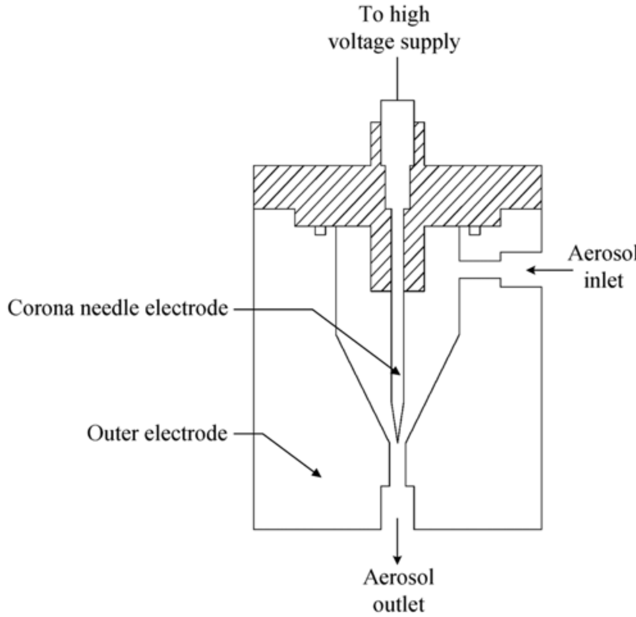


Fig. 2. Schematic diagram of the corona-needle charger.

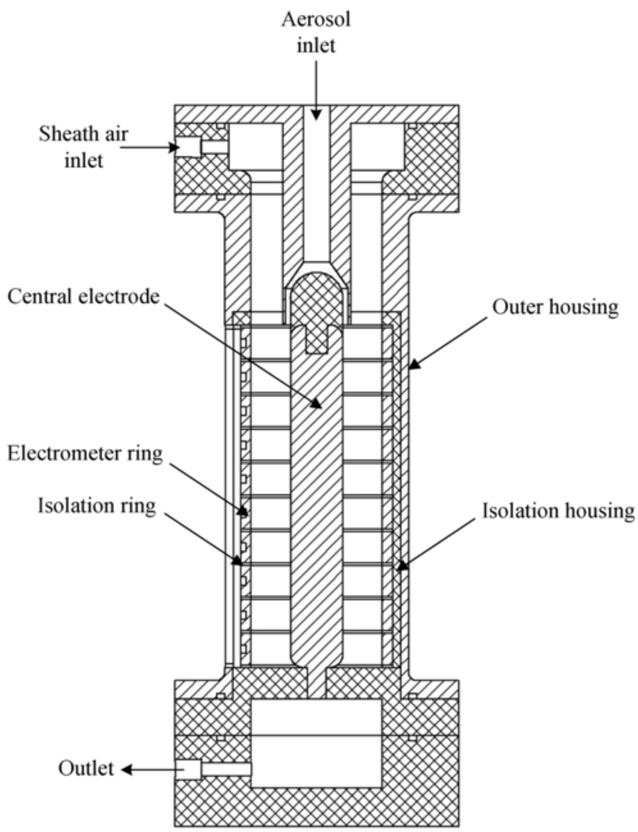


Fig. 3. Cross section of the mobility classifier.

ing." For super-micron particles (>1 μm), field charging is dominant. For ultrafine particles (<0.1 μm), thermal diffusion becomes dominant, and "diffusion charging" becomes important. [13].

The positively charged aerosol then passes into the multi-channel size classifier column (Fig. 3). This size classifier column is 131 mm long with an internal diameter of 50 mm. The short EMS column has one short column that consists of two concentric electrodes. There are two streams: the aerosol and sheath air flows. The inner electrode of the classifier is maintained at a positive high voltage while the outer chassis of the classifier is grounded. An adjustable DC high voltage power supply is used to maintain this voltage difference, generally in the range between 500 V-3.0 kV. The positively charged particles enter the classifier column close to the inner electrode by a continuous flow of air and surrounded by a sheath air flow. Since the inner electrode is kept at a positive high voltage, the positively charged particles are deflected outward radially. They are collected on a series of 10 electrically isolated electrometer rings positioned at the inner surface of the outer electrode of the column. Resolution and size range of the classifier is determined mainly by the number and width of the electrometer rings. Table 1 shows the width and the position of the electrometer rings along the mobility classification column. The 10 electrometer rings used result in the classification of every measured aerosol into 10 mobility ranges. The electrometer rings have a width of 12 mm. The first electrometer ring is located 1 mm downstream from the aerosol inlet, while a 1.0 mm gap is allowed between the electrometer rings for isolation. Additionally, operation and performance of the instrument depend upon aerosol transport under the influence of flow and electric fields. It is important to ensure that both flow and electric fields are laminar and uniformly distributed inside the classifying column. Thus, the incompressible Navier-Stokes equation and Maxwell's equations were numerically solved in previous studies [14] to investigate flow

Table 1. Electrometer ring width and positions along the size classification column

Electrometer ring number	Electrometer ring width (mm)	Midpoint location (mm)
1	12	7
2	12	20
3	12	33
4	12	46
5	12	59
6	12	72
7	12	85
8	12	98
9	12	111
10	12	124

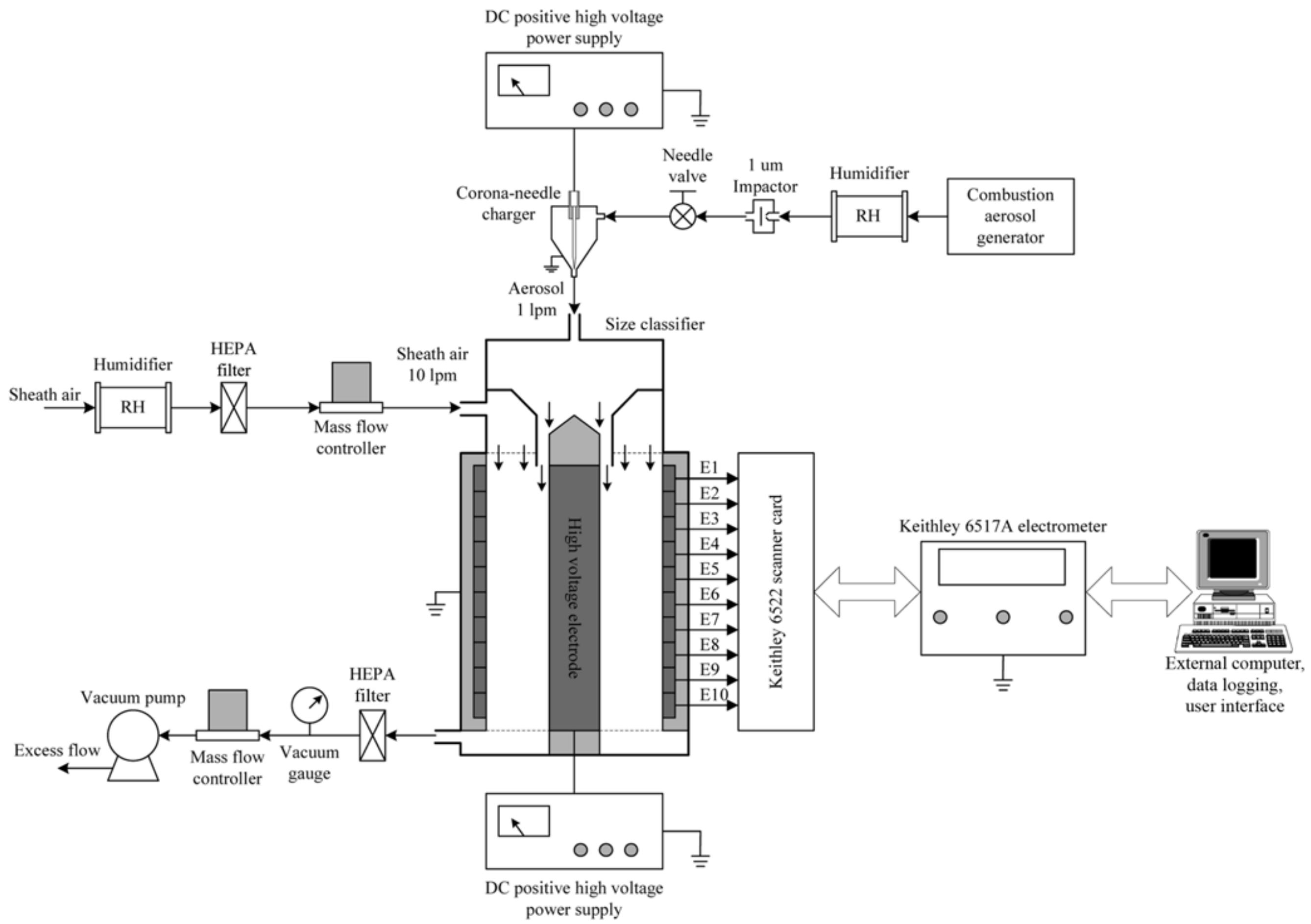


Fig. 4. Experimental setup to characterize the short EMS.

and electric fields inside the size classifier column.

A multi-channel Keithley 6517A electrometer incorporating a Keithley 6522 low current scanner card interfaced to an external personal computer via RS-232 serial port interface connected to these electrometer rings measures signal currents corresponding to the number concentration of particles of a given mobility which is related to the particle size. Software running on an external computer was developed, based on Microsoft Visual Basic programming for all data processing. This software is able to display both size distribution and number concentration.

PERFORMANCE EVALUATION OF THE SHORT EMS

To investigate the performance of the short EMS, the SEM technique was used [8,9]. A schematic diagram of the experimental system used to evaluate the performance of the short EMS is shown in Fig. 4. 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^{13} particles/m^3 were obtained [15]. An adjustable DC high voltage power supply, Leybold Didactic model 521721, was used to maintain the voltage difference between the inner and outer electrodes of the classifier, typically in the range between 1.0-3.0 kV. The short EMS was operated at aerosol flow rate in the range of 1.0-3.0 *l*/min, and pre-filtered sheath air flow rate of 10.0 *l*/min. To increase mobility resolution for particles with diameter greater than 100 nm, the short EMS was maintained at sub-atmospheric pressure in the range of 526-580 mbar [7]. Finally, the deposited particles inside the classification column at each electrometer ring were analyzed for their size by using the SEM. The particle sizes obtained from SEM were approximately 10-1,000 nm. Fig. 5 shows the particle morphologies of agglomerates collected obtained from the scanning electron micrograph (taken with a JEOL JSM-6335F Field Emission-SEM, operated at a 15 kV and magnification of 27,000×).

Fig. 6 shows a comparison of the predicted geometric midpoint mobility diameter with average measured geometric mean equivalent sphere projected area diameter from SEM observation at selected electrometer ring in the classifier column. The data represented particles in the size range between 50-550 nm. It was found that the diameters derived from projected surface area of agglomerates analyzed by SEM agreed well with those predicted from particle mobility diameter by the short EMS. The largest difference observed was about 15% at 130 nm. For other sizes, the differences were within 5%. Taking into account the fact that the classification performance of our short EMS approximately followed the theoretical prediction, a 15% difference was considered to be acceptable. It was therefore confirmed that the spectrometer was capable of correctly determining particle mobility diameter. The reason for the difference of the mean particle diameter obtained by SEM and the short EMS was considered to be due mainly to the non-spherical shape of the particles and the multiply charged particles [16]. Another reason for the underestimation of SEM might be the simplification of the SEM size measurements, which were the lack of high quality focusing (which probably had 5-10% measurement uncertainty), changes in particle sizes during sampling, calibration errors, all the coagulated particles shown in these figure were formed on the SEM sampling plate, and difficulties in size determination. In case of coagulated particles, because the mobility of a sphere having volume equivalent to such coagulated particles was slightly greater than the coagulated particles, the size of primary particles of the coagulated particles classified by the short EMS was slightly smaller than the predicted size of the short EMS. The detailed reasons for these differences should be theoretically and experimentally investigated further.

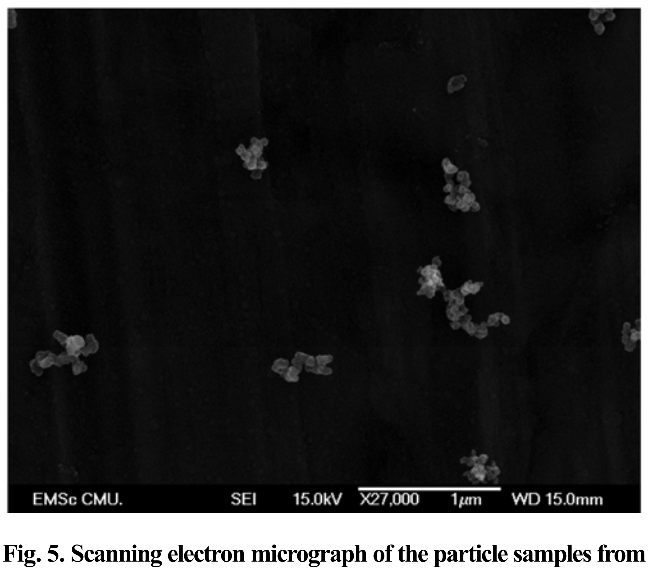


Fig. 5. Scanning electron micrograph of the particle samples from the generator.

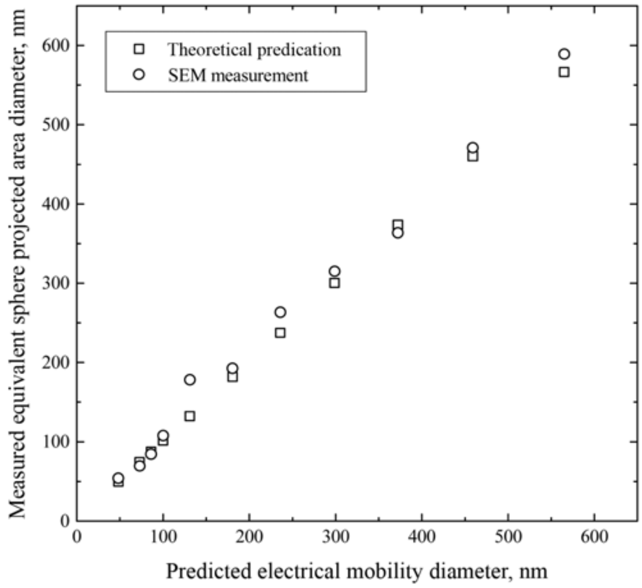
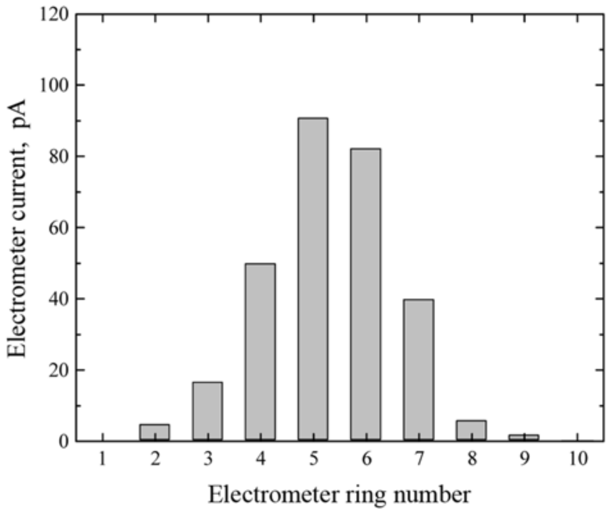


Fig. 6. Comparison of mean particle diameters between the short EMS and SEM measurements.

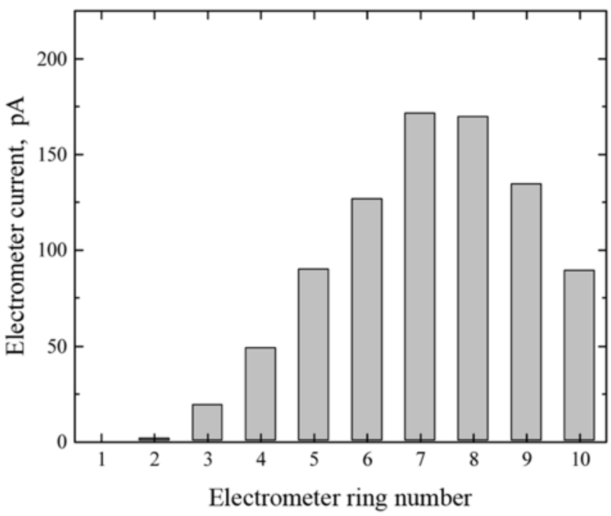
RESULTS AND DISCUSSION

1. Effect of the Aerosol Flow Rate

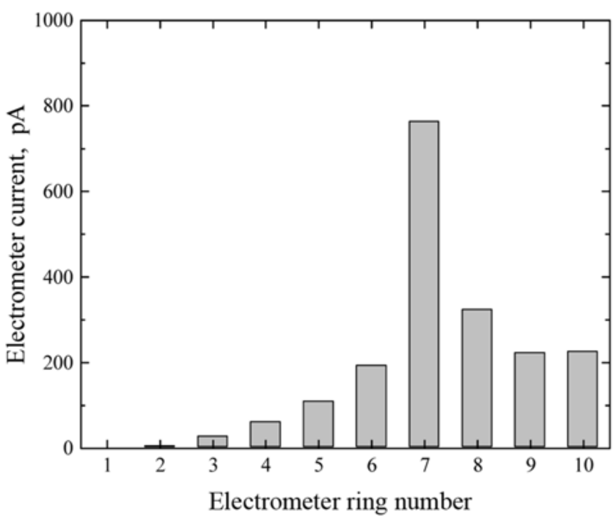
The aerosol flow rate was varied by adjusting the inlet mass flow controller, Dwyer GFC-1142, in the range of 1.0-3.0 *l*/min. Fig. 7 shows the signal current measured at each electrometer ring of the



(a) 1.0 l/min



(b) 2.0 l/min



(c) 3.0 l/min

Fig. 7. Measured electrical signals from the short EMS (10.0 *l*/min sheath air flow, and 3.0 kV inner electrode voltage).

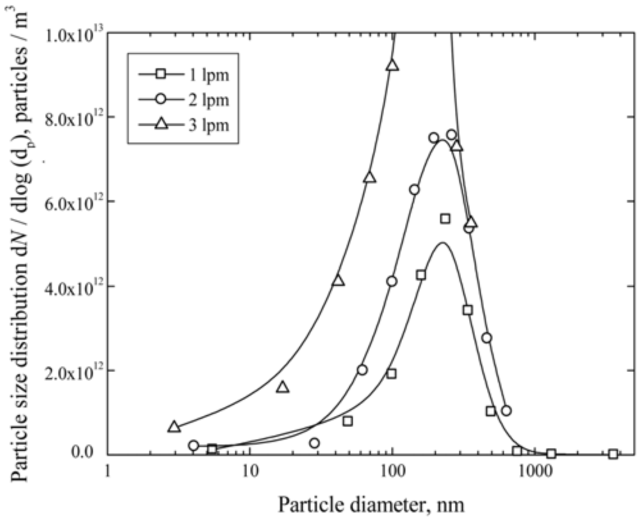


Fig. 8. Particle size distributions from the short EMS (10.0 *l*/min sheath air flow, and 3 kV inner electrode voltage).

classifier for the inner electrode voltage of 3 kV; the sheath air flow rate was set at 10.0 *l*/min, and the operating pressure in the range of 526-580 mbar. It was found that 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 shift of peak current at each electrometer ring was the major cause of this phenomenon. Fig. 8 shows particle size distribution at different aerosol flow rates. At high aerosol flow rates, the measured particle size distribution range was relatively low for a fixed inner electrode voltage. Faster aerosol flow rates forced a particle of a given size to impact the wall further downstream. Likewise, higher aerosol flow rates resulted in a shorter aerosol residence time in the charger, leading to a poorer performance of the particle charger. Higher aerosol flow rates caused a high number concentration of charged particles, as shown in Fig. 7. It should be noted that at high number concentration of charged particles, the cloud of unipolarly charged particles migrating toward the electrometer ring created a space-charge field that was superimposed on the applied field. This led to a voltage shift and mobility classification breakdown due to strong space-charge effects in the classifier [17,18]. It was also observed that operation at these conditions may lead to a breakdown in mobility classification due to strong space-charge effects in the classifier. A breakdown in mobility classification was observed at electrometer ring number 7 with aerosol flow rate of 3.0 *l*/min; the current was found to exhibit a fluctuation in an uncontrollable manner, Fig. 7(c).

2. Effect of the Size Classifier Voltage

Three different classifier operating conditions were experimentally studied for the effect on the signal current and particle size range measurements. Electric field strength was varied by adjusting the high voltage applied to the inner electrode of the classifier. Fig. 9 shows a representative set of signal currents measured at each electrometer ring of the short EMS. These measurements were taken at an aerosol flow rate of 1.0 *l*/min, a sheath air flow rate of 10.0 *l*/min, Reynolds number of 116.6, and an operating pressure of 526 mbar. The inner electrode voltage was varied in the range of 1.0 to 3.0 kV. The measured electrical current from the electrometer was

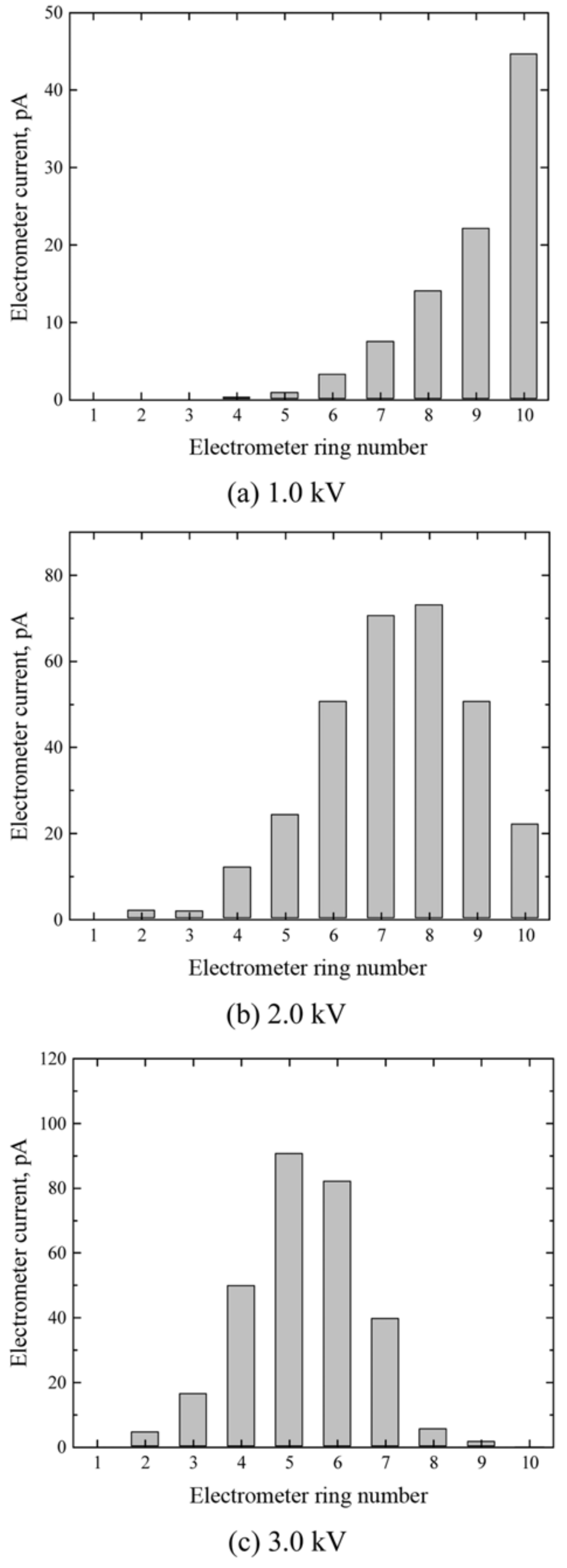


Fig. 9. Measured electrical currents from the short EMS (1.0 *l*/min aerosol flow, 10.0 *l*/min sheath air flow, 116.6 Reynolds number, and 526 mbar operating pressure).

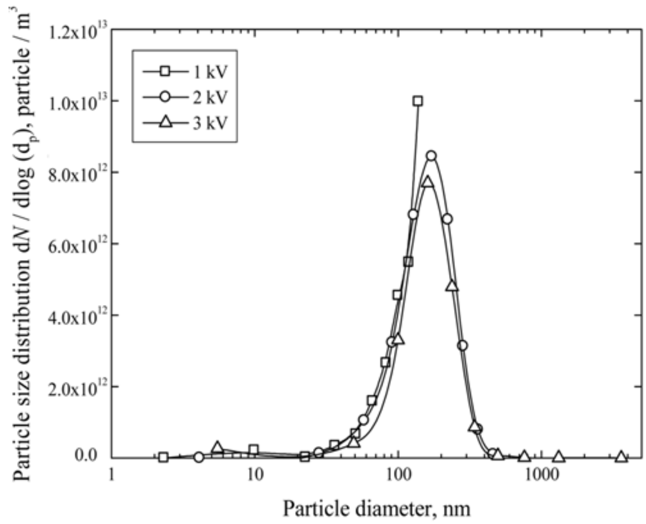


Fig. 10. Particle size distributions from the short EMS (1.0 *l*/min aerosol flow, 10.0 *l*/min sheath air flow, 116.6 Reynolds number, and 526 mbar operating pressure).

in the range between 1-100 pA. An overall shift in the peak current as a result of the different electric field strengths is shown in Fig. 9. At high inner electrode voltage, the peak signal current shifted from the last electrometer ring closer to the first electrometer ring. As shown in Fig. 10, the increase in the inner electrode voltage resulted in the increase of the measured particle size distribution range. This was expected because the electrical mobility of 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. It should be noted that the inner electrode voltage was limited by the breakdown voltage. For air at 20 °C and 1 bar pressure, the breakdown voltage is approximately 30 kV/cm. For the 15 mm gap between the inner and outer electrodes, this amounted to a breakdown voltage of 45 kV. Assuming that a large margin of safety was used to guard against the possibility of electrical breakdown, the inner electrode should easily be capable of handling 20-30 kV. In practice, the maximum applied voltage was restricted to 25 kV by the limitation of the power supply used.

3. Short EMS Time Response

The short EMS time response, defined as sample transport delay time between the aerosol sample inlet and the electrometer rings of the size classifier column of the short EMS, was investigated by means of the step change in the concentration of the incoming aerosol sample. Figs. 11 and 12 show the time response of the short EMS to step changes in aerosol sample concentration. The short EMS operating conditions were 1.0 *l*/min aerosol flow rate, 10.0 *l*/min sheath air flow rate, Reynolds number of 117, and 1.0 kV inner electrode voltage. For this operating condition, the peak in the signal current was found to be at 143 nm, corresponding to the electrometer ring 10. Both figures showed time responses at the electrometer ring 10 of the classifier column. Fig. 11 corresponds to the measurement starting while Fig. 12 corresponds to the measurement stopping. As shown in Fig. 11, the time response for the aerosol concentration changing from zero to slightly steady-state value was in the order of approximately 46 s. Fig. 12 shows the time response of

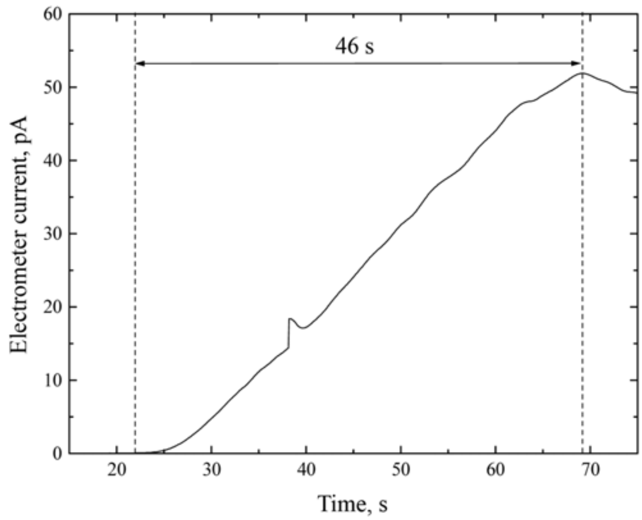


Fig. 11. Short EMS time response to aerosol step up change (measurement staring) at electrometer ring 10 (1.0 *l*/min aerosol flow, 10.0 *l*/min sheath air flow, 1.0 kV inner electrode voltage, and 526 mbar operating pressure).

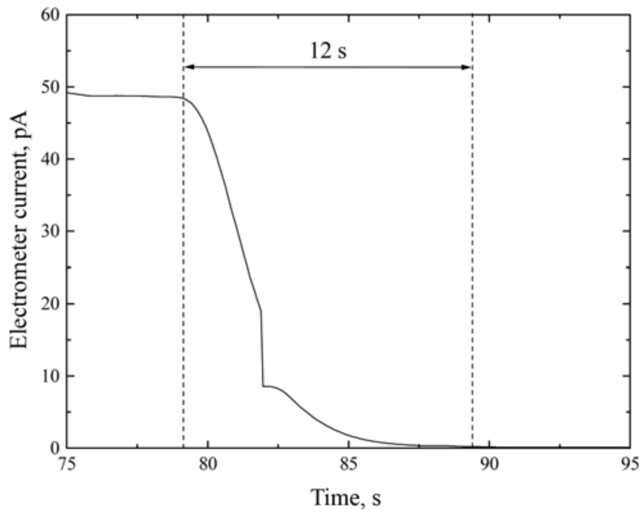


Fig. 12. Short EMS time response to aerosol step down change (measurement stopping) at electrometer ring 10 (1.0 *l*/min aerosol flow, 10.0 *l*/min sheath air flow, 1.0 kV inner electrode voltage, and 526 mbar operating pressure).

the aerosol concentration changing from steady-state value to zero, about 12 s. The time response of the short EMS was relatively short. This instrument time response may be improved by increasing the sheath air flow rate in the classifier column. It should be noted that at high sheath air flow rate, the fluid flow field became more unstable.

4. Measurement Repeatability

The repeatability of test run results is essential to the quality of a particle sizing instrument. Repeatability is the deviation of the results acquired from the same sample and measured by the same instrument many times. Fig. 13 shows the repeatability of the measured electrometer current at each electrometer ring for a 10 times recording. The short EMS operating conditions were 1.0 *l*/min aerosol flow rate, 10.0 *l*/min sheath air flow rate, 116.6 Reynolds number, and

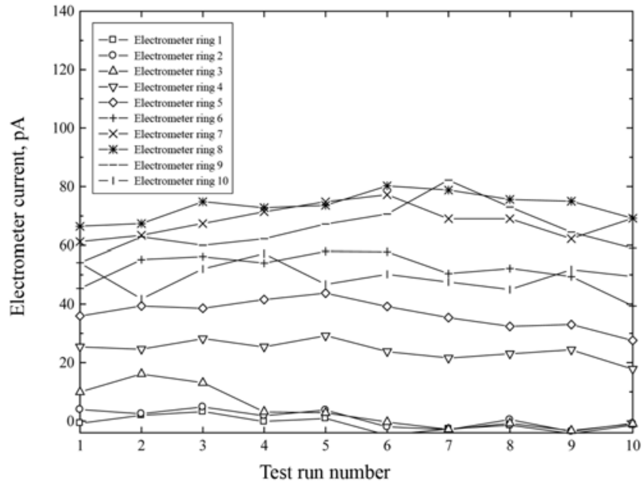


Fig. 13. Measurement repeatability of the short EMS (1.0 *l*/min aerosol flow, 10.0 *l*/min sheath air flow, 2.0 kV inner electrode voltage, and 526 mbar operating conditions).

2.0 kV inner electrode voltage. The peak current was found to be at the 8th 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. For example, in electrometer ring 8, a standard deviation was 4.57 with the relative error of about 6.23%. To enhance measurement repeatability, deviations from the measured current should be minimized. The possible error source is the stability and variability of the aerosol generator itself. It is known that the stability of the instrument is also dependent on the environment, including temperature and humidity. Vibrations and fluctuations in the power supply can lead to discrepancies in the measurements.

5. Limitations

The measured particle size range of the classifier is limited by particle diffusion and electric field between the electrodes. Particle diffusion determines the lower size limit, whereas electric field between the electrodes determines the upper size limit. The largest particle size that can be measured at a given flow rate with the classifier is thus limited by the gas breakdown voltage. For air at 20 ºC and atmospheric pressure, the gas breakdown voltage is approximately 30 kV/cm. To extend the measured particle size range and resolution of the instrument, it is therefore desirable to increase the physical length of the classification section. This can be achieved by simply lengthening the existing classifier column and increasing the number of electrometer rings. Because the electrical mobility of collected particle is a linear function of axial length within the size classifier, the change in electrical mobility with increasing particle size becomes much smaller as particle size increases. Consequently, in order to maintain good resolution across the particle size range, the electrometer ring width should be small at the entrance of the classifier, and can be allowed to increase gradually toward the exit of the classifier. By increasing the electrometer ring width close to the exit of the classifier, a larger range of particle sizes may be collected on a single electrometer sensor, thus increasing signal strength sufficiently to avoid noise sensitivity issues.

The time response depends on two factors: the fluid time response and the electrical time response. For the fluid time response, simple improvement may be done by using high sheath air flow rate inside the classifier. For the electrical time response, sensitivity of the short EMS depends on the electrometer circuit sensitivity. The sensitivity of the electrometer circuit determines the range of particle number concentration which can be measured by the instrument. This sensitivity is limited by noise levels. Further research should be carried out to improve the sensitivity in order to increase the measured number concentration range. Another way to reduce the response time of the short EMS is by using high aerosol sample flow rates.

CONCLUSIONS

A short EMS design was introduced in this paper. The prototype instrument and its performance were described. Experimental validation of the short EMS was performed by using the SEM. Good agreement was obtained from the comparison between the short EMS classifier and the SEM analysis. Signal current from the detector was also analyzed to give the number concentration of particles. Experimental results obtained agreed well with the theoretical predictions. The short EMS is capable of measuring in the size between approximately 10 nm to 1,000 nm in diameter and the particle number concentration of 10^{11} to 10^{13} particles/m^3, with a time response of about 46 s.

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