CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORKS

The objective of this final Chapter of the thesis is to provide the main conclusions of the present work and provides recommendations for future works. The first Section of the Chapter gives the main conclusions for performance of each component of the EMS prototype. Finally, a few recommendations are proposed for future works on both the theoretical and experimental parts of the thesis.

6.1 Conclusions

6.1.1 Performance of Each Component

The following paragraphs provide the main theoretical and experimental of each component achievements of this thesis:

- A prototype of the unipolar needle and wire-cylinder corona charger based on corona discharge were designed, constructed and tested. The electrostatic properties in terms of voltage-current relationships of both needle and wire-cylinder corona chargers were compared and discussed for positive and negative coronas in the charging zone. Experimental investigation of the voltage-current characteristics of both chargers was compared with theoretical prediction. Results were used to characterize the electrostatic properties of both chargers. A semi-empirical method to calculate ion concentrations in the aerosol charger based on the ion current measurements was presented. Numerical models were successfully developed to investigate flow and electric field patterns in the charging zone of the charger. Analytical expressions were derived to yield the radial distribution of the $N_i t$ product, the corresponding particle penetration and average charge on particle of different sizes for the chosen charger geometry. Ion number concentration and electric field strength as a function of corona voltage were evaluated. The $N_i t$ product and resulting particle size-charge distribution were presented. It was also shown that the ionic space charge has a significant influence on the electrostatic properties of the charger and particle loss due to electrostatic attraction was not negligible. The needs for surrounding sheath flows to the aerosol stream and AC high voltage supply to increase charging efficiency were also discussed. Finally, the effect of particle deposition on the evolution of discharge current was presented.

- A prototype of the size classifier based on electrical mobility classification technique was designed, constructed and tested. Analytical and numerical models were successfully developed to predict the particle trajectories along the classifier column, mobility and size classification ranges of the classifier, and to investigate flow and electric field patterns inside the classifier. The overall performance of the instrument was tested with a polydisperse carbonaceous diffusion flame aerosol which was produced by the combustion aerosol generator. Its performance to evaluate particle size was compared with SEM results. Measured signal currents were used to evaluate number concentration of aerosol.

Comparison of the results with both the experimental and theoretical investigations of the size classifier showed good agreement for a range of operating conditions. Effect of electric field strength inside the classifier and aerosol flow rate on the signal current measurement of the instrument were presented and discussed. Finally, the EMS time response was also briefly addressed.

- A prototype of the electrometer circuit was designed, constructed and tested. The circuit was a combination of sample current to voltage converters and the two cascaded negative feedback amplifier. The analytical model was developed to calculate the output voltage of the circuit. The overall performance of the electrometer circuit was calibrated with a high impedance current source, and compared with a commercial electrometer, Keithley model 6517A. Experimental results were found to have good agreement between the in-house design and commercial one.

- A simple data acquisition and processing system was developed to convert the electrical mobility measurement to aerosol size distributions, based on Microsoft Visual Basic programming. The measurement system of the instrument was controlled and data sampled by an external personal computer via RS-232 serial port cable. It was capable of displaying both size distribution and number concentration.

6.1.2 Overall Performance of the Spectrometer

The 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% cutpoint is approximately 1 μm in diameter, and particle size resolution is 10 channels electrometer detector. The EMS is capable of aerosol size distribution measurements in the range of approximately 10 nm to 1000 nm in diameter with a time response is approximately 46 s for full up and down scan. The particle number concentration that the EMS can measure range with particle size is approximately 10^{11} to 10^{13} particles/m^3. The operating flow rate of the EMS should be set as the aerosol flow rate range from 1.0 to 2.0 l/min and the sheath air flow rate fixed at 10.0 l/min, and the inner electrode voltage of the classifier can be varied in the range from 500 – 3,000 VDC. The EMS operates at pressure below ambient, typically at 526 mbar. The computer requirements of the measurement system of the EMS is Pentium® 4 Processor or better with Windows® XP or better operating system, interfaced to an external personal computer via a 9-pin RS-232 serial port cable. A comparison between the present instruments and the existing instruments is shown in Table 6.1. It was shown that the specifications of the four instruments are likely to exist. Nonetheless, there were collective differences between the present spectrometer and each of the existing instruments, which were as follows; (i) the concept of the present instrument was based on a compact, inexpensive and portable unit. Short column classifier and a small number of detection channels were used to reduce diffusion effect of the particle inside the classifier. Overall dimensions and weight were such that it was easy to handle and move around; (ii) the instrument adopted 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 employed unipolar corona (diffusion and field) charging method; (iv) the applied voltage was set to maintain at low level, well below the corona onset voltage, to avoid unintentional charging of the particles inside the classifier; and (v) the incompressible Navier-Stokes equation and Maxwell's equations were numerically solved in previous studies (Intra and Tippayawong

2005) to investigate flow and electric fields inside the classifier and obtain appropriate dimensions, geometries and arrangement of the charger and the electrostatic classifier in this instrument.

Table 6.1 Comparison between the present instrument and the existing spectrometers

	EAS (Tammet *et al.* 2002)	DMS (Biskos *et al.* 2005)	BCAC (Kulon *et al.* 2001)	EMS (this work)
Measurement technique	Electrical mobility	Electrical mobility	Electrical mobility	Electrical mobility
Size range	10 to 10,000 nm	5 to 1,000 nm	< 3,000 nm	10 to 1,000 nm
Concentration range	$10^8 - 10^{11}$ to $2 \times 10^4 - 5 \times 10^7$ particles/m^3	1×10^9 to 4×10^{13} particles/m^3	n/a	10^{11} to 10^{13} particles/m^3
Time response	< 1 s	200 ms	10 s	30 s
Charger type	Corona charger	Corona charger	Corona charger	Corona charger
Charging method	Unipolar diffusion and field charging	Unipolar diffusion charging	Bipolar diffusion charging	Unipolar diffusion and field charging
Particle detector	Electrometers	Electrometers	Electrometers	Electrometers
Electrometer channels	26	26	10	10
Aerosol inlet technique	n/a	n/a	n/a	Tangential inlet
Aerosol flow rate	12 l/min	5 l/min	2 l/min	1 l/min
Sheath air flow rate	36 l/min	35 l/min	58 l/min	10 l/min
Operating pressure	n/a	25.3 kPa	n/a	34.5 kPa
Electrode applied voltage	800 V	5 kV to 10 kV	5 kV	500 V to 3 kV
Classifier length	n/a	700 mm	2000 mm	131 mm
Inner electrode radius	n/a	12.5 mm	1.5 mm	10 mm
Outer electrode radius	n/a	26.5 mm	25 mm	25 mm
Projected production cost	~ $ 80,000	~ $ 80,000	n/a	~ $ 20,000

n/a: information not available

6.2 Recommendations for Future Works

The following paragraphs give a few suggestions for further research on both the theoretical and experimental parts of this thesis, and provide some suggestions-improvements that can be included in future EMS refinement.

- For most impactors, the cut-point curve is 50% collection efficiency. The one of the principle limitations of the inertial impaction method is that a significant fraction of the particles greater than the cut-point diameter (50% is from particle larger than the cut-point) that pass through the impactor are contributed to multiply charged aerosols. These multiply charged aerosols have the same electrical mobility diameter, and may therefore be collected on the same electrometer ring. Consequently, the electrical signal current measured at any given electrometer ring will be due to particles of different physical sizes. Therefore, further research should be focused on the effect of a fraction of the particles larger than the cut-point diameter on the overall performance of the EMS.

- The actual charging performance of the charger should be investigated with monodisperse particles to determine the equilibrium unipolar charge distribution of the multiply charged particles at the outlet of the charger. Use of different aerosol generators that cover the greater size range will give a better understanding on the charging performance. The theoretical model of unipolar diffusion and filed charging used to examine the evolution of equilibrium charge distribution on monodisperse and polydisperse particles should be further studied. Testing of the charger has to be done experimentally, and the results should be compared with the different unipolar diffusion charging theories. Work towards improving the performance of the charger by reducing particle losses inside the charger should be studied. This can be carried out by (i) introduction of surrounding sheath air flows at the boundary between the aerosol stream and the wall to allow more space for the charged particles to follow the random paths without precipitating on the charger walls, (ii) application of an AC voltage to the electrode instead of DC voltage. The AC voltage was shown to produce high charging efficiencies due to lower particle losses.

- As diffusion charging is independent of particle material it can be concluded that for particles smaller than 0.5 μm particle material is irrelevant considering the charging process. For larger particles, depending on the dielectric constant of material. However, if the dielectric constant of particle material differs significantly from calibration mater values, the difference can be greater. Thus, the effect of particle dielectric constant on the charging performance should be theoretical and experimental studied further.

- The measured particle size range of the classifier is limited by two phenomena: 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 a classifier is thus limited by the gas breakdown voltage. For air at 20°C 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 extending the existing classifier column and increasing the number of electrometer ring. 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 increase. Consequently, in order to maintain good resolution across the particle size range, electrometer ring width should be minimized at the entrance of the classifier, and can be allowed to increase significantly 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 current sufficiently to avoid noise sensitivity issues.

- Due to practical materials and fabrication/assembly limitations, further investigation can be focused on phenomena that might affect the size classification performance of the classifier column such as non-ideal flow or electric field, inner electrode acentricity, and misalignment of various components.

- Further research should be theoretical analysis of the particle size distribution at each electrometer ring to give better understanding of the particle size classification performance of the classifier. In order to verify particle size predictions, direct measurements of particle size distribution at different axial positions along the electrometer ring surface within the classifier should be conducted further.

- When the aerosol number concentration is high, the cloud of unipolarly charged aerosol move outwards the electrometer rings creates a space charge field between two concentric cylinders which is superimposed to the applied field. This effect can cause voltage shifts and mobility classification breakdown. Therefore, further research should be theoretical and experimental studied the space charge field effect inside the classifier.

- In order to measure transient number concentrations of airborne particle size distribution in automotive exhaust gas, the time response of the instrument should be improved. The time response depends on two factors which are the fluid time response and the electrical time response. For the fluid time response, the easy way to improve the time response of the instrument is by using high sheath air flow rate inside the classifier. For the electrical time response, sensitivity of the 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 was limited by noise levels. Further research should be improved this sensitivity in order to increase the number concentration range. Another way to increase the sensitivity of the EMS is by using high aerosol sample flow rates.

- Most particles in nature such as asbestos fibers, soot aggregates, and bioaerosols are non-spherical. The shape of a particle affects the drag force, settling velocity and electrical mobility. Non-spherical particles have smaller electrical mobility than the spherical particles. In this thesis, all the theoretical predictions on the EMS were assumed for spherical particles. Therefore, further research may be focused on the effect of particle shape on the overall performance of the EMS. 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. Finally, calibration and comparison of the instrument with other particle measuring devices (e.g. SMPS, EAS, DMS, and ELPI) should be conducted further.